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Deep U-tube heat exchanger breakthrough: combining laser and cryogenics gas for geothermal energy exploitation

Cryogenics in the drilling of deep, multi kilometer geothermal wells

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Agenda

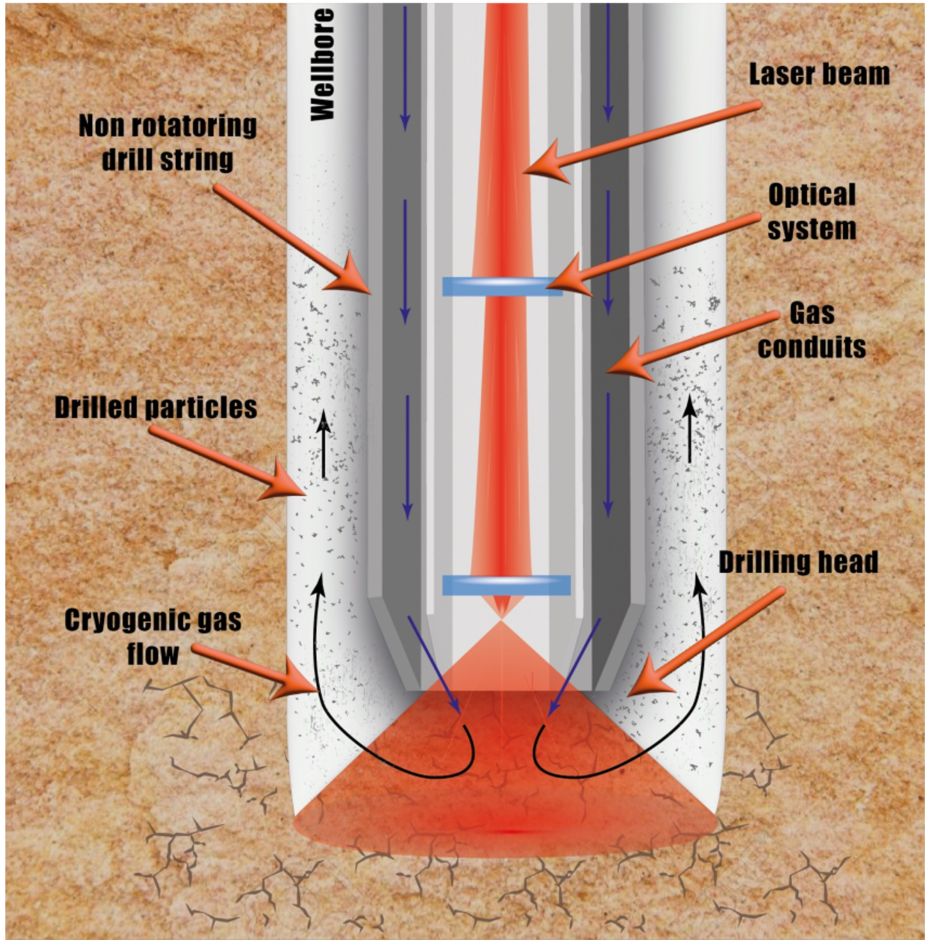
- Role of flushing medium for deep drilling
- Cryogenic supercritical nitrogen supply system
- Modelling and validation of pneumatic transport and supply system
- Mechanical design for a low temperature nitrogen supply system
- Risk assessment of a cryogenic system
- Summary

Flushing medium for deep drilling

The primary role of the flushing medium is to transport rock cuttings to the surface, remove excess heat and protect the lens housed within the drill head.

Due to the pressures reaching hundreds of bars and temperatures in the range of thousands of degrees present at the bottom of the borehole, water-based agents are not a suitable option, primarily because of the associated safety risks. In addition, thermodynamic stability, heat transfer capabilities, and economic feasibility must all be carefully considered.

Taking all these factors into account, the focus shifts toward gaseous flushing agents—particularly inert or noble gases. Based on the results of the economic analysis, **nitrogen** has been identified as the most suitable candidate for the flushing medium.



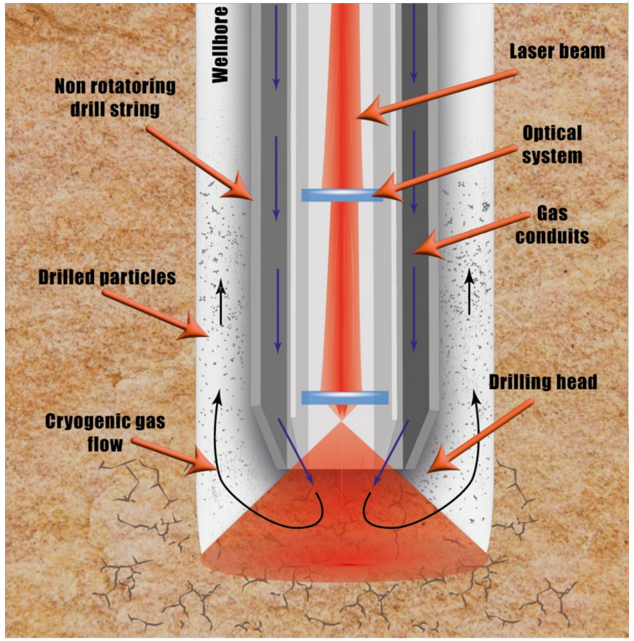
Process requirements

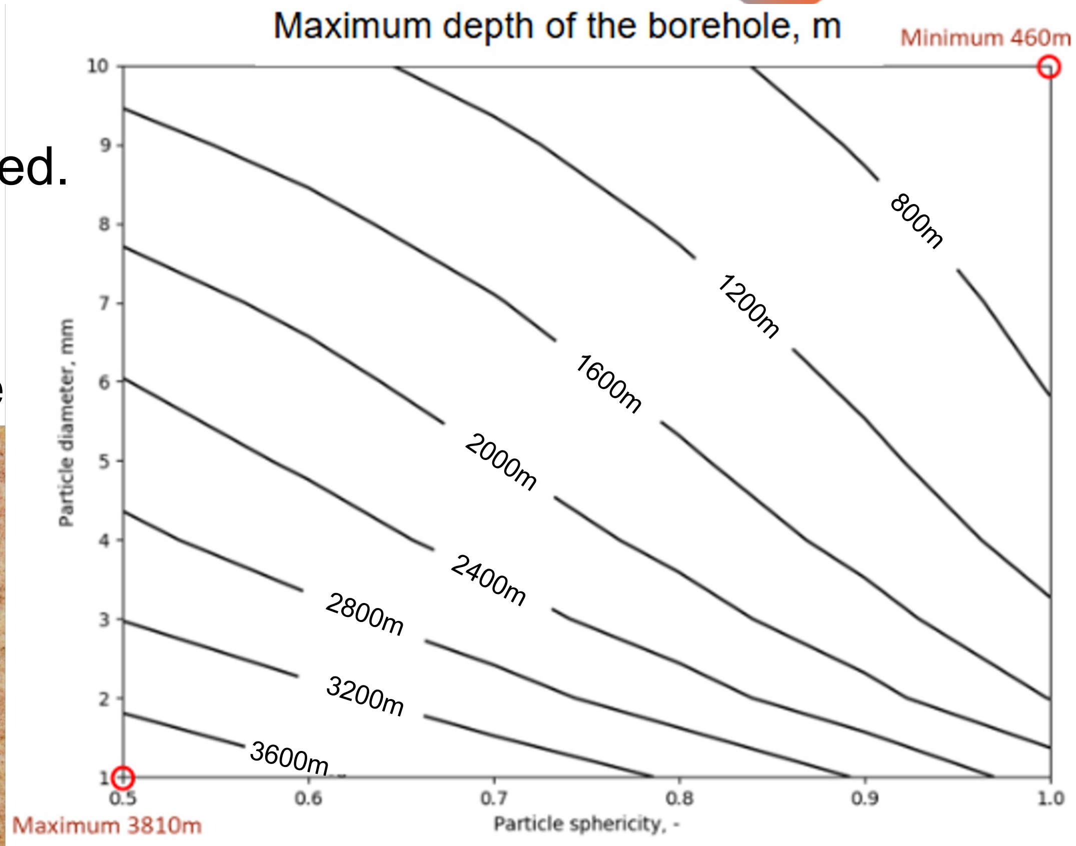
To clean the borehole of spalled or melted and resolidified cuttings, a sufficient flow rate of working gas must be supplied.

As borehole depths reach several kilometers, pressure losses in both the supply line and the return annulus may become a limiting factor for deeper operation if the pressure at the bottom is to be limited.

The required flow rate depends on several factors:

- Shape, size and density of the drilled particles
- Borehole depth, diameter, and annulus area
- Thermodynamic state of the flushing gas





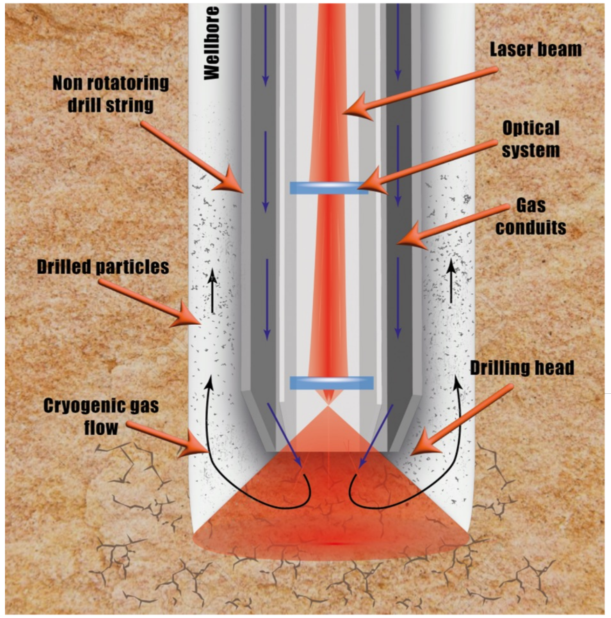
Assumption: pressure at the bottom limited to 30 bar(a). Higher allowable pressures enables deeper boreholes.

