

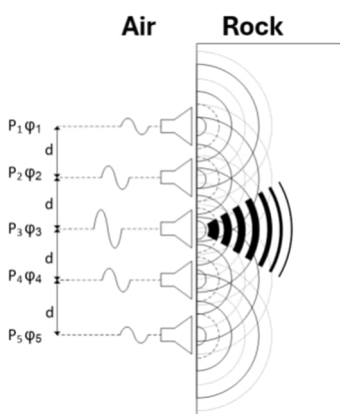
Raphael Speck | Herrenknecht AG

## ADVANCEMENTS IN MICROWAVE PRE-CONDITIONING OF HARD ROCK FOR MECHANICAL EXCAVATION

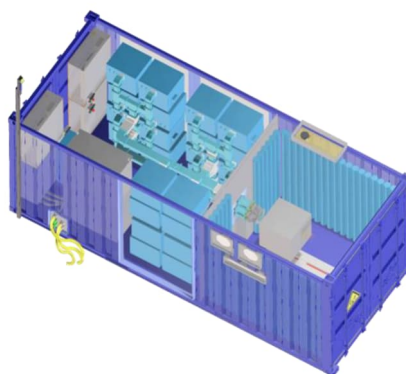
In subsurface operations, mechanical rock excavation using compact, mobile equipment such as roadheaders and continuous miners offers advantages in operational continuity, process control, automation, and ventilation over drill-and-blast methods, while also providing greater flexibility and lower CAPEX than full-face TBMs. However, in hard rock with high strength and abrasivity, partial-face cutting often becomes economically infeasible due to excessive tool consumption.

Rock pre-conditioning aims to reduce rock strength prior to excavation by inducing fractures within the rock mass and thereby lowering cutting forces and tool wear. High-power microwave rock pre-conditioning (HPM-RPC) relies on rapid volumetric dielectric heating, which generates strong temperature gradients within the rock, creating mechanical stresses and subsequent rock failure. Its practical implementation, however, remains challenging because the achievable microwave output and pre-conditioning speed are significantly limited by economic, technical, and process-related constraints.

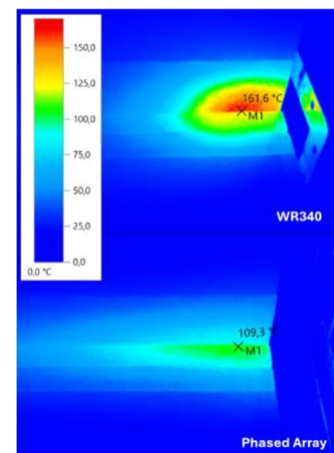
At Herrenknecht AG, a novel phased-array HPM-RPC system was developed within the scope of the Microwave Assisted Rock Shattering (MARS) programme. Compared to existing methods, it enables targeted power focusing, resulting in significantly greater rock failure and higher overall efficiency. This contribution introduces the concept and presents initial results of its experimental validation.



'Phased Array'-Principle



Modular 144 kW MARS  
HPM-RPC Test Facility



Experimental Results



**TUBAF**

The University of Resources.  
Since 1765.