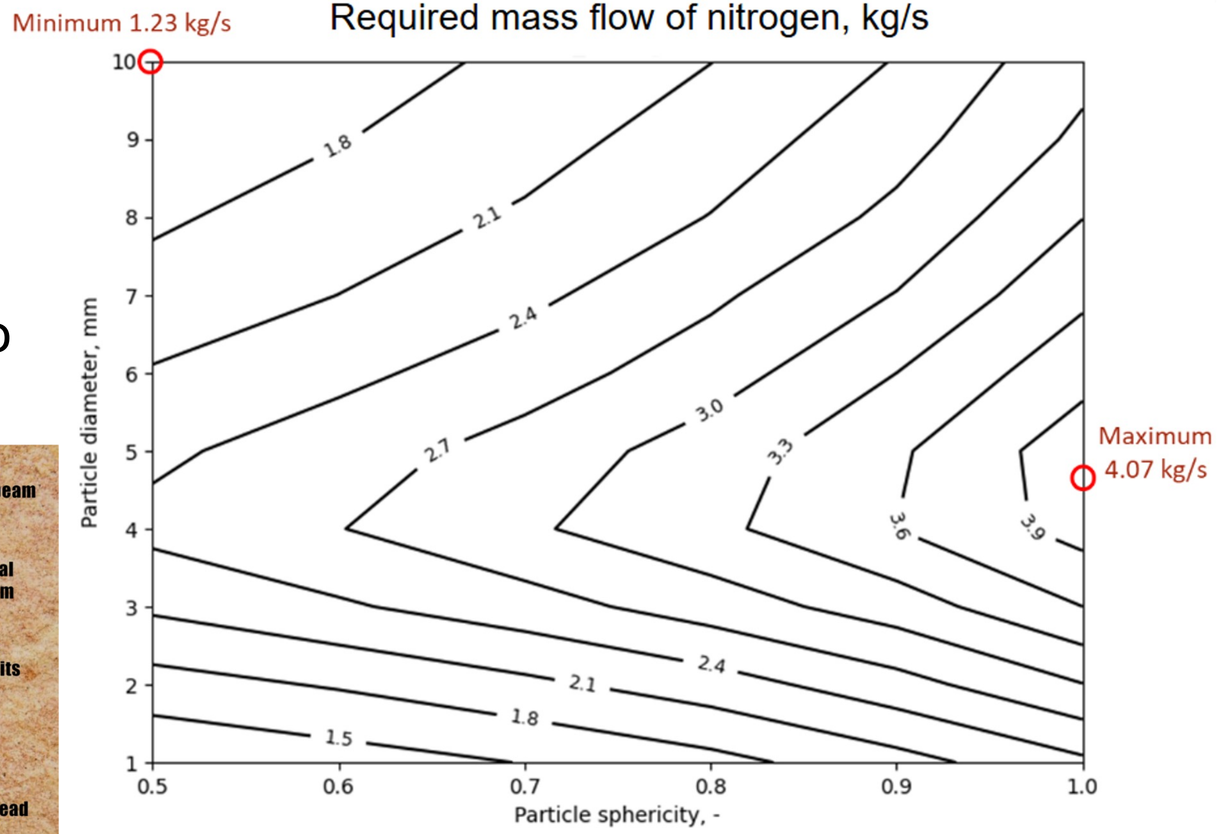
Process requirements – cooling and pneumatic transport

Since the mass flow rate required for pneumatic transport is the highest, meeting it also ensures sufficient cooling and effective lens protection.

Laser pipe severely limits the space available for the supply lines. Fluid with sufficient density is required to provide necessary flow rates at depths reaching over 4000m.

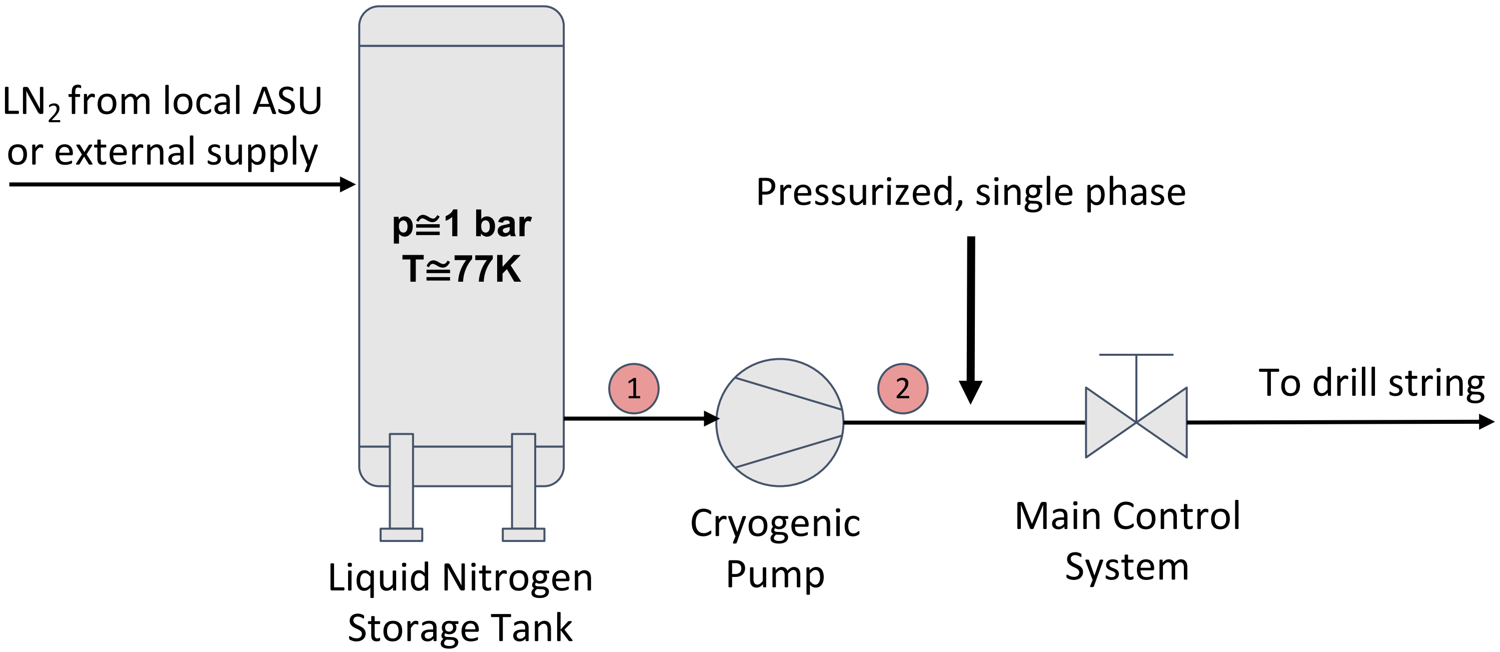
The supercritical state is essential to maintain an adequate mass flow rate despite significant pressure drops in small process pipes and to prevent the formation of two-phase flow.

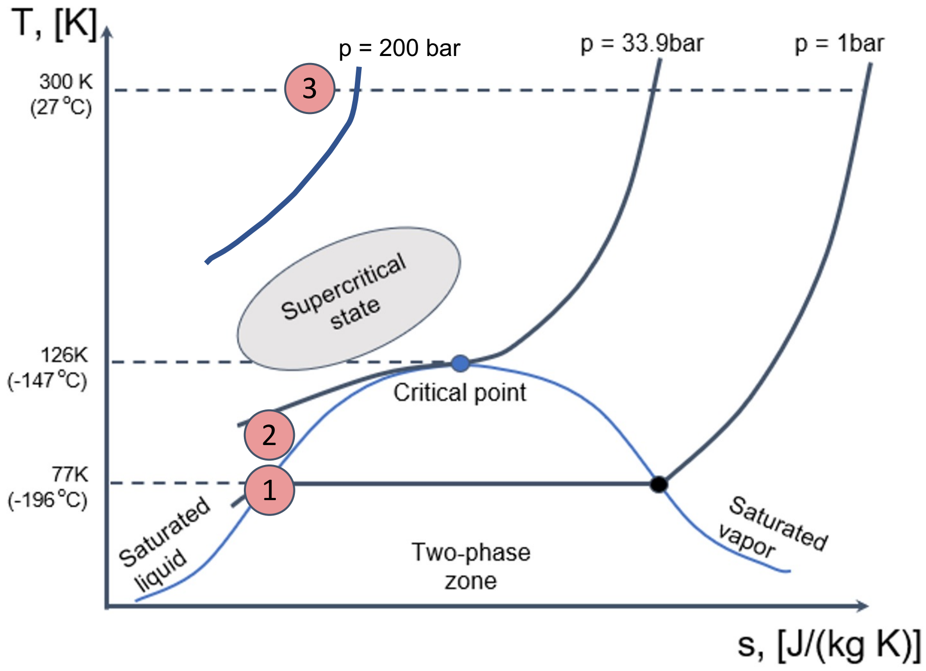




Assumption: pressure at the bottom limited to 30 bar(a). Higher allowable pressures require even higher mass flow rates.

Cryogenic supercritical nitrogen supply system





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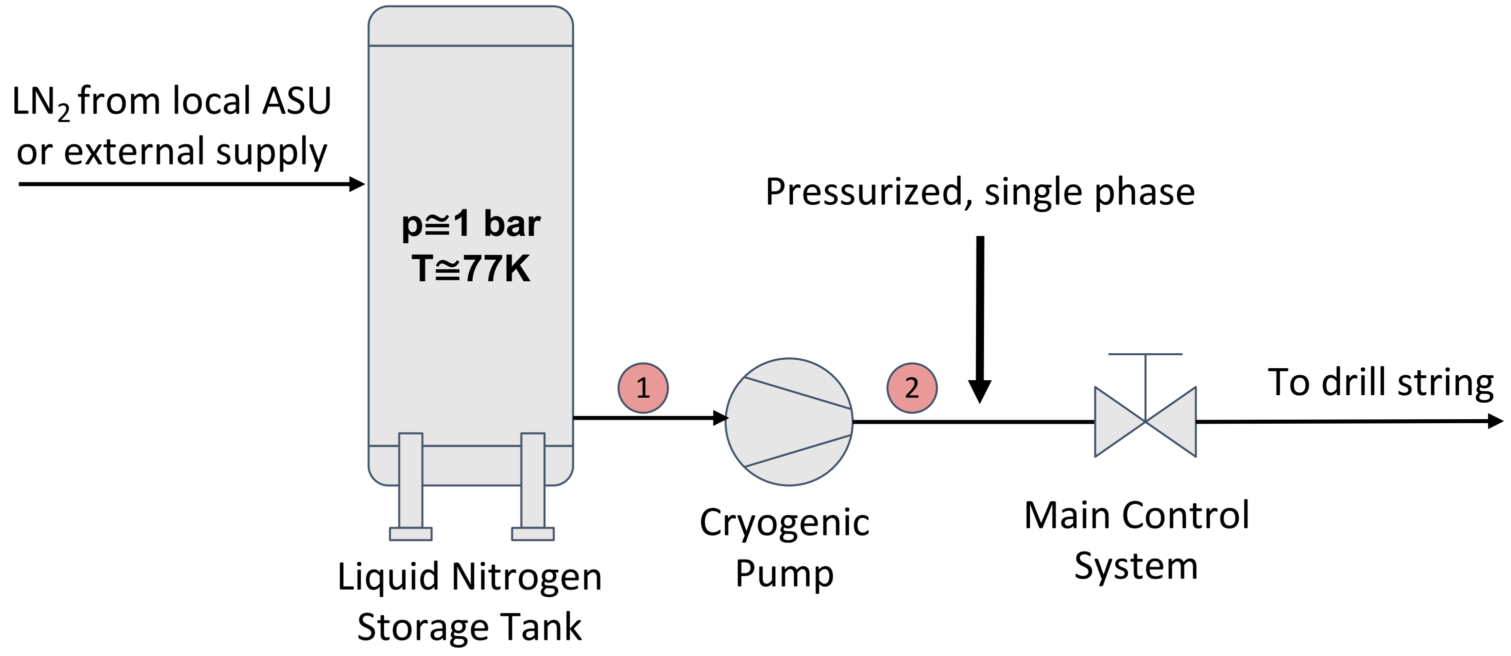
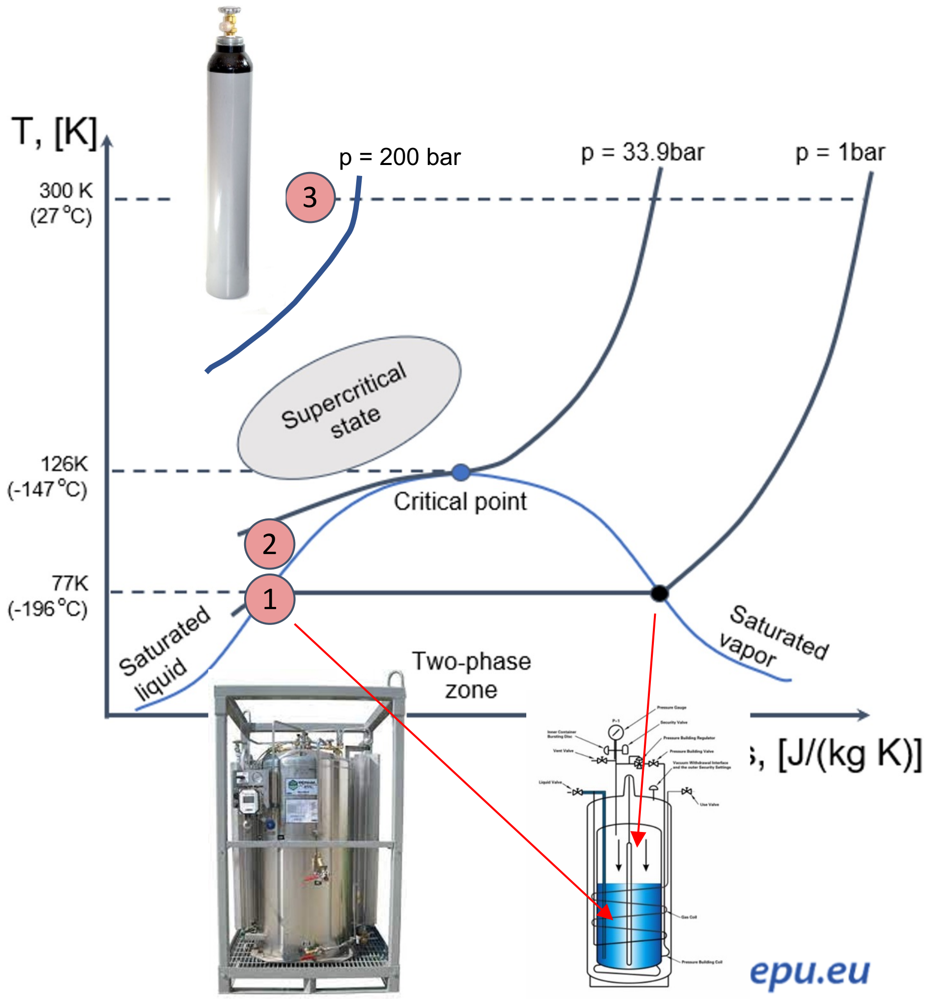
Cryogenic supercritical nitrogen supply system





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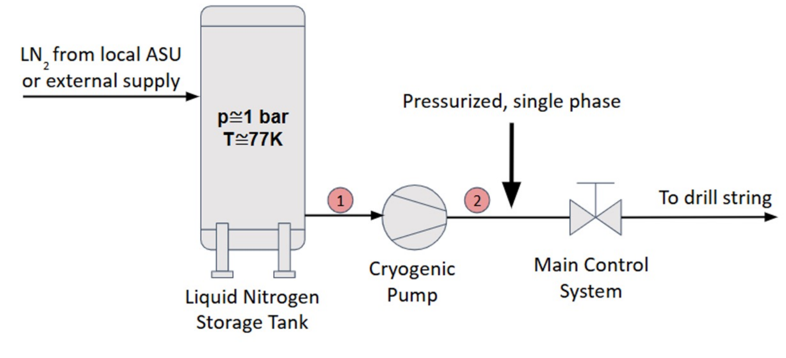
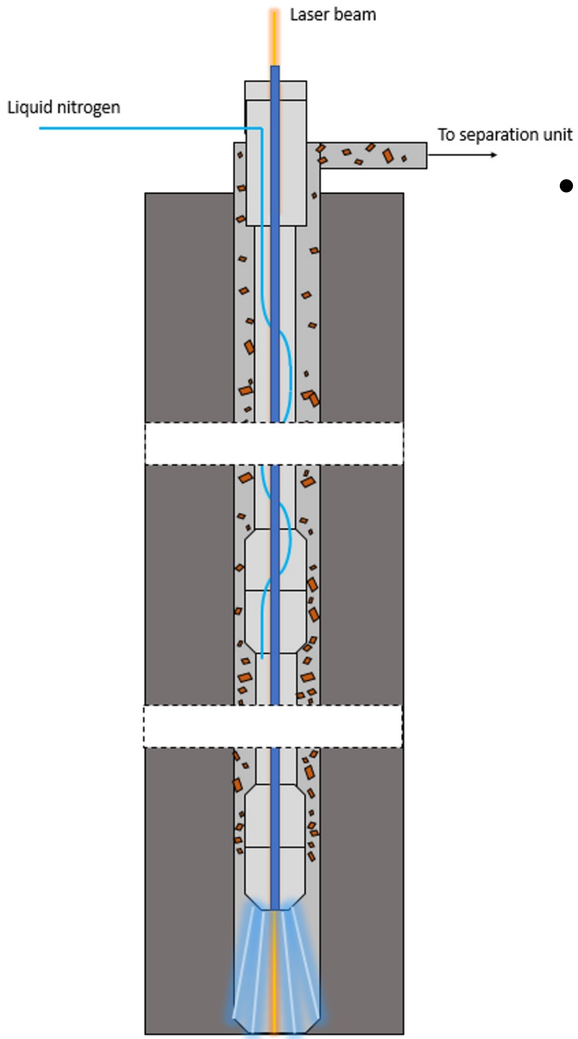
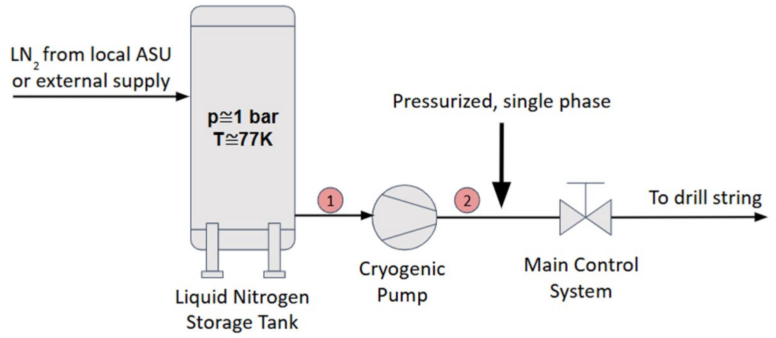
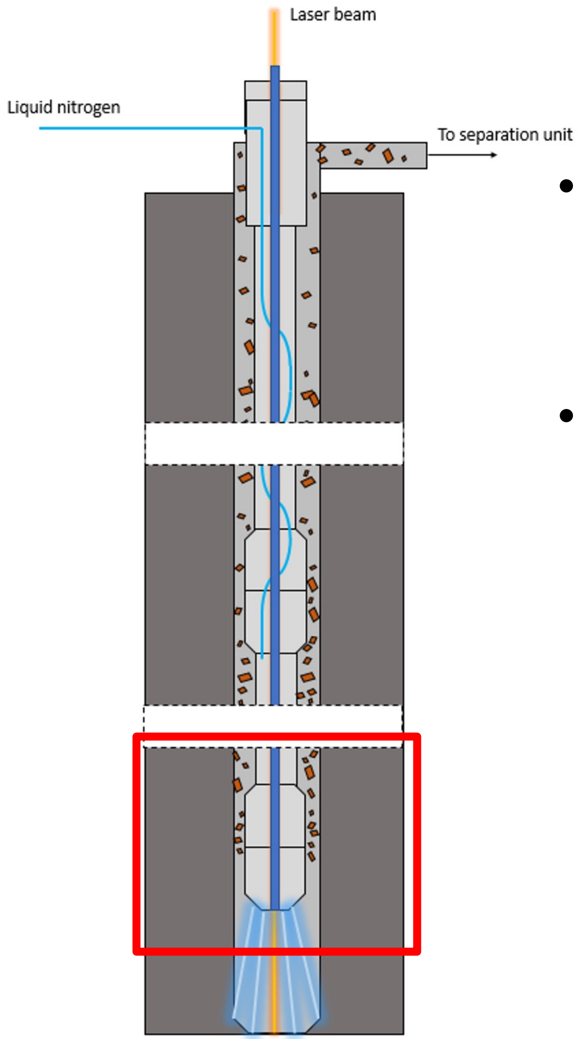




- Supercritical nitrogen is supplied to the drill string and must be delivered to the borehole bottom at sufficient temperature, pressure and rate.