**HERRENKNECHT**



**Tunnelling Systems**

# **ADVANCEMENTS IN MICROWAVE PRE- CONDITIONING OF HARD ROCK FOR MECHANICAL EXCAVATION**

June 8<sup>th</sup>, 2026

77. BHT - Advanced Drilling Technologies and Subsurface Engineering

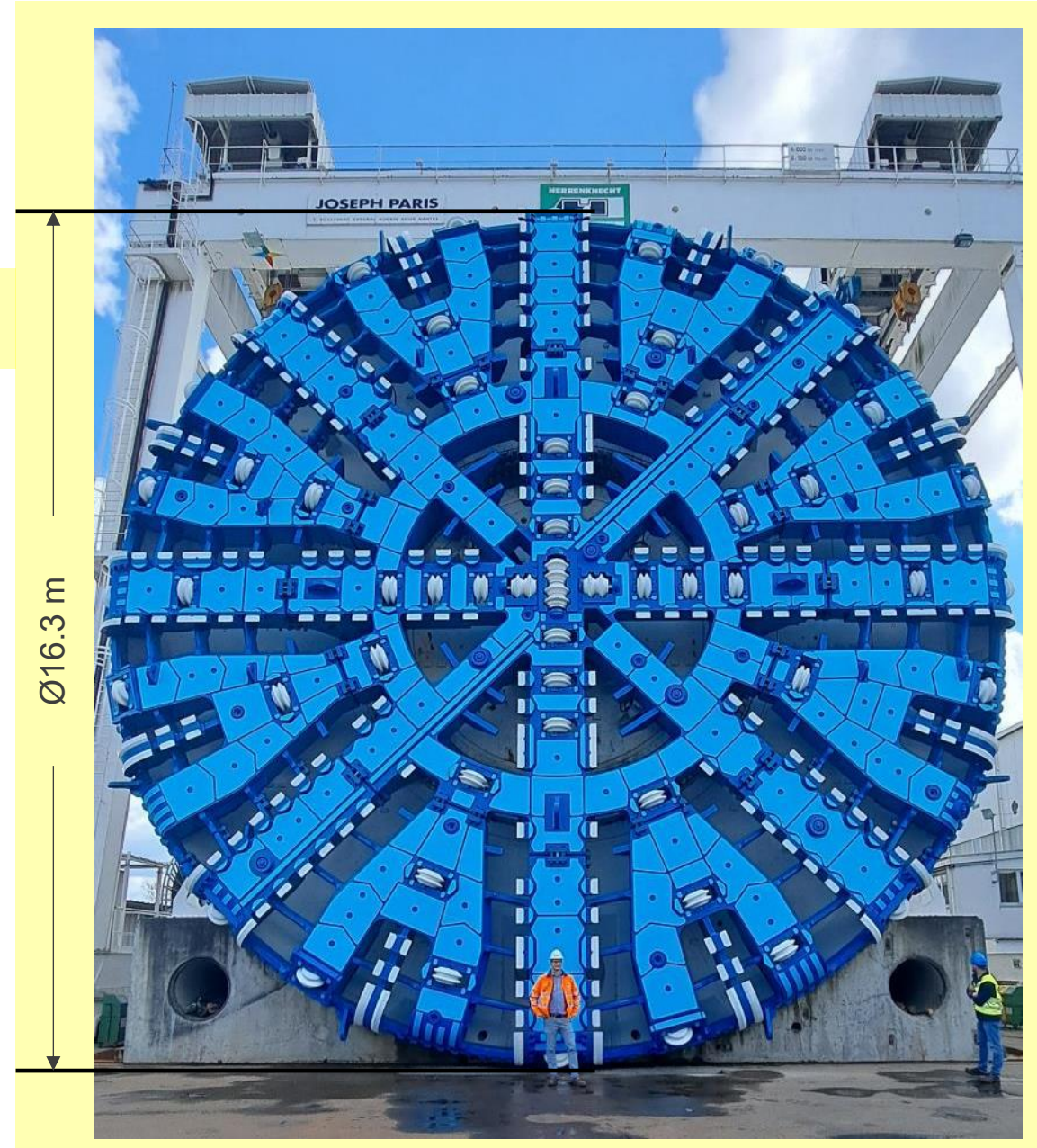
**Raphael Speck**

Head of Design, Business Unit Mining

Herrenknecht AG

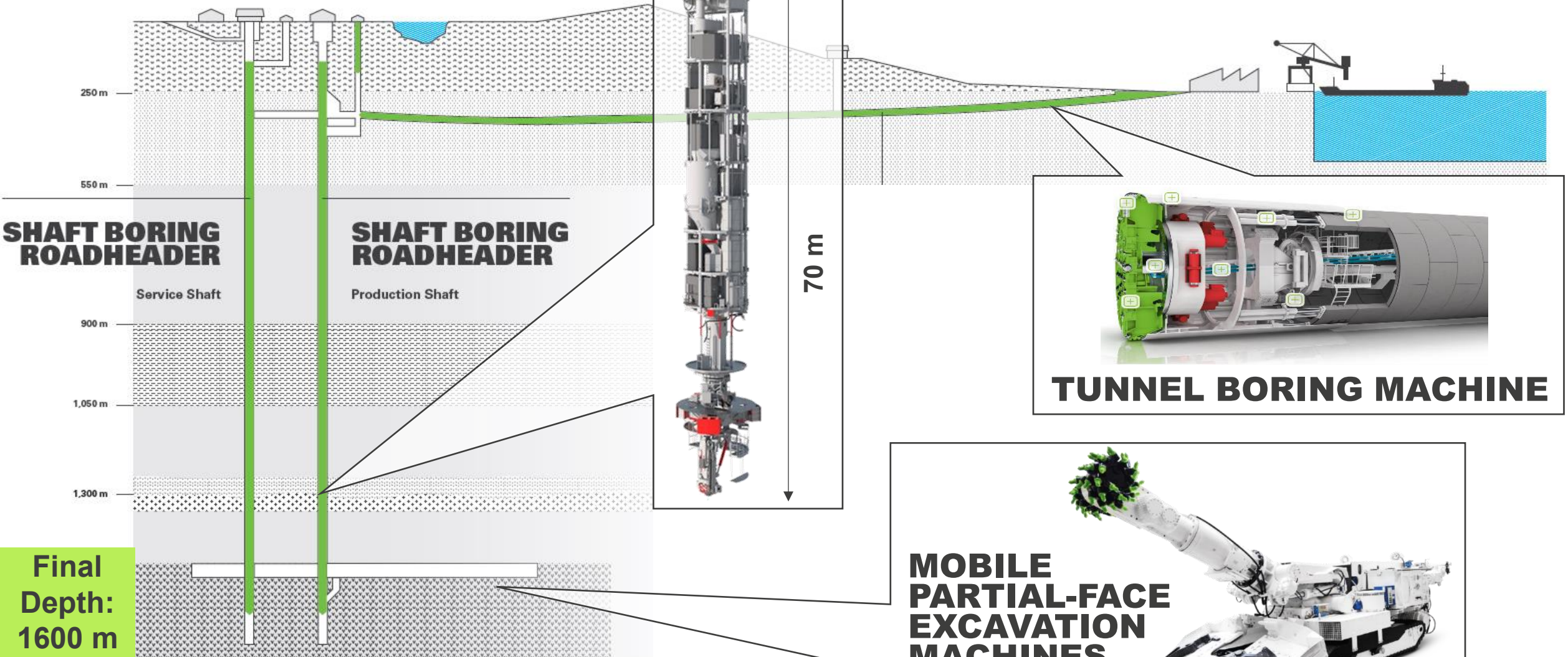
Introduction

# HERRENKNECHT AG



Introduction

# MECHANICAL ROCK EXCAVATION IN MINING

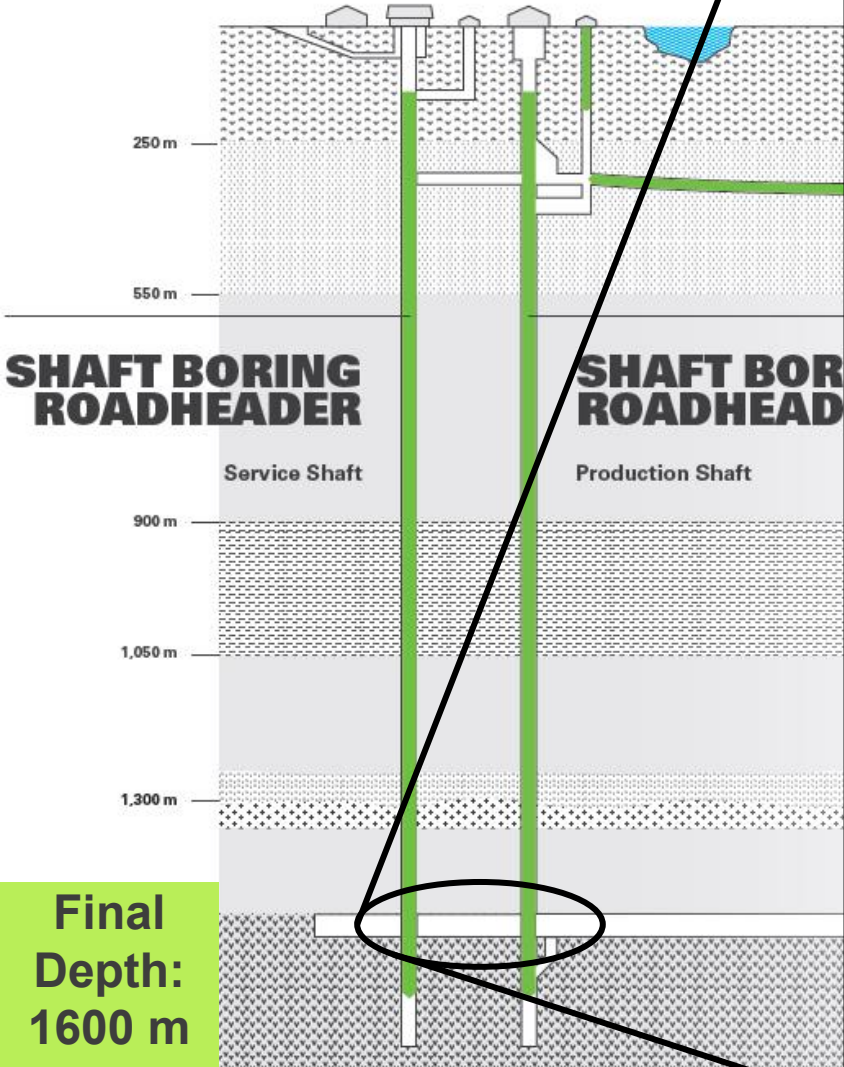


Final Depth: 1600 m

Project Example: Woodsmith Polyhalite Project (UK), Anglo American

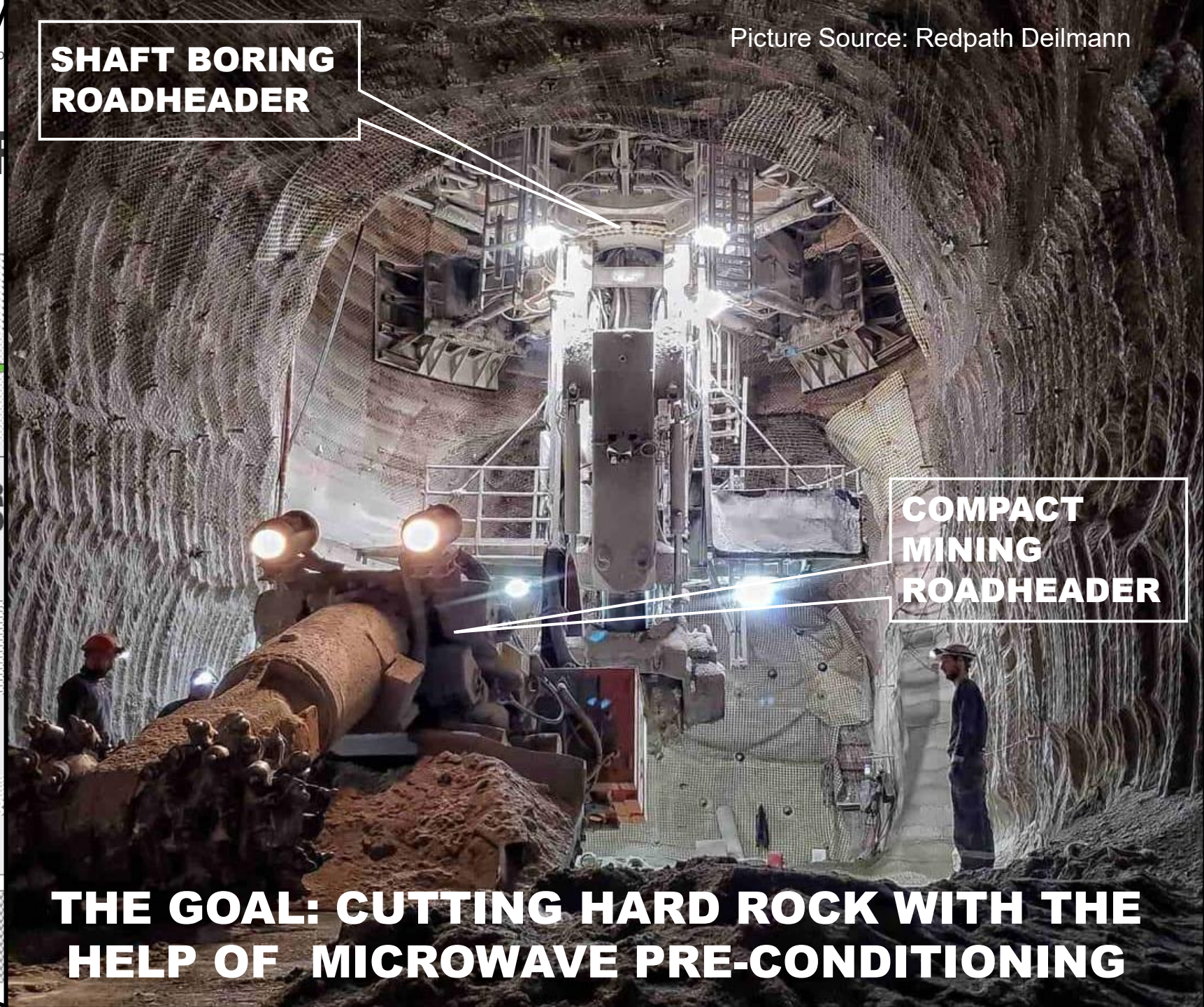
Introduction

# MECHANICAL P



Picture Source: Redpath Deilmann

**SHAFT BORING ROADHEADER**



**COMPACT MINING ROADHEADER**

**THE GOAL: CUTTING HARD ROCK WITH THE HELP OF MICROWAVE PRE-CONDITIONING**

Introduction

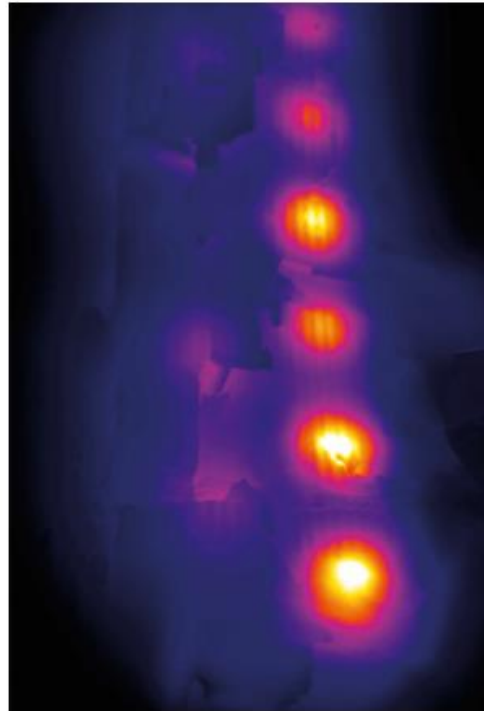
# MICROWAVE ASSISTED ROCK SHATTERING (MARS)

› Full-Scale Trials 2023, Sandstone Quarry, 200 kW / 915 MHz HPM-RPCS

Irradiation of hard rock with high power microwaves



Strong localized heating and steep temperature gradients



Pre-fractured rock with reduced strength



Roadheader excavation

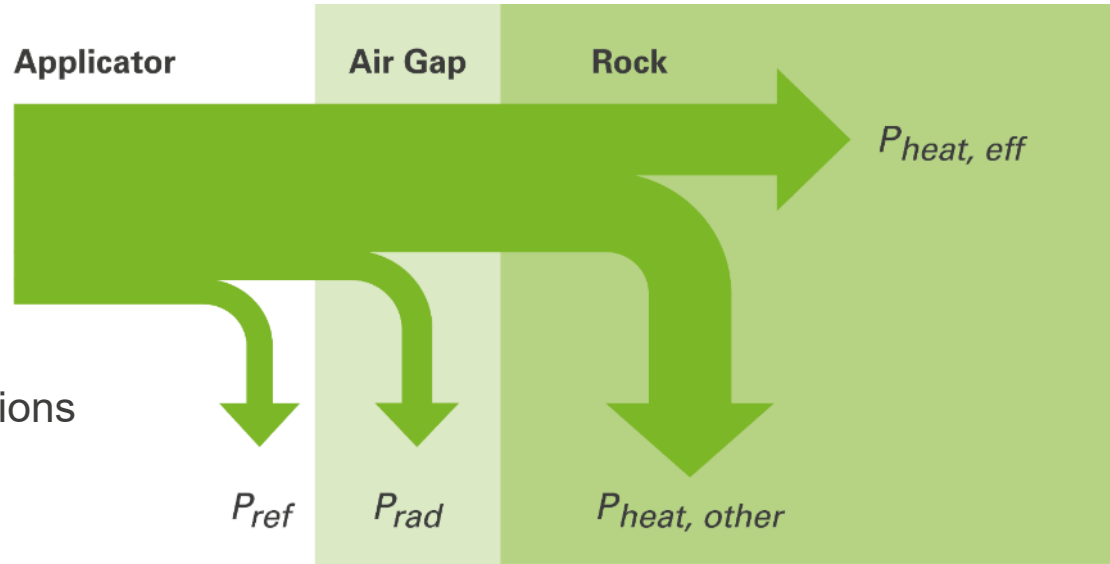


Introduction

# MICROWAVE AS

## > Full-Scale Trials 2022

### What makes a good High Power Microwave Rock Pre-Conditioning System (HPM-RPCS)?



> Low Reflections  
 $P_{ref}$  min.

> Good coupling  
 $P_{rad}$  min.

> High volume of damaged rock per unit energy  
 $V_{RFA}$  max.

> Targeted heating:  
 $P_{heat, eff}$  max.  
 $P_{heat, other}$  min.