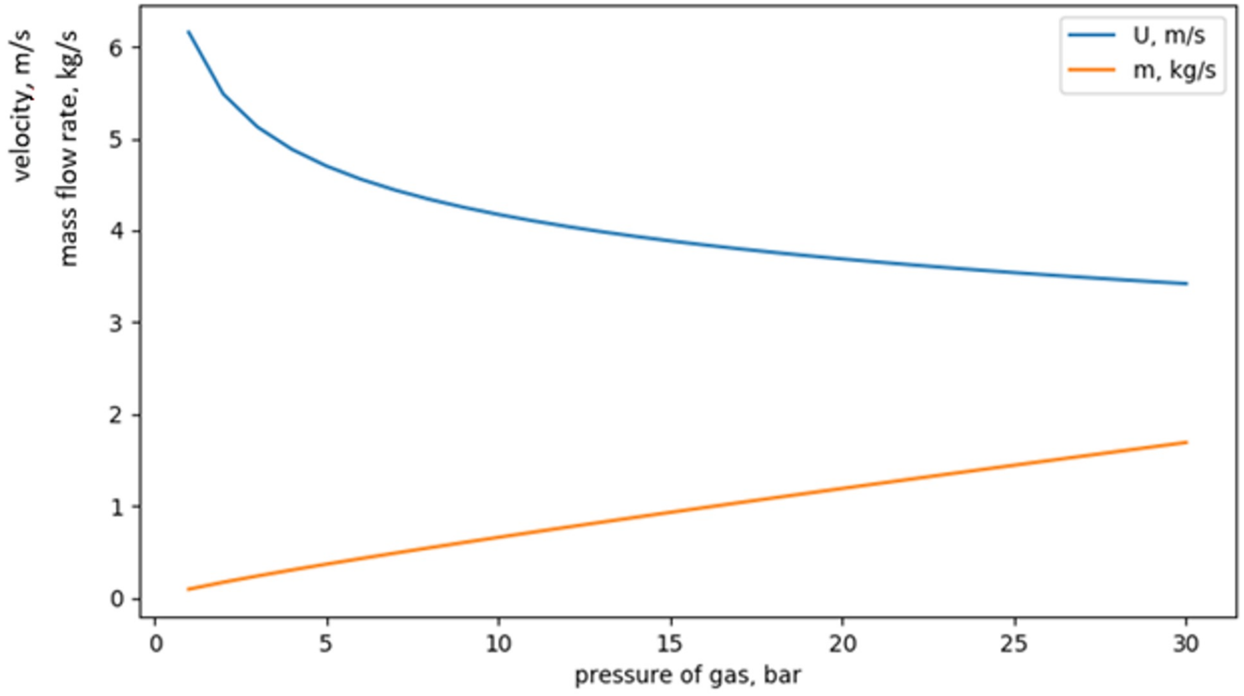




- Supercritical nitrogen is supplied to the drill string and must be delivered to the borehole bottom at sufficient temperature, pressure and rate.
- Pneumatic transport requirements were identified as essential for determining required mass flow of flushing medium

Pneumatic transport model

- Gas velocity ensuring pneumatic transport conditions decreases with pressure of the gas
- Required mass flow for pneumatic transport increases with pressure and so with the depth of the borehole



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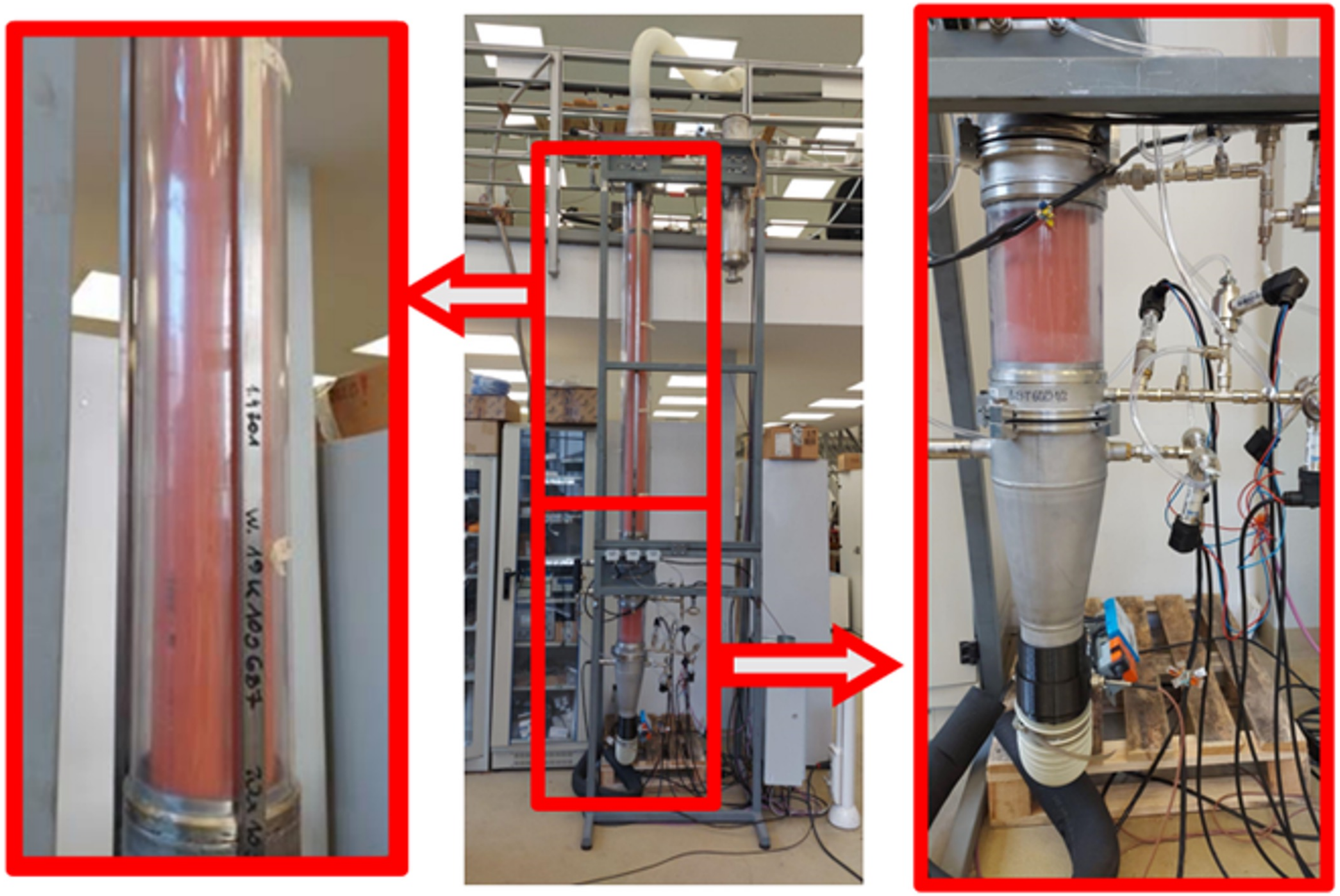
Model validation

Experimental test stand for pneumatic transport model validation consists of over 2-meter-long transparent PC pipe.

Borehole annulus geometry is consistent with test stand accordingly to the equivalent flow diameter.

The purpose is to ensure the model's accuracy and reliability by validating it against experimental results.



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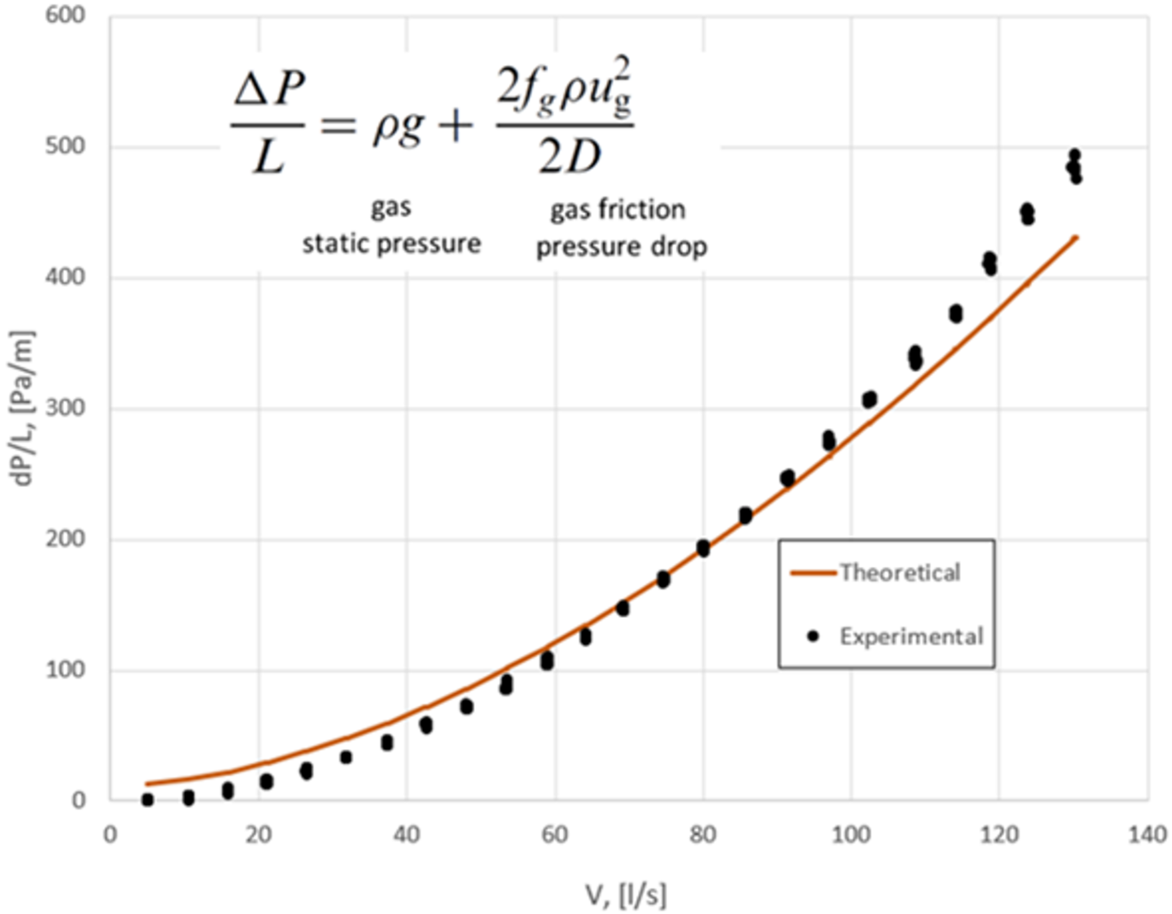
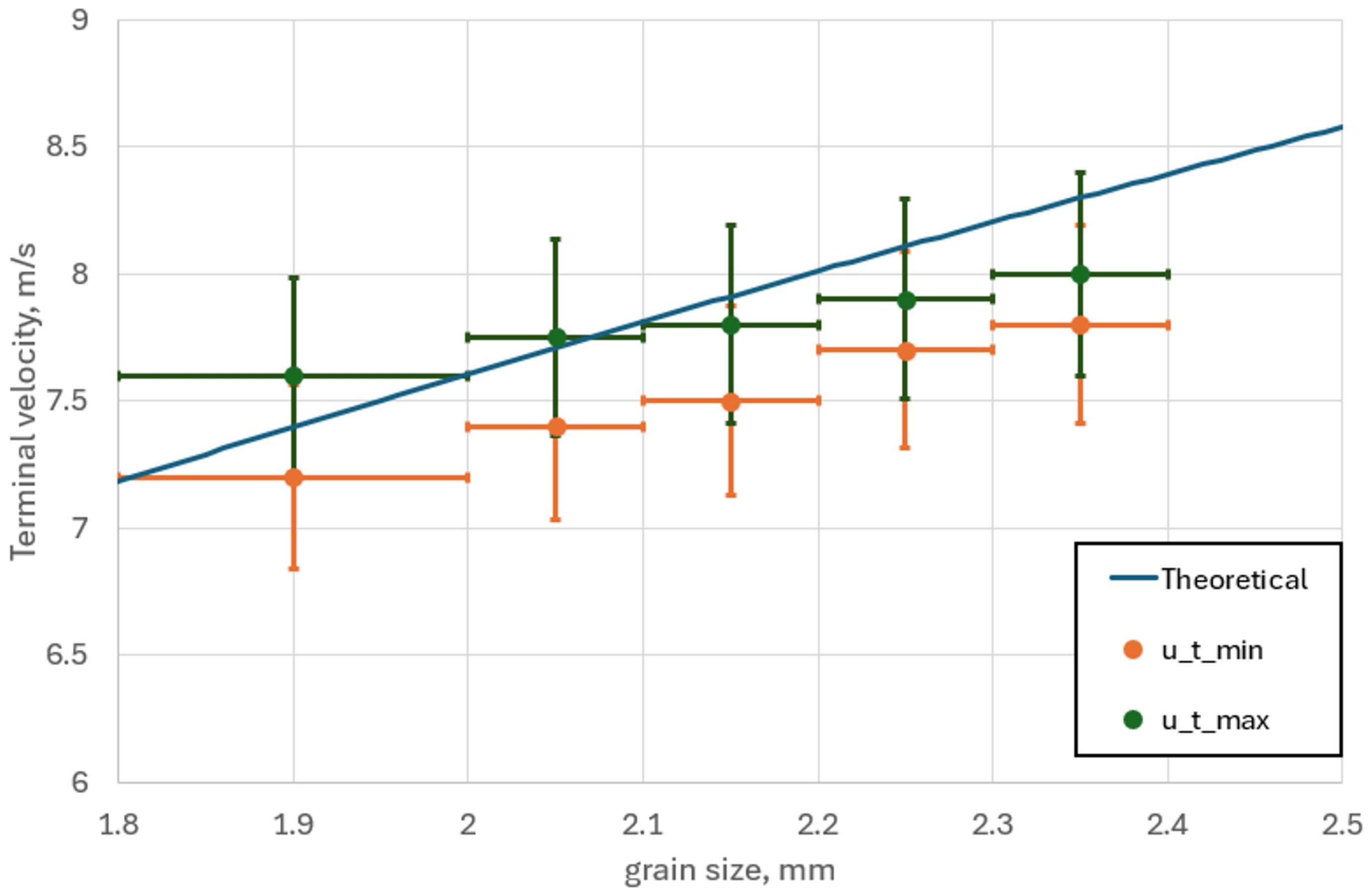
Model validation

An initial experimental campaign was conducted to measure pressure drop in a single-phase gas flow within an annular section without cuttings. The results showed good agreement with theoretical values.

Further experimental campaigns for two-phase flows (gas + cuttings) are planned with various cuttings size, density, shape, as well as variable flushing gas flow rate to validate complete theoretical model.



Model validation



- Zeolite particles
- Good agreement of the model with experimental values

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Model validation

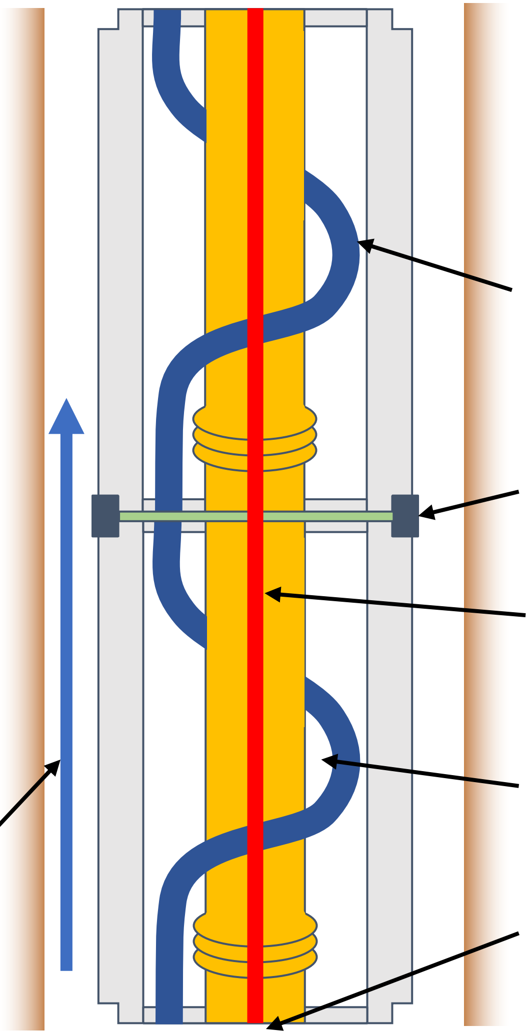
Table 4.2: Terminal velocity measurements with granite cuttings

Particle diameter, mm	Assumed sphericity, -	Theoretical terminal velocity, m/s	Measured lower terminal velocity, m/s	Measured upper terminal velocity, m/s
1	0.49	3.01	3.89+/-0.19	5.60+/-0.28
1	0.65	3.68		
2	0.49	4.37		
2	0.65	5.36		

Modelling of cryogenic laser drilling process

Complex analytical model had to be developed to cover following phenomena:

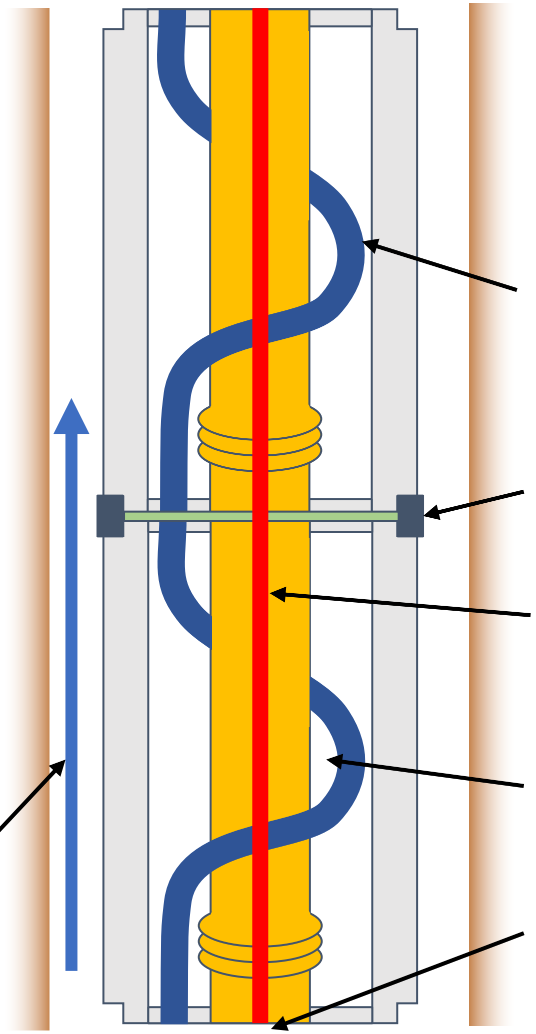
- Heat inleaks through insulation and coupling
- Pressure losses within supply pipe
- Pressure losses in the annulus from both solid and gas friction components
- Laser power dissipation into the returning supercritical nitrogen