Applicator Design

# STATE OF THE ART

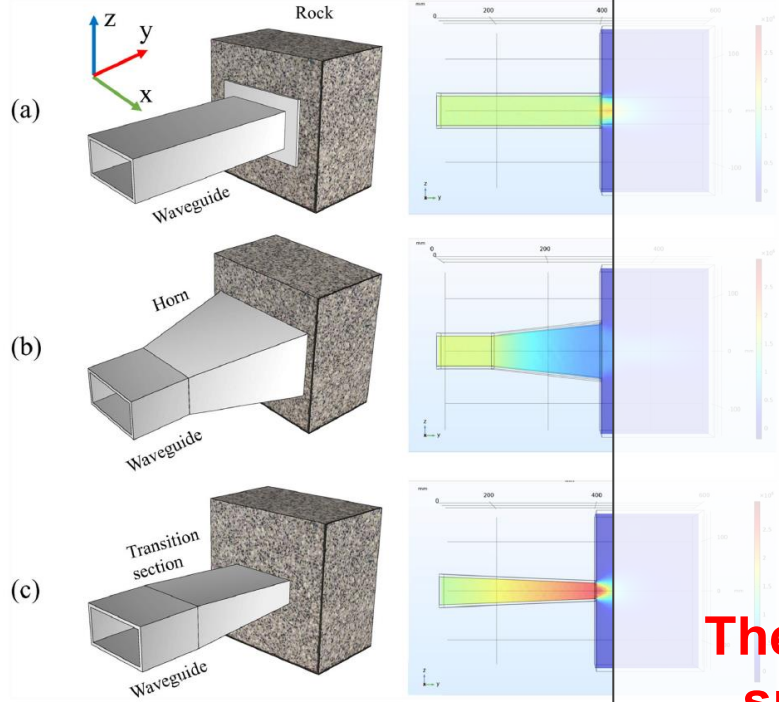
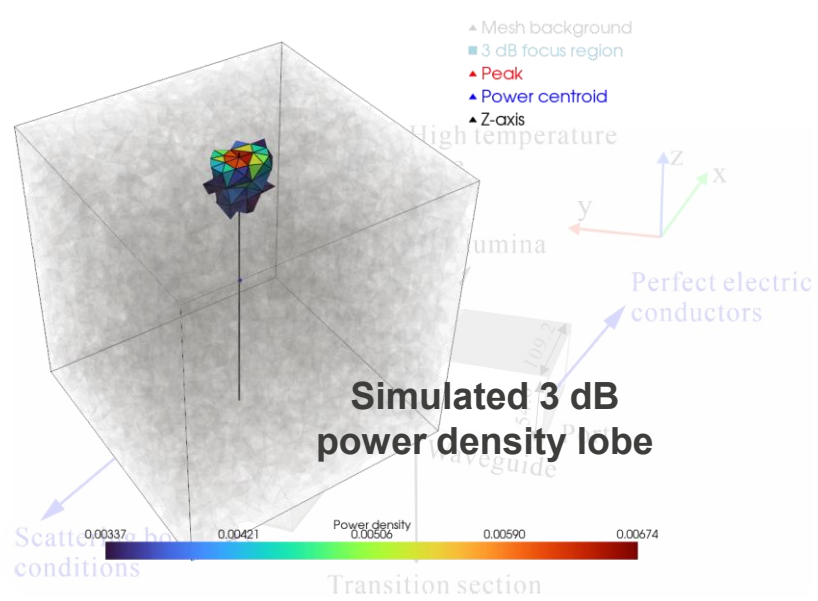


Fig. 1 Schematics of the three types of microwave antennas for rock fracturing and the microwave power intensity distribution (W/m<sup>2</sup>) at 6 kW. a Standard waveguide antenna, b horn antenna, c converging waveguide antenna

Ma et al (2021) Design and performance of an open-ended converging microwave antenna in fracturing biotite diorite at low microwave power levels

## Air-Filled Waveguides



**The problem: power is absorbed in a shallow surface layer rather than deep in the rock!**

Ma et al (2022) A Dielectric-Loaded Converging Waveguide Antenna for Microwave Fracturing of Hard Rocks

## Dielectric Loaded Waveguide

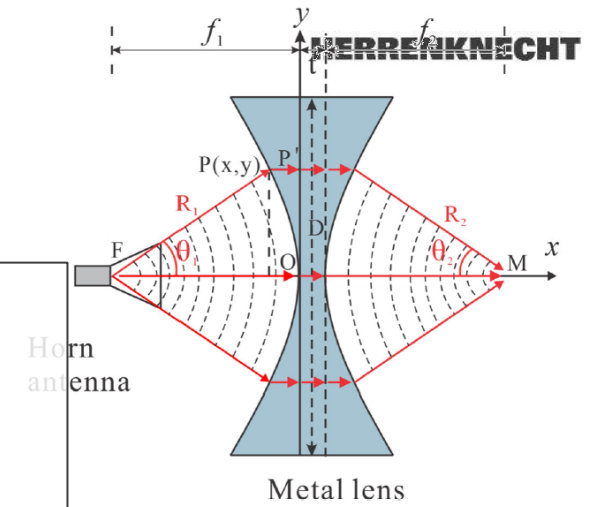


FIGURE 1 | Diagram of the composition of the metal-plate lens antenna.

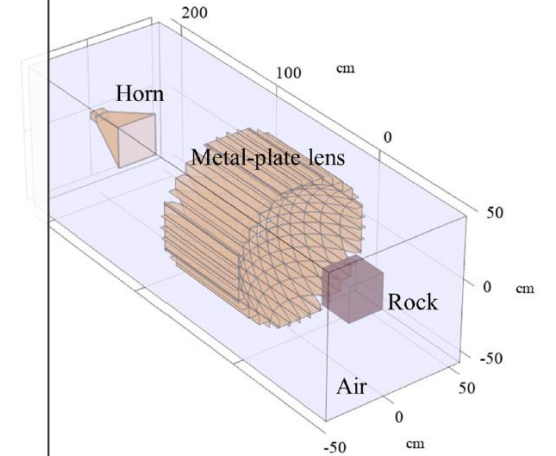


FIGURE 2 | Numerical setup using metal-plate lens antenna to heat rock specimen.

Zheng et al (2025) Developing a High-Power Metal-Plate Lens Antenna for Microwave Fracturing of Rocks

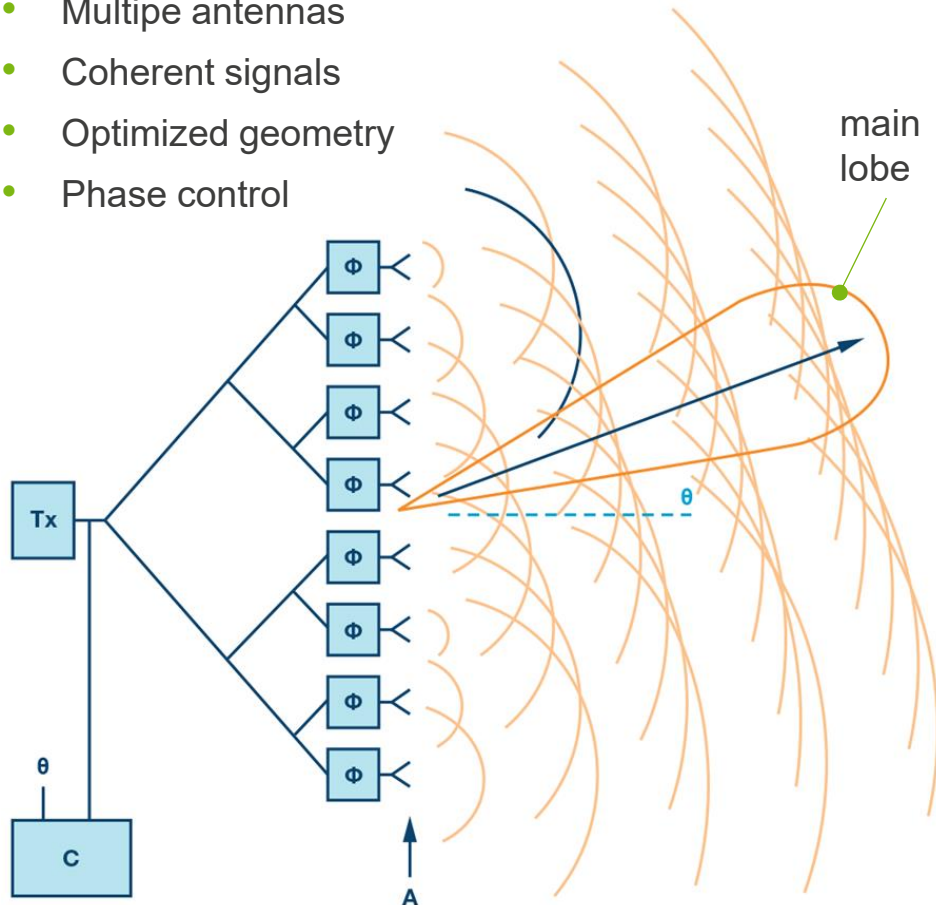
## Horn and Lens

## Applicator Design

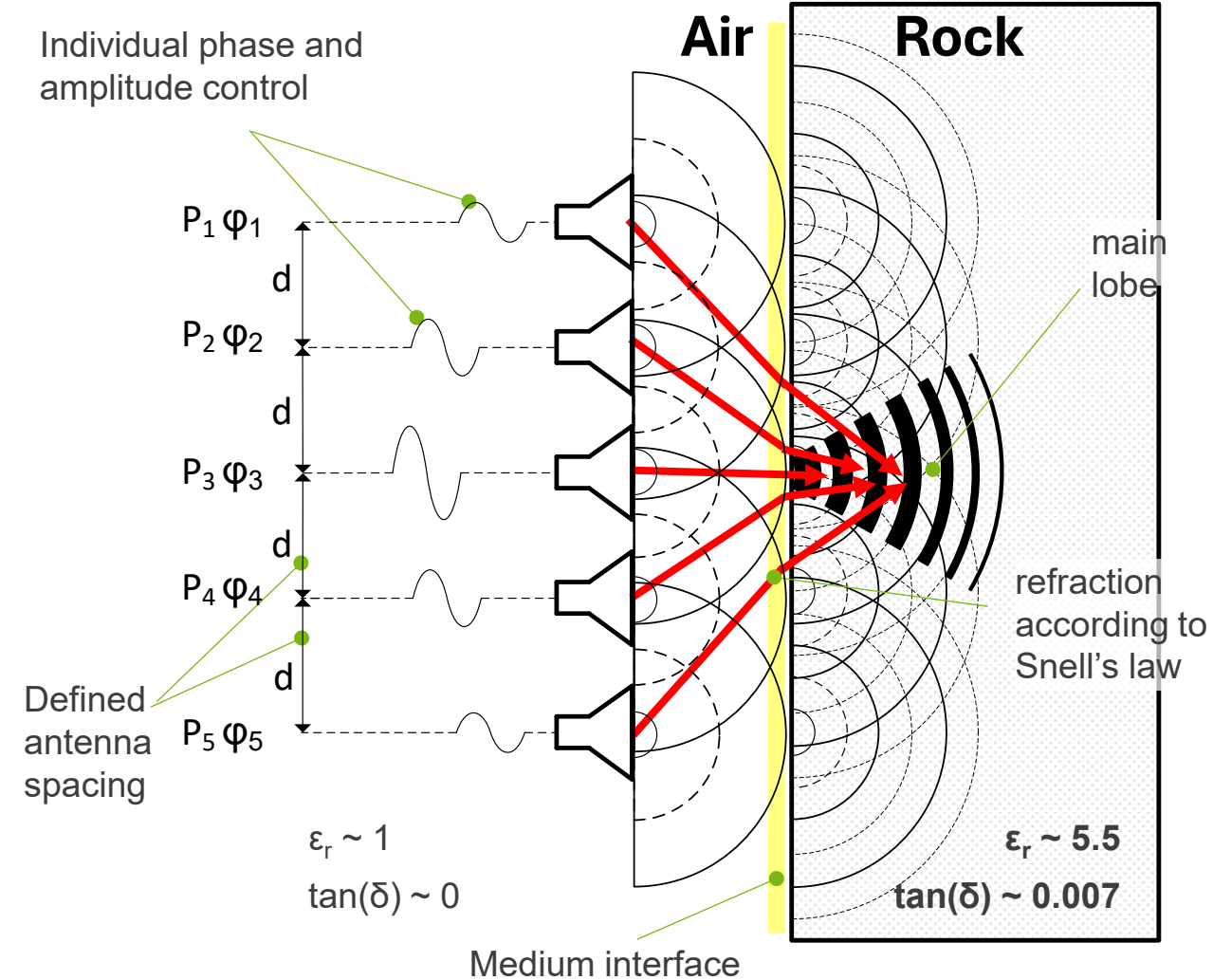
**'PHASED ARRAY' - APPROACH**

## › General Principle: Phased Array

- Multiple antennas
- Coherent signals
- Optimized geometry
- Phase control

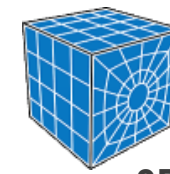


## › Rock Face Irradiation Context



Applicator Design

# 'PHASED ARRAY' - SIMULATION

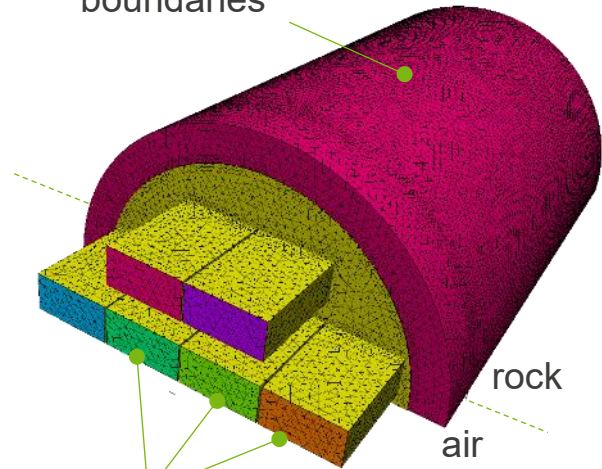


## FLAC3D™

3D FDM Geomechanical Solver

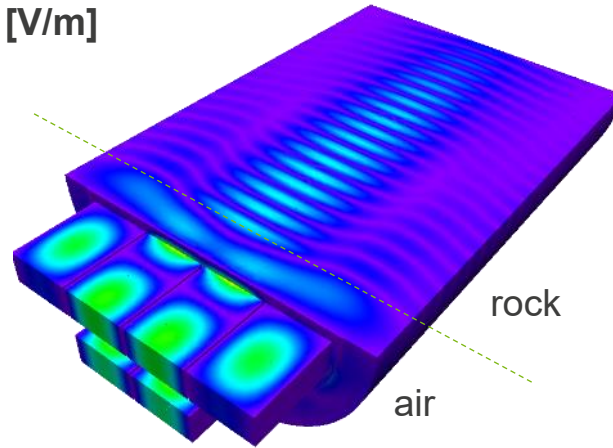
MiCIAN  
**μWave Wizard™**  
3D FEA EM Solver

absorbing  
boundaries

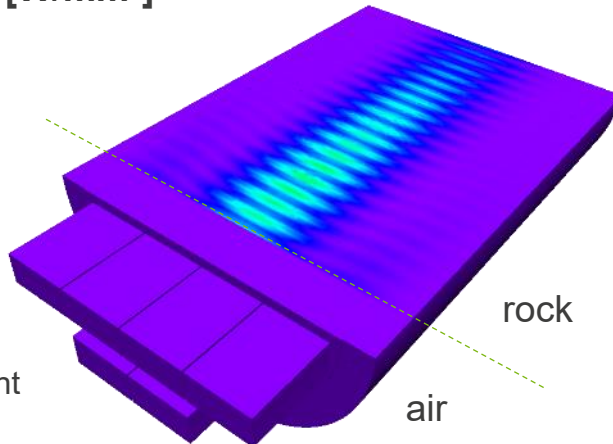


waveguide  
antennas

Electric Field  
[V/m]



Power Density  
[W/mm³]

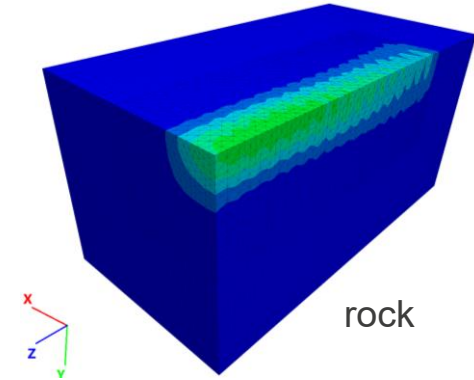
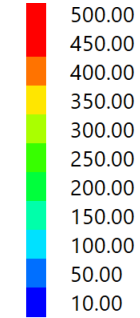


$P_i$

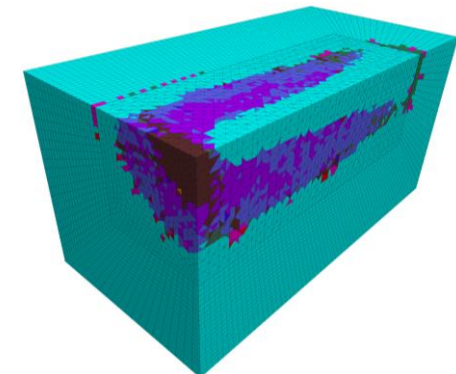
$\epsilon_{ri}(T)$

Iterative, fully  
thermally  
coupled update

Temperature Field [°C]



Volume of Failed Rock  $V_{RFA}$  [cm³]  
Failure Modes



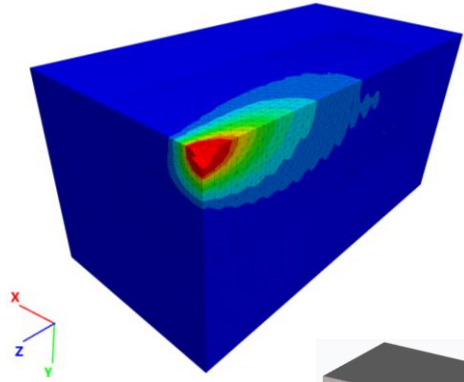
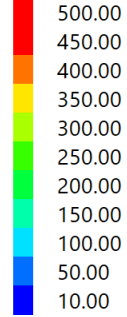
Details:

Speck et al (2026): A Novel Phased Array Applicator for Efficient Microwave Pre-Conditioning of Hard Rocks.

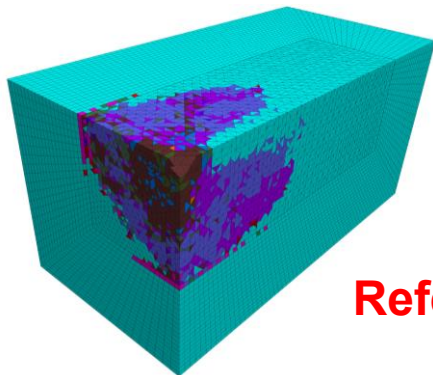
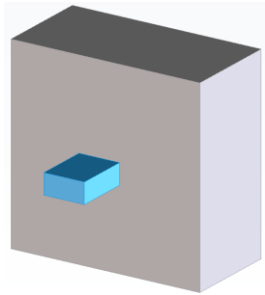
Applicator Design

# SINGLE WAVEGUIDE VS 'PHASED ARRAY'

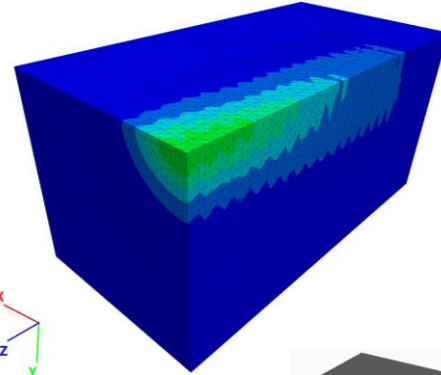
Temperature [°C]



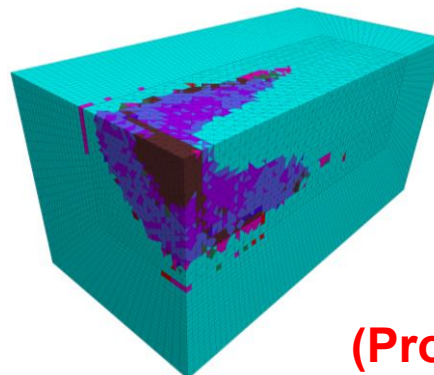
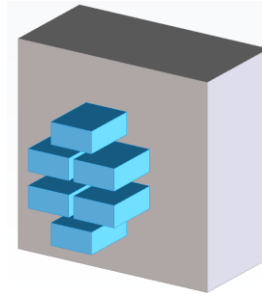
Single WR340 Waveguide



Reference

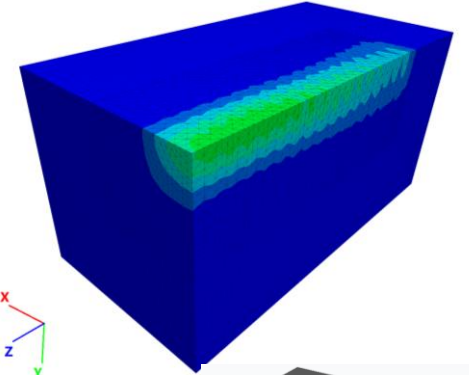


6-Port Phased Array

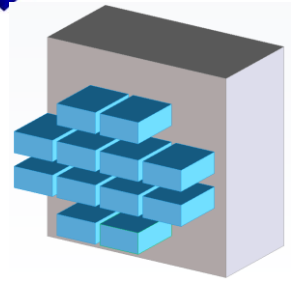


Gen 1 (Prototype)