Modelling of cryogenic laser drilling process

Complex analytical model enables:

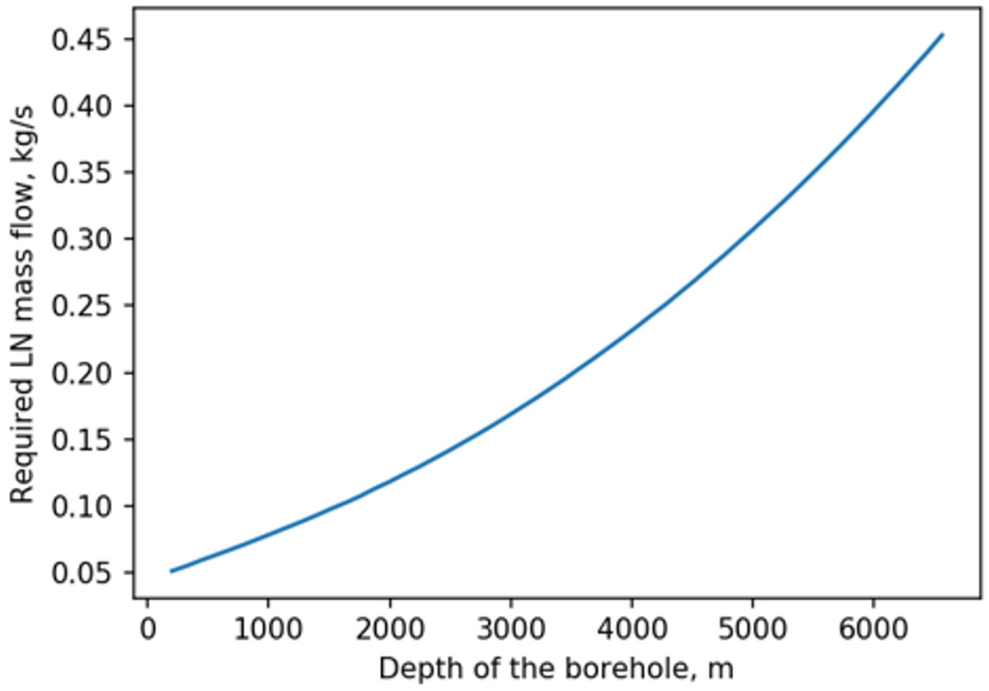
- Determine drilling depth for given parameters set
- Analyze the sensitivity of drilling performance to selected parameters and support the mechanical design



Modelling of cryogenic laser drilling process

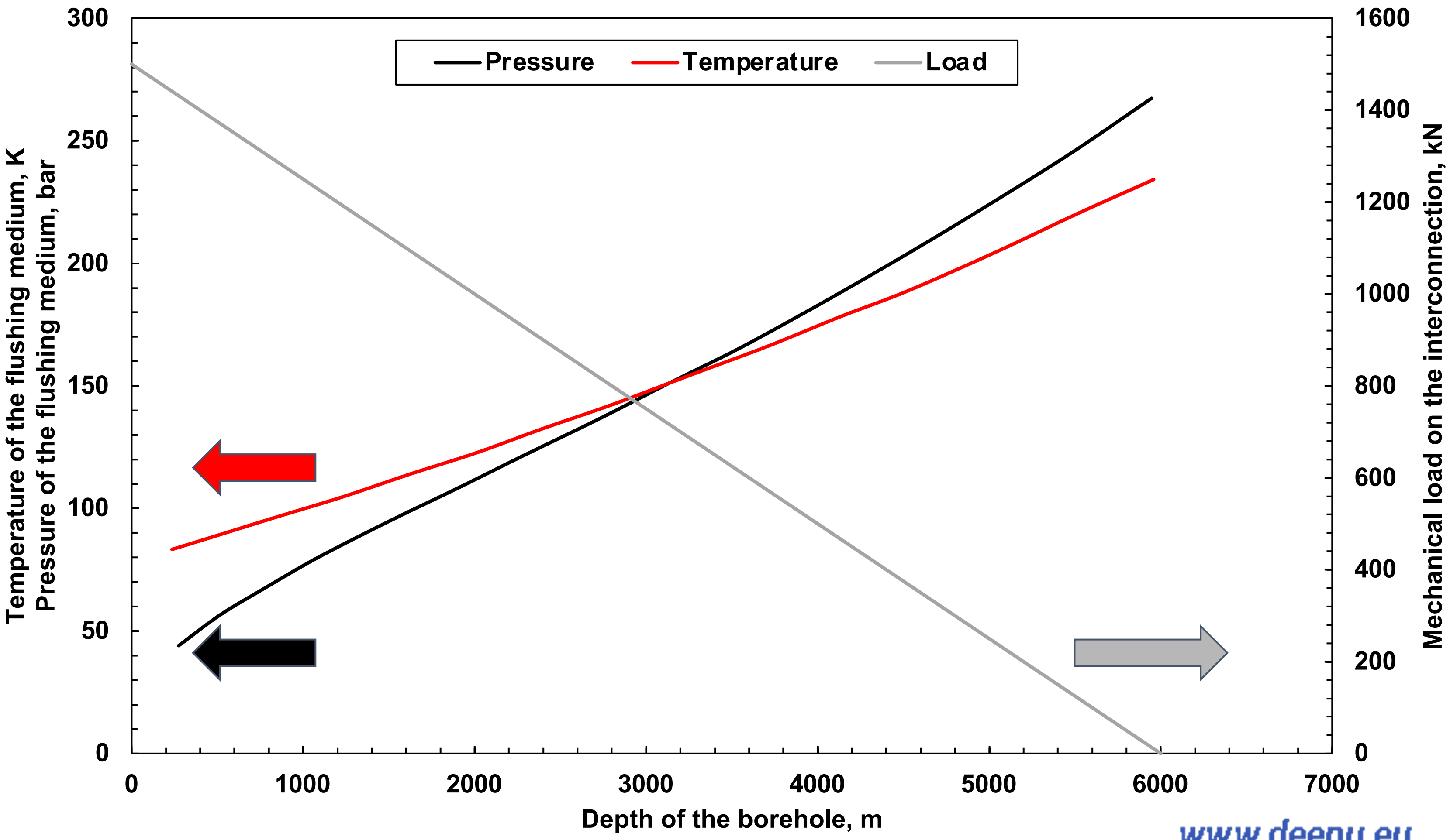
MAIN RESULTS:

- Drilling depth possible to 6500m for small particles and 5000m for bigger
- Performance depends strongly on heat inleaks
- Drilling depth can be further improved



particle diameter 1mm, sphericity 0.5, laser power 30kW, drilling speed 20 m/h, outlet pressure 2 bar,

- Important input for mechanical design
- Maximum values of mechanical load, pressure and temperature do not occur at the same depth



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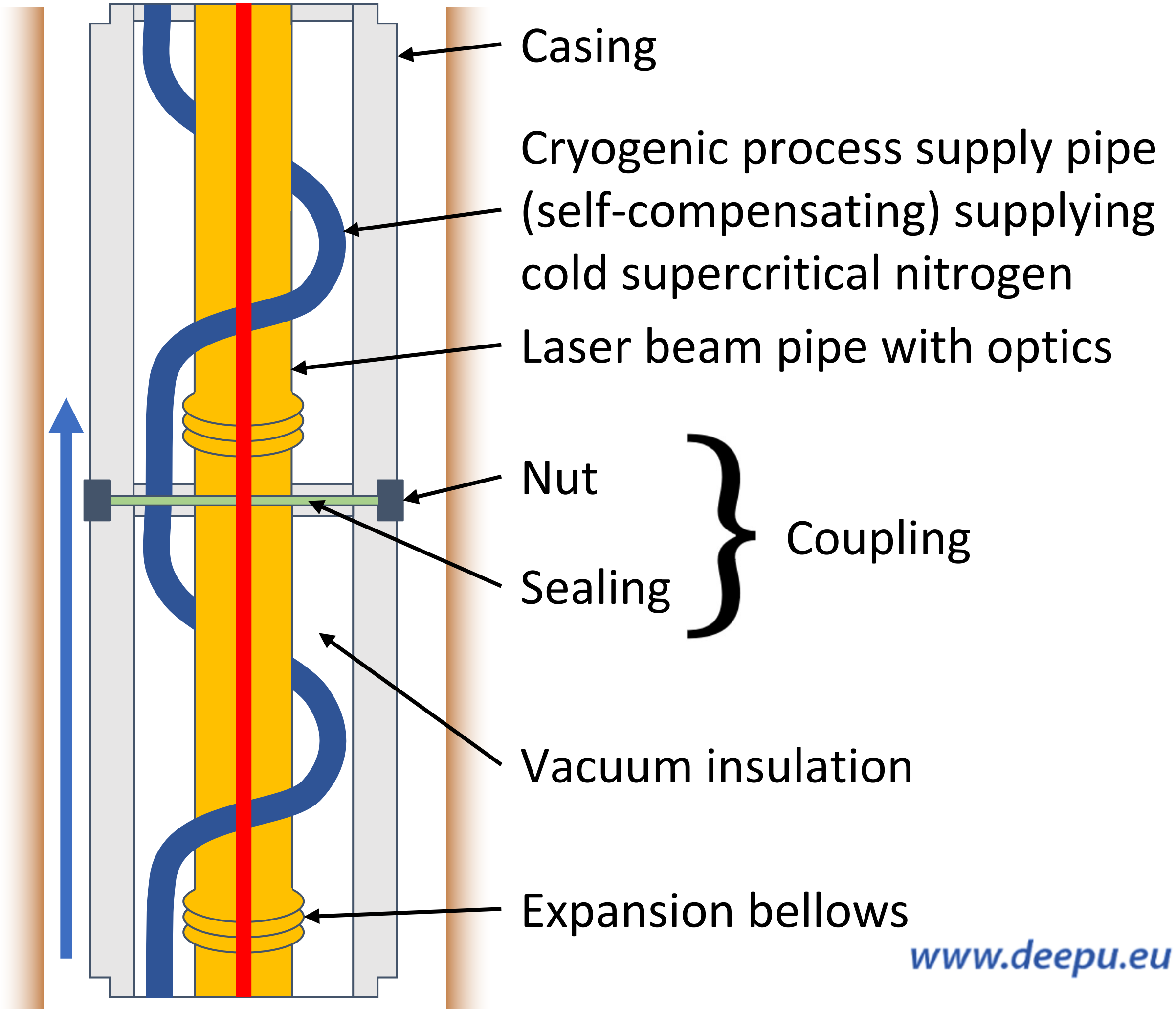
Mechanical design - requirements