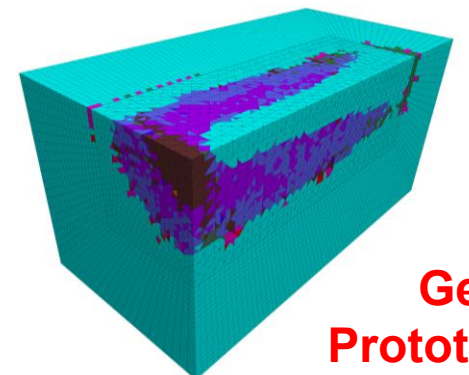
Lower Temperature



12-Port Phased Array



More Damage



Gen 2 Prototype

## High-Power Microwave Rock Pre-Conditioning Test Facility

# MODULAR HPM-RPC TEST FACILITY

› 144 kW Microwave Power, 2.45 GHz

› Solid-state generators by  
TRUMPF Hüttinger

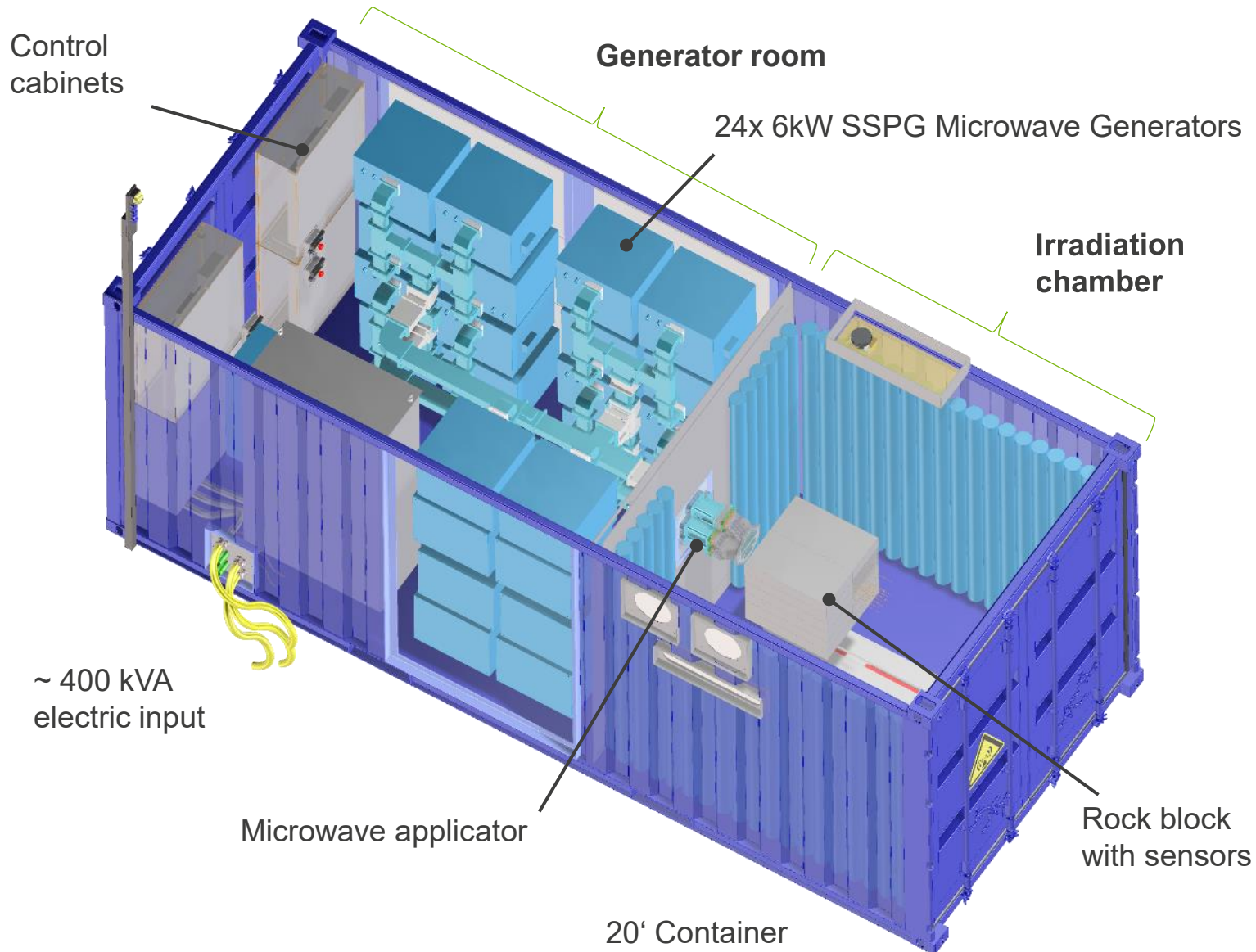


› System design by  
Herrenknecht



› Features:

- › Central PLC control for power and phase
- › Safety interlocks
- › Arc detection
- › Leak radiation monitoring
- › Coolant flow, temperature monitoring
- › Video and audio monitoring of both rooms
- › ...

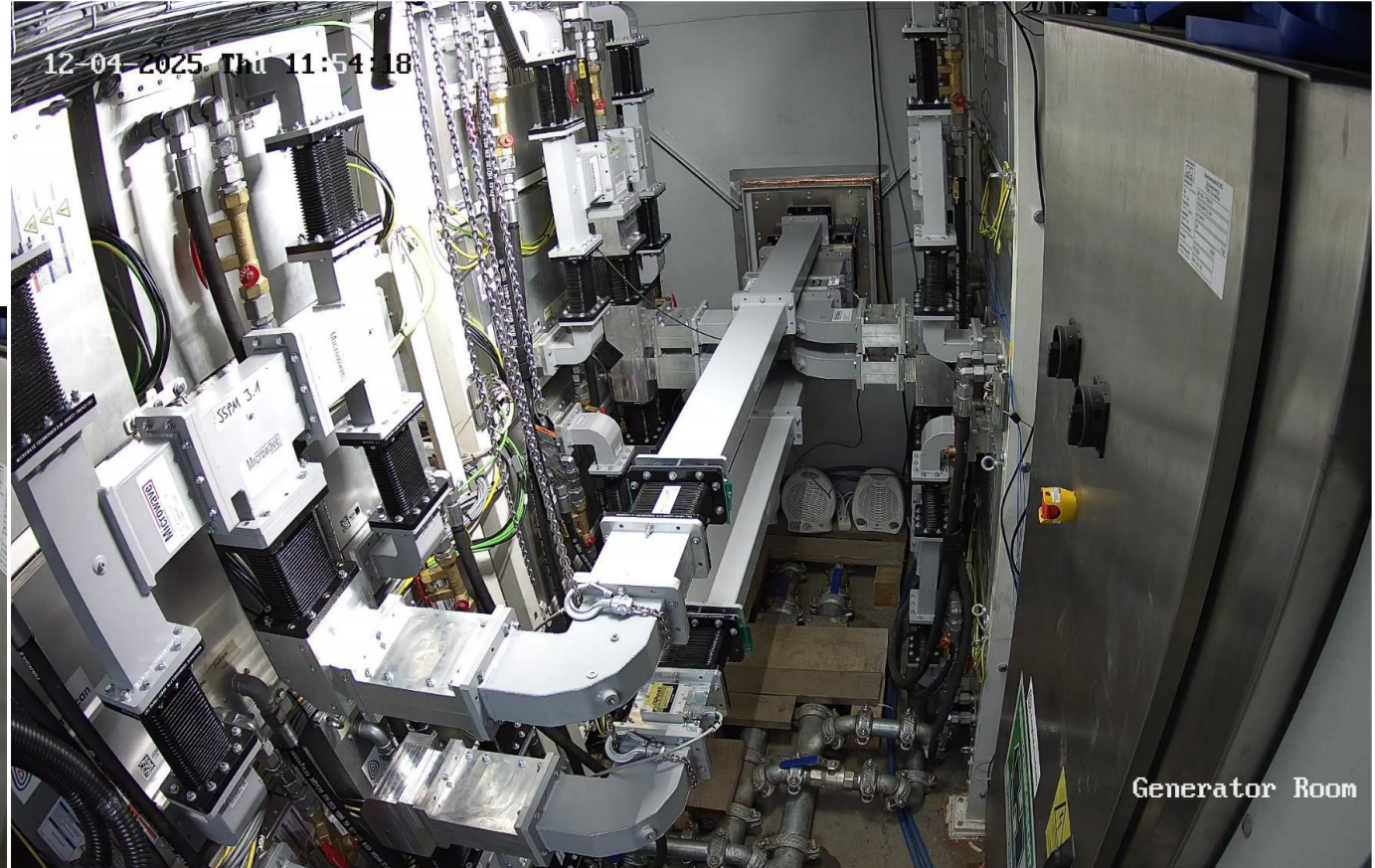
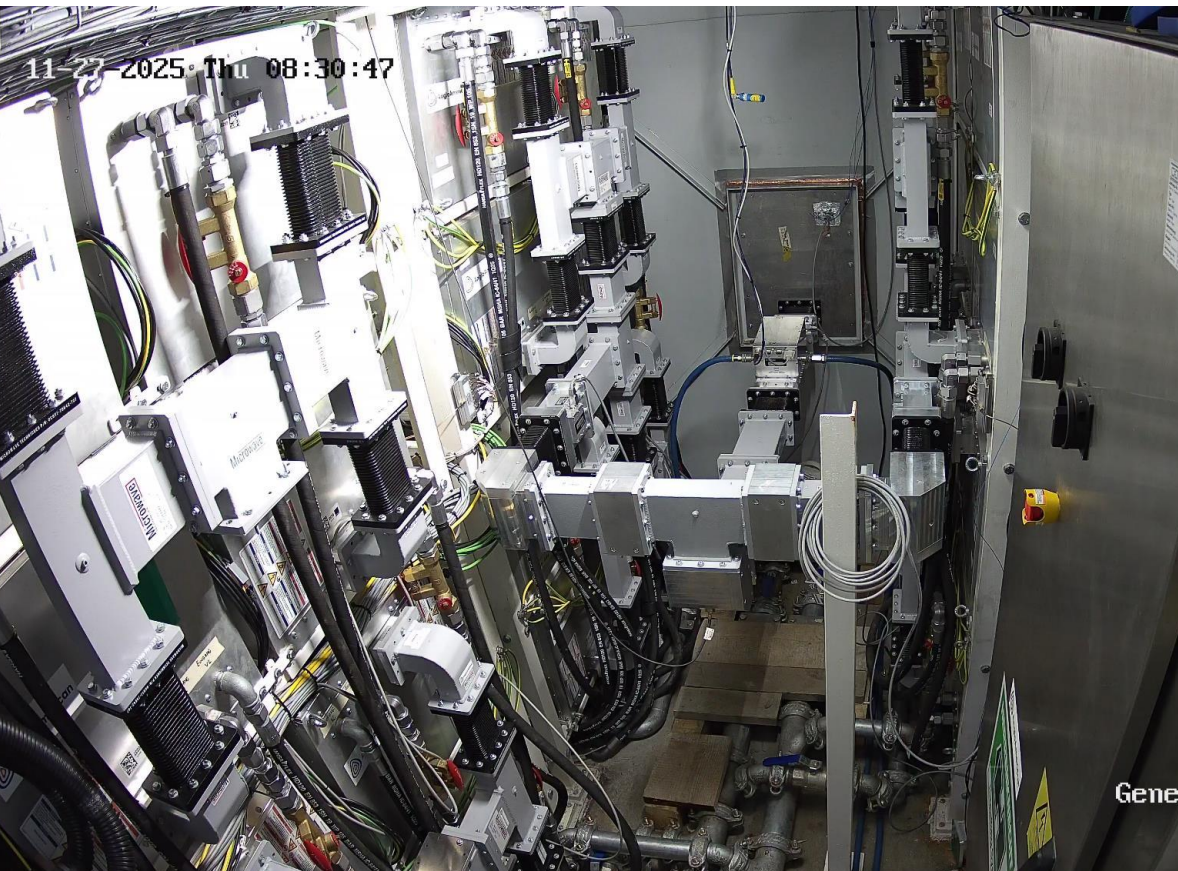


Experimental Validation

# MODULAR HPM-RPC TEST FACILITY

## Single Waveguide Configuration:

- › Max. 96 kW single output
- › Automatic tuner



## Phased Array Configuration:

- › 6 phase-coherent generator groups
- › Max. 6x 24 per output = 144 kW total

Experimental Validation

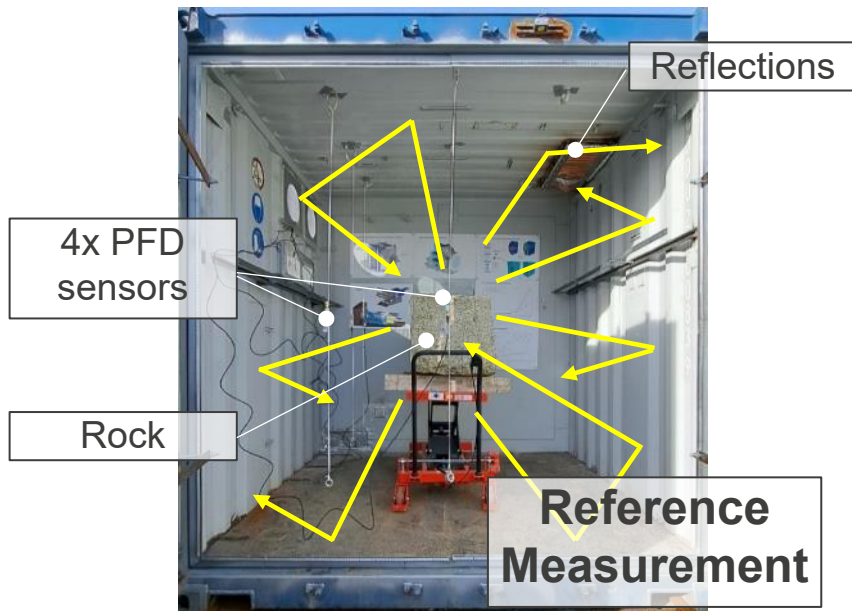
# IRRADIATION CHAMBER

Goal: Replication of underground rock face irradiation conditions by suppressing reflections

- › Basic steel chamber ('faraday cage'):
  - › **Multi-mode field distribution**
  - › Very high reflections
  - › High power flux density (PFD)
  - › Undesired **secondary heating effects in rock sample**

- › Water-filled pipes:
  - › PFD reduction ~47 % on average
  - › **local PFD maxima of 189 % due to reflections at medium interface air-water**

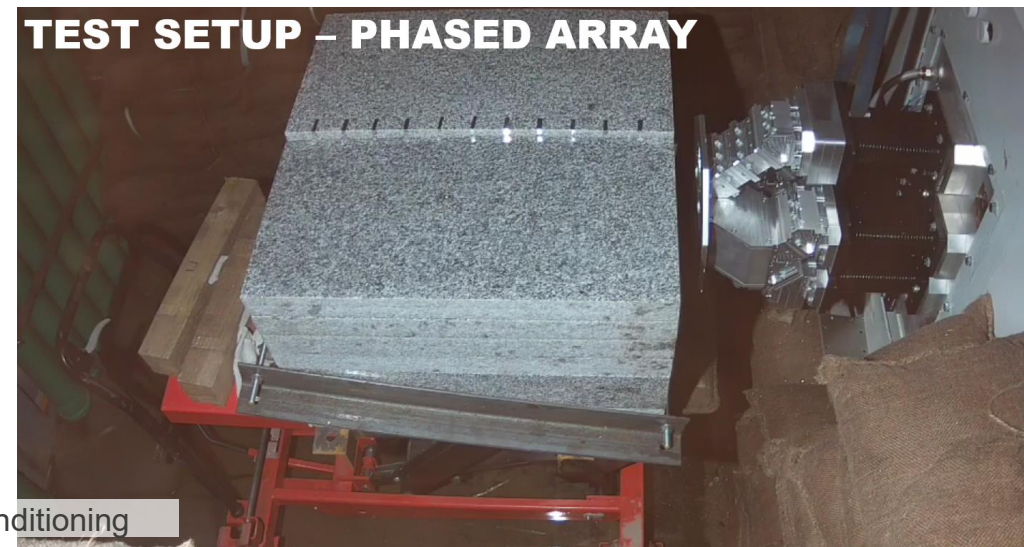
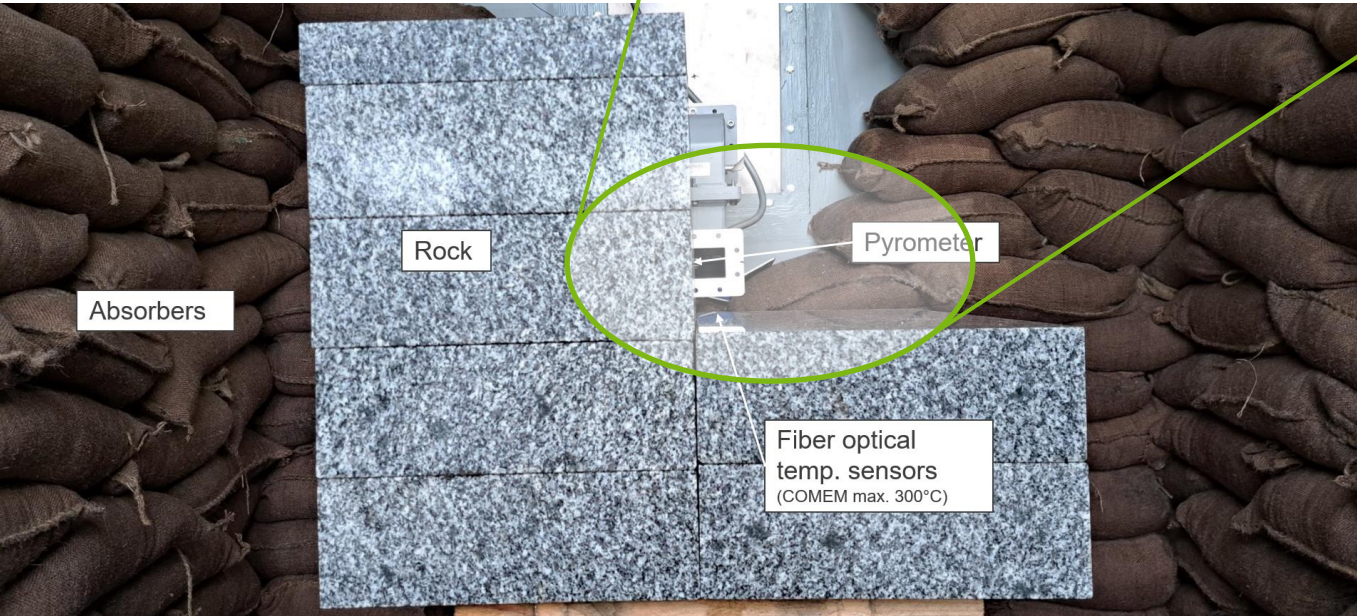
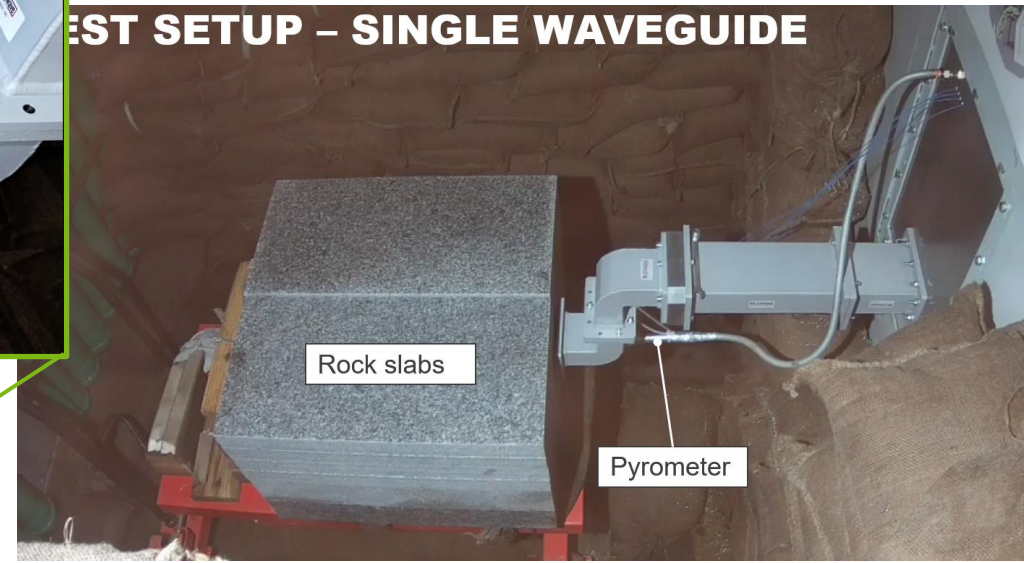
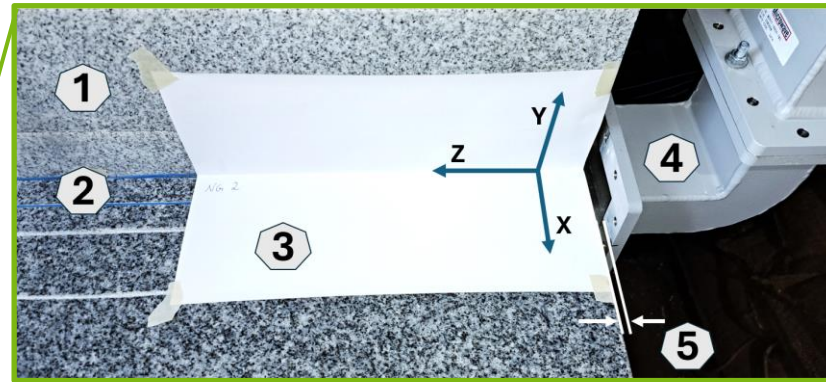
- › Water-filled pipes and wet sandbags:
  - › consistent PFD reduction by 66 %
  - › Very low reflected power in the rock sample