The mechanical design of the cryogenic system must meet numerous requirements related to:

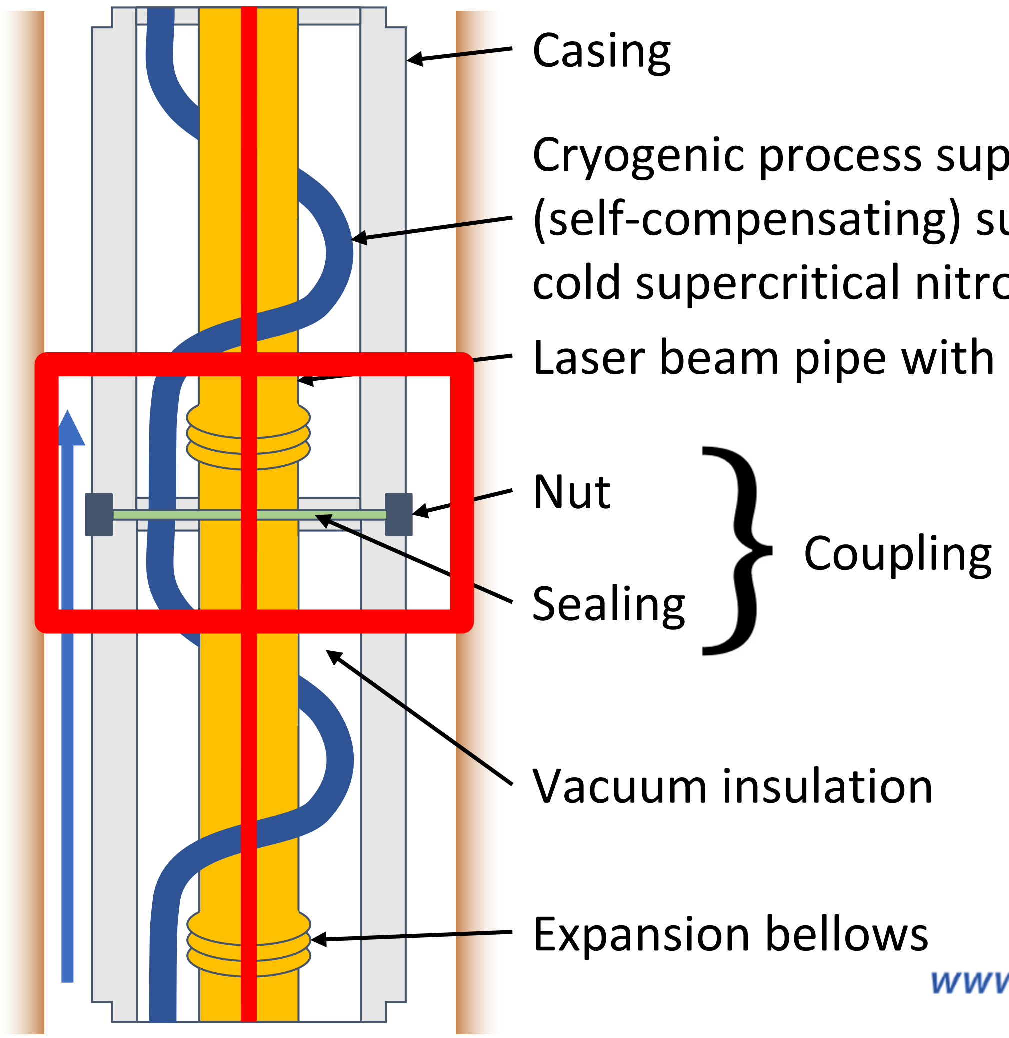
1. **Temperature** - materials must retain their key properties even at cryogenic temperatures.
2. **Heat load** - The design should minimize thermal bridges between cryogenic and room-temperature components.
3. **Vacuum** - The casing and process pipes should exhibit low permeability and outgassing rates.
4. **Mechanical load** - Significant pressure differences and weight pose challenges for many common materials.
5. **Economics** - Materials should be readily available and easy to work with, such as being suitable for welding and machining.



Mechanical design - coupling

Coupling two drill string segments in a cryogenic environment presents several engineering challenges. The connection must perform reliably under extreme conditions while remaining practical for field operations.

- **Leak-tight sealing feasible at cryogenic temperatures**
- **Mechanical strength**
- **Fast and robust assembly**
- **Low thermal load**



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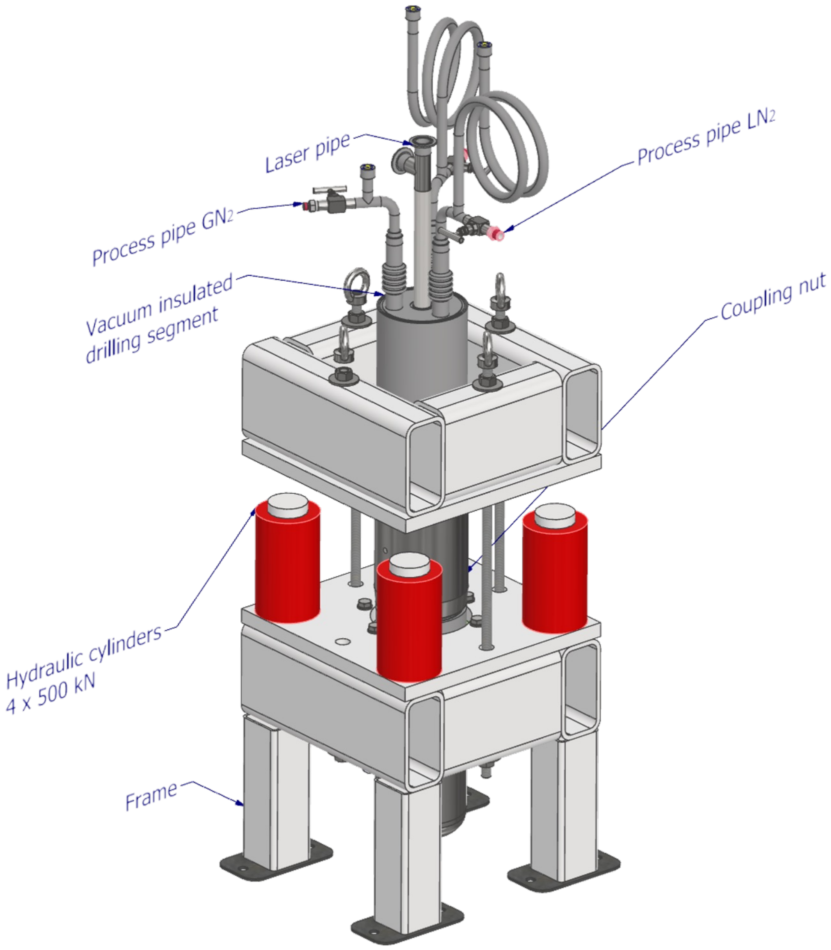
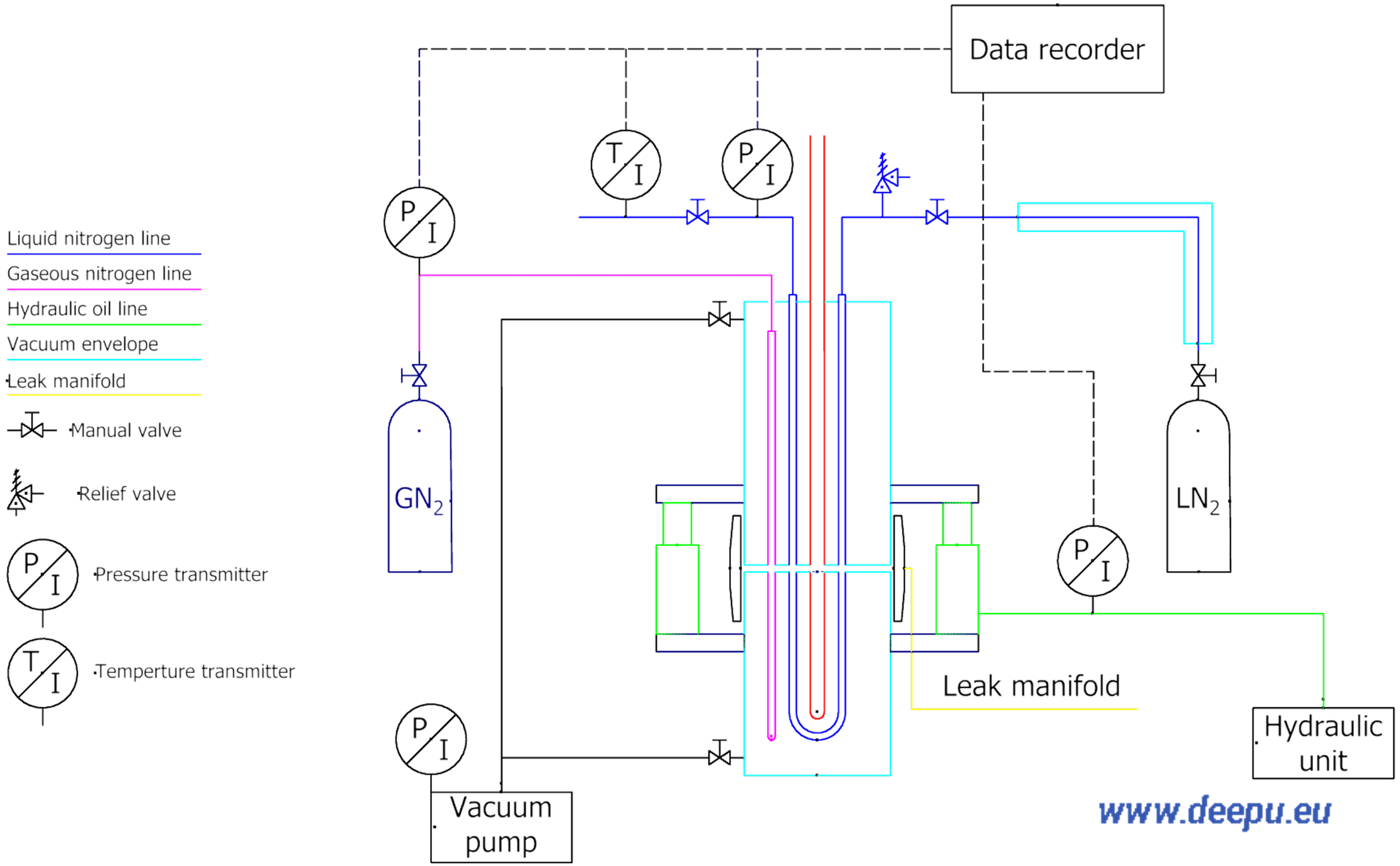
Mechanical design - validation