Experimental Validation

# 'PROOF OF CONCEPT' TRIALS – JANUARY 2026

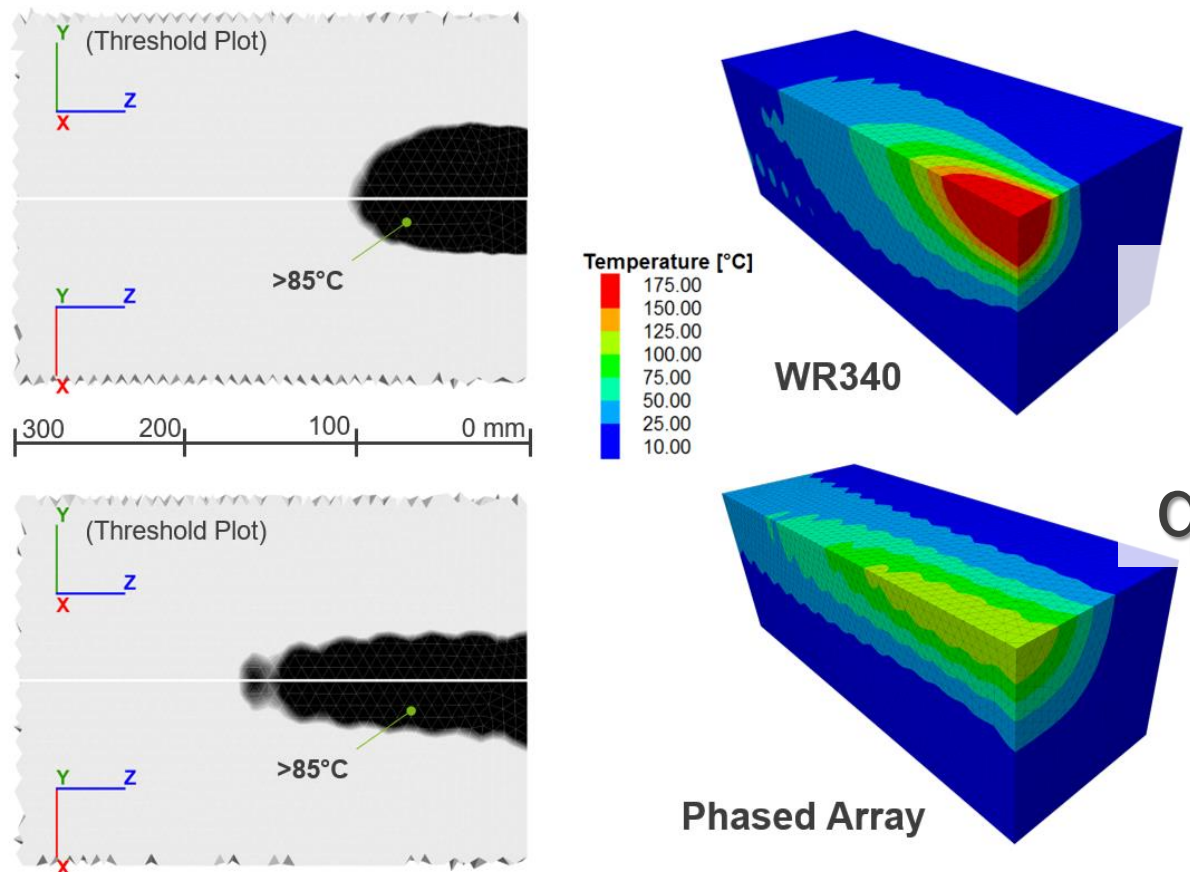
- 1. Granite slabs
- 2. Fiber optical temperature sensors
- 3. Thermal paper
- 4. Applicator
- 5. Air gap



Experimental Validation

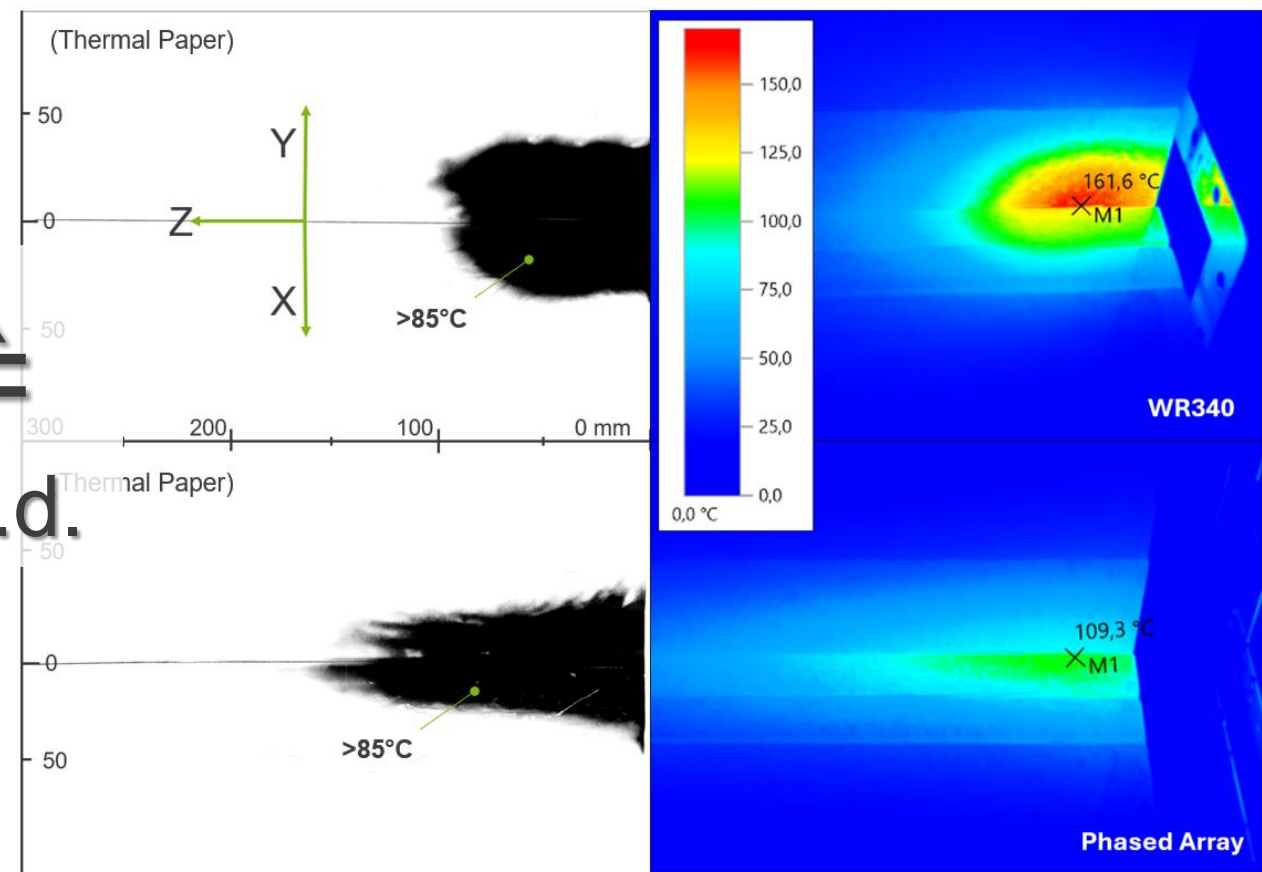
# 'PROOF OF CONCEPT' TRIALS – JANUARY 2026

**Simulated** temperature field in granite after irradiation with E ~ 0.3 kWh



**SIMULATION**

**Measured** temperature field in granite after irradiation with E ~ 0.3 kWh



**MEASUREMENT**

q.e.d.

## Experimental Validation

# IRRADIATION TRIALS WITH ACOUSTIC EMISSION MONITORING – JUNE 2026

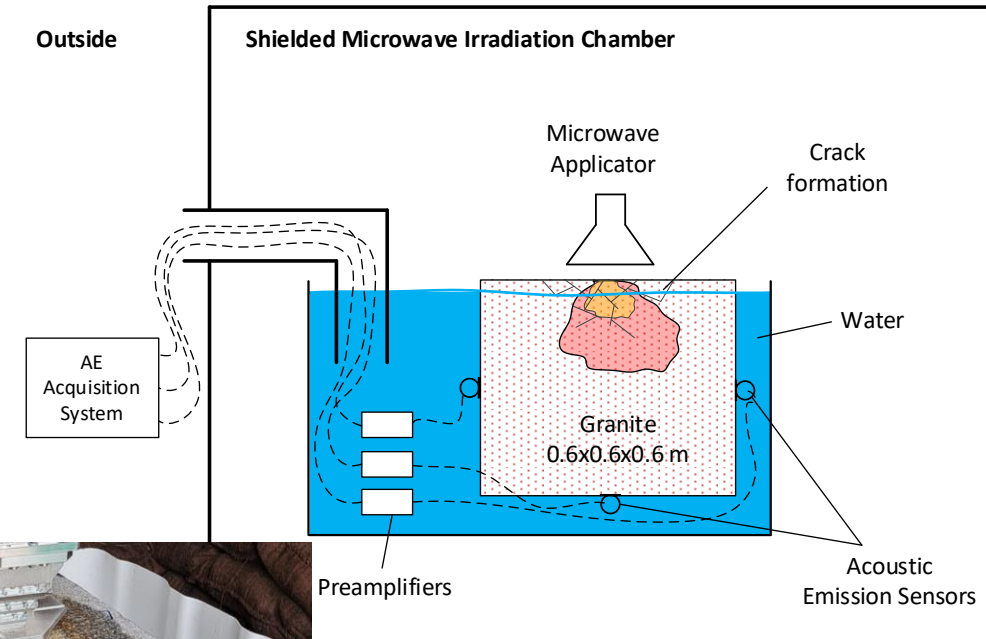
## Goal: Rock fracturing performance analysis and comparison

### Equipment:

- › Vallen Systeme AMSY-6 SP2 Acoustic Emission (AE) measurement system
- › Rock blocks with 8 VS150-RSC-V2 Vallen Smart Line™ AE-Sensors (100-450kHz)

### Procedure:

- › Online monitoring during irradiation:
  - › Event **count** over microwave energy
  - › Event **intensity**
  - › Event **location** (post-processing)
- › Before and after irradiation:
  - › **Damage analysis** with ultrasonic speed (P-wave) measurements



### Rock type:

- › 'Neuhauser' Granite
- › UCS 145 N/mm<sup>2</sup>
- › TS 9.7 N/mm<sup>2</sup>
- › Poisson ratio 0.16
- › Young' Modulus 62 Gpa
- › Cohesion 21.5 Mpa
- › Friction angle 56.8 °

06-03-2026 Wed 15:50:17

Experimental Validation

# TEST SETUP – SINGLE WAVEGUIDE

Pyrometer

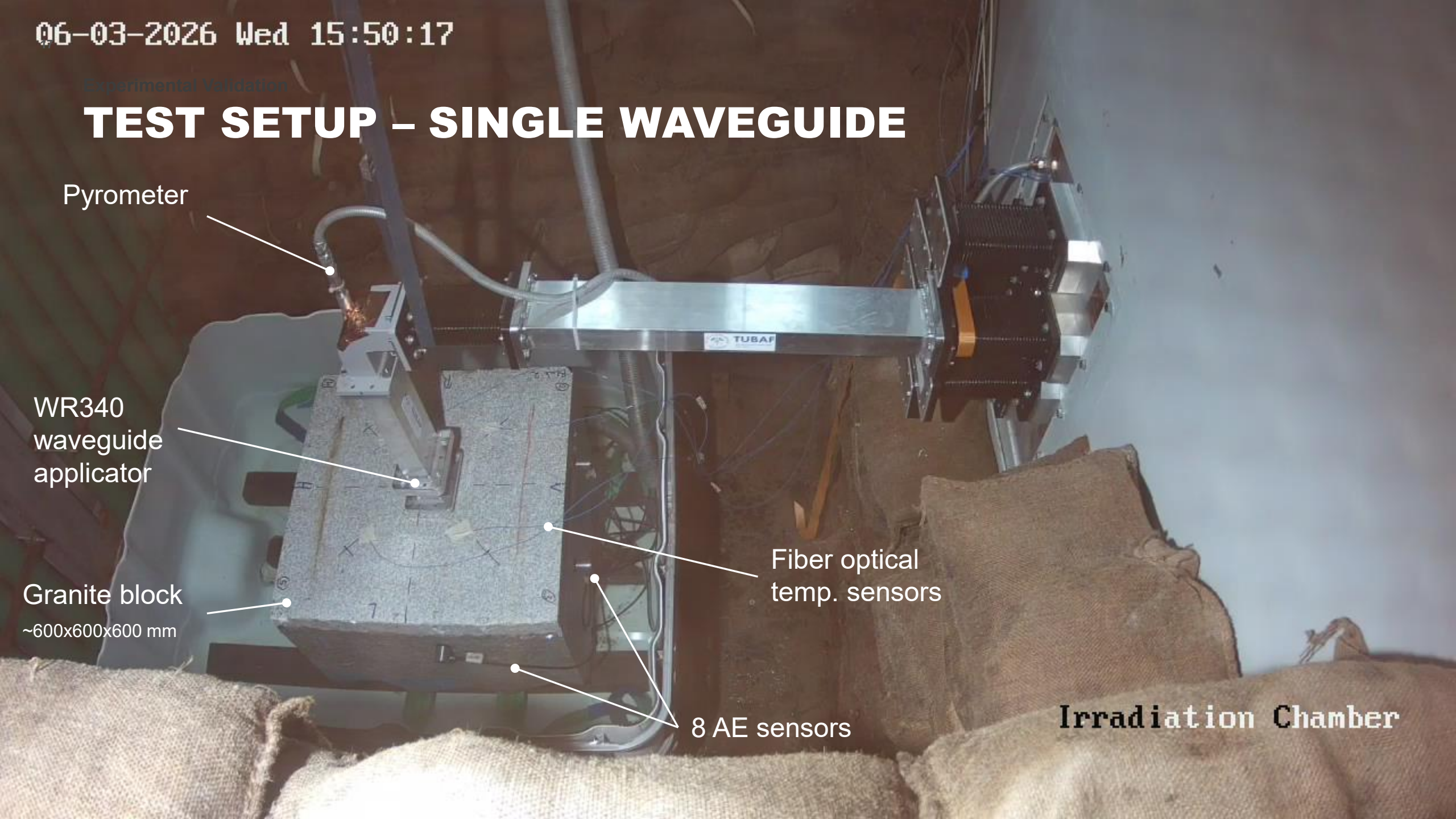
WR340  
waveguide  
applicator

Granite block  
~600x600x600 mm

Fiber optical  
temp. sensors

8 AE sensors

Irradiation Chamber



06-03-2026 Wed 12:59:49

Experimental Validation

# TEST SETUP – PHASED ARRAY

Phased array applicator

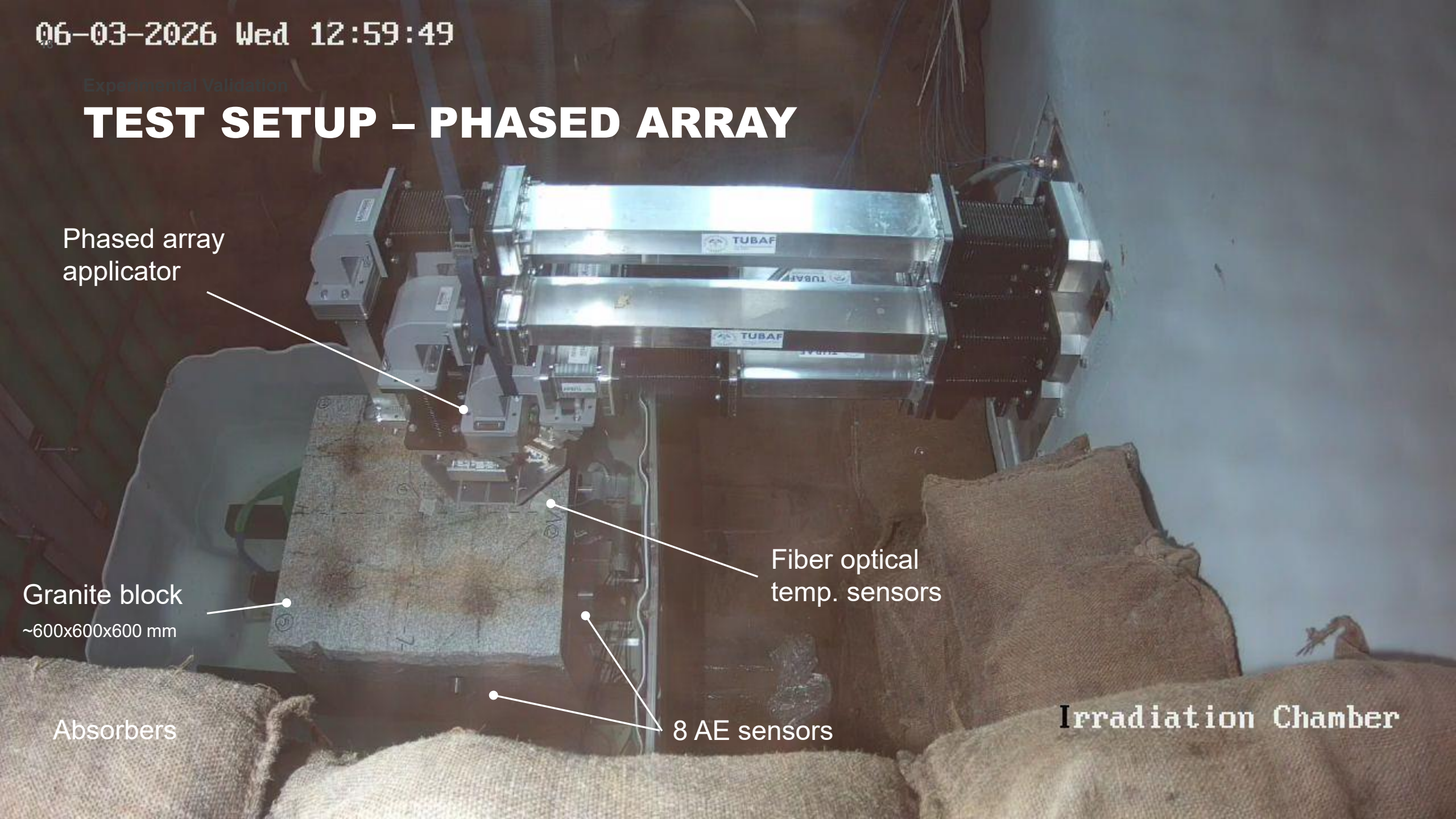
Granite block  
~600x600x600 mm

Absorbers

Fiber optical temp. sensors

8 AE sensors

Irradiation Chamber



### Experimental Validation

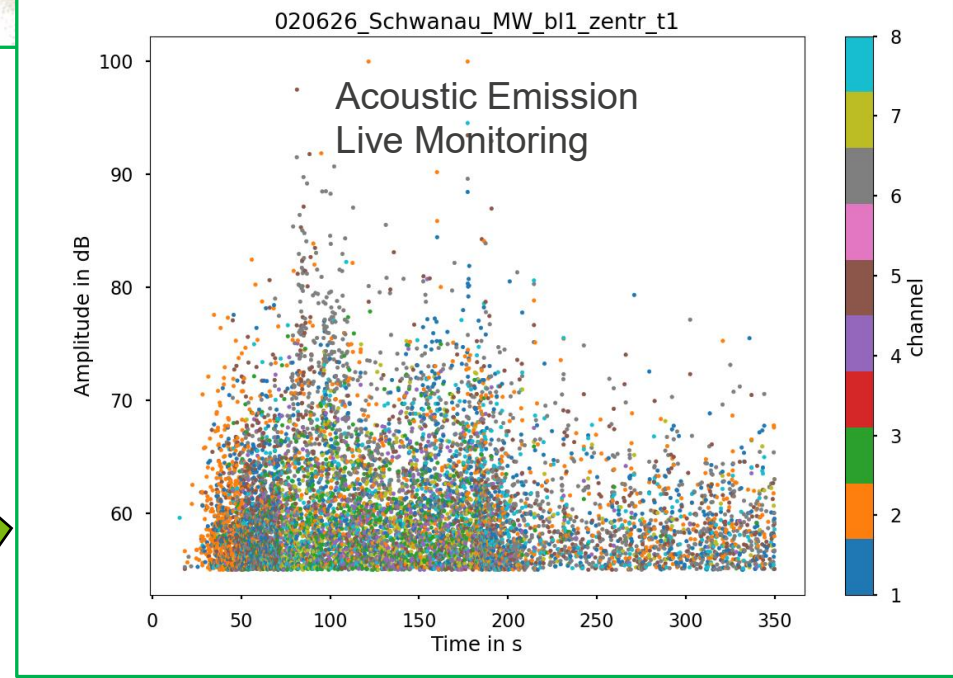
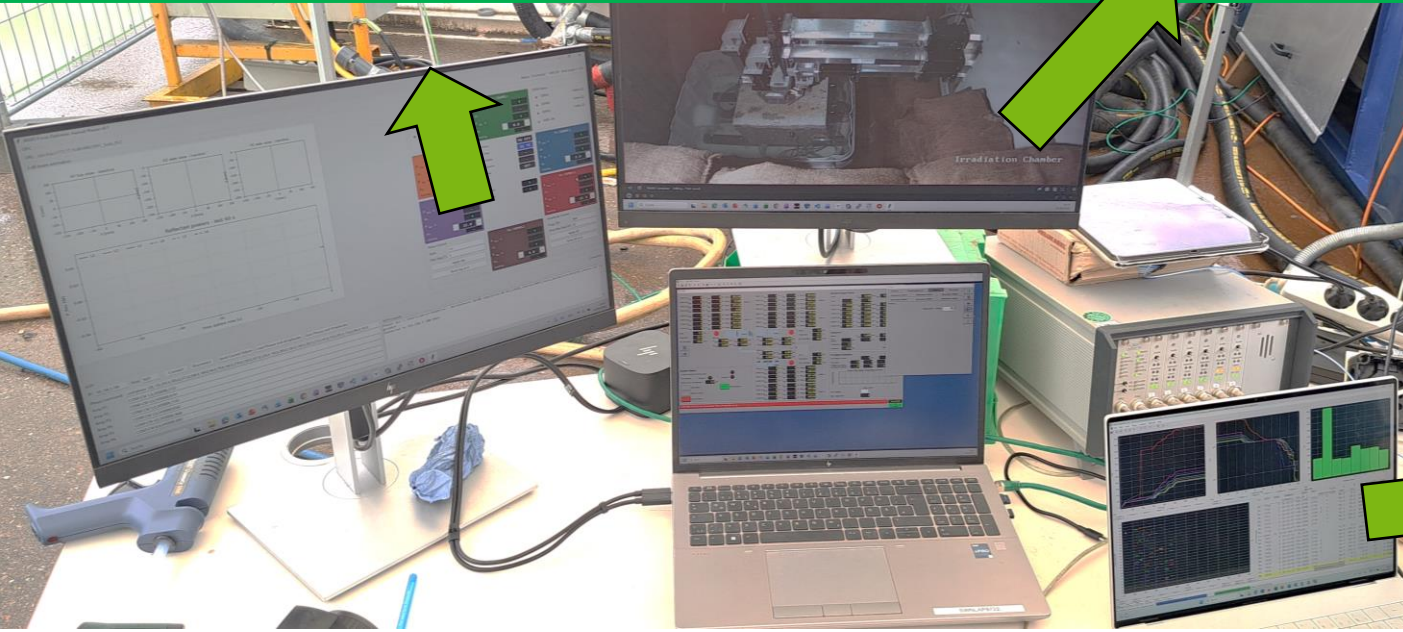