Mechanical design - validation

- Conceptual design of drill string interconnections was successfully tested and validated and it is ready for the further design
- Drill string interconnection was tested for the worst, non-realistic combination of temperature, pressure and mechanical load and its reliability was still proven

Risk assessment for cryogenic system

Introducing a cryogenic system into deep geothermal drilling brings new failure modes that must be considered.

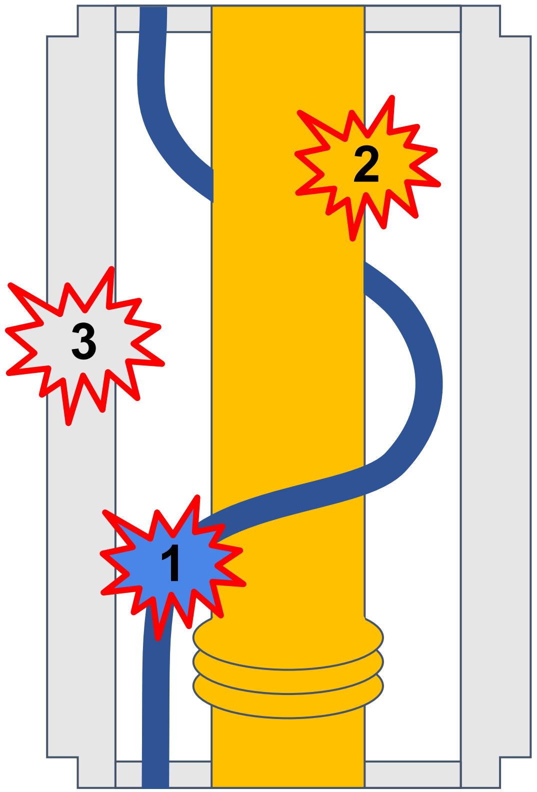
Failure modes directly related to the cryogenic system in most cases are related to vacuum insulation degradation.

Vacuum loss can result from the following failure scenarios:

1. **Process pipe break** – cryogenic fluid leaks into the vacuum space
2. **Laser pipe break** – warm shielding gas enters the vacuum
3. **Casing pipe break** – warm return gas, contaminated with cuttings, flows into the vacuum

Each failure mode has a different set of potential consequences to all subsystems within the drill string.

Proper mitigation actions were proposed for each identified failure scenarios.



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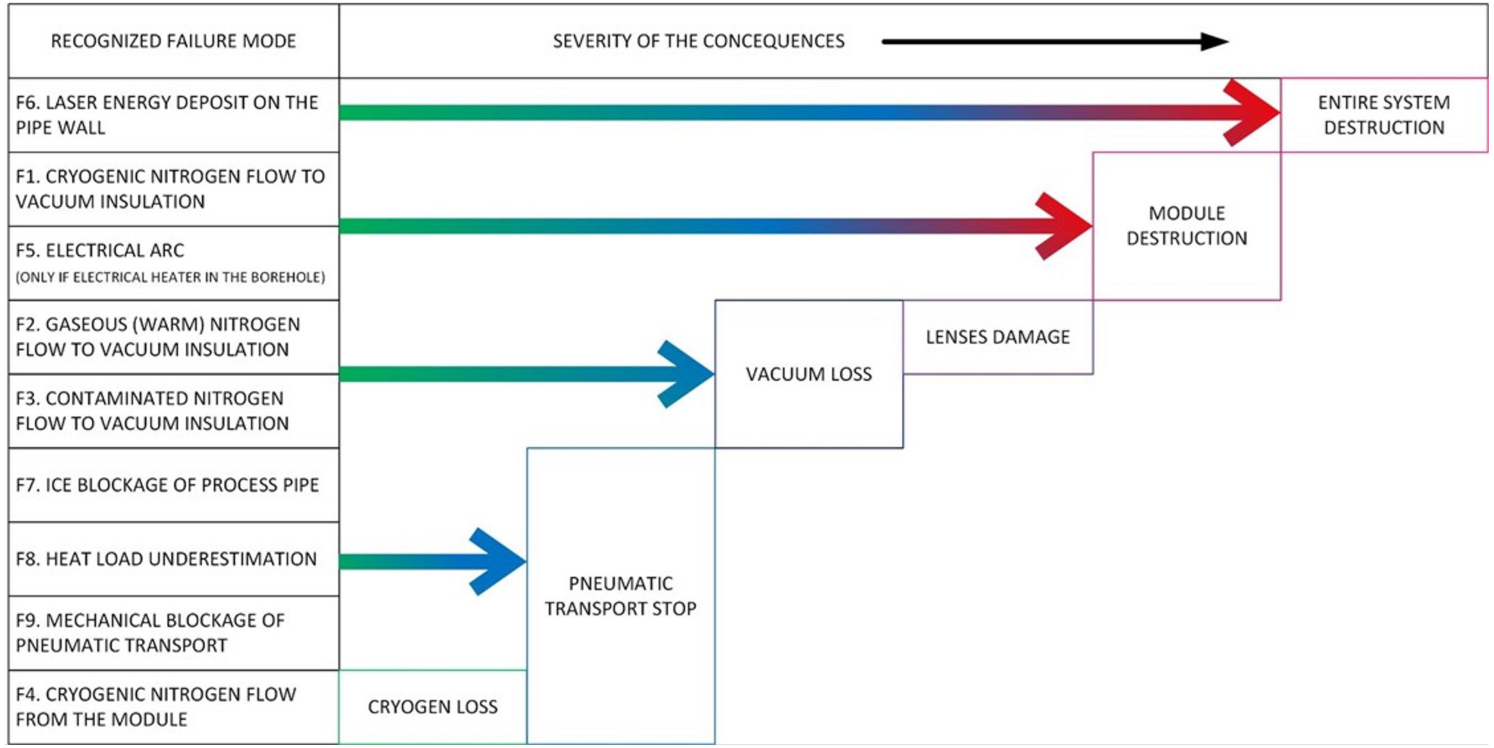
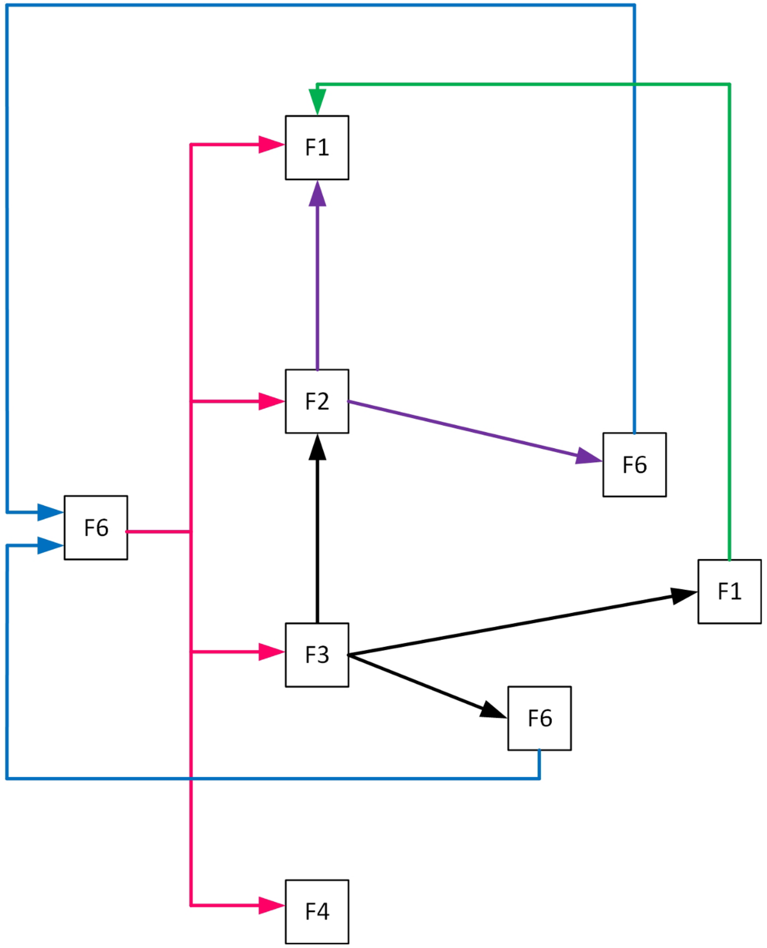
Risk assessment for cryogenic system

Nitrogen gas flow into the vacuum space and laser energy deposition on the pipe wall are two failure modes with the most severe consequences to the whole system due to the possible chain of subsequent failure modes.





SUMMARY

- Modelling of the laser drilling process based on validated pneumatic transport theory shows that current drill string design allow to reach projected depths or even exceed them.
- Conceptual design of drill string interconnections was successfully tested and validated and it is ready for the further design
- Risk analysis identified two worst case scenarios with the most serious consequences, proper mitigation actions have been proposed
- Cryogenic solutions can be adapted to deep drilling requirements providing both robust construction and efficient thermal insulation

Thank you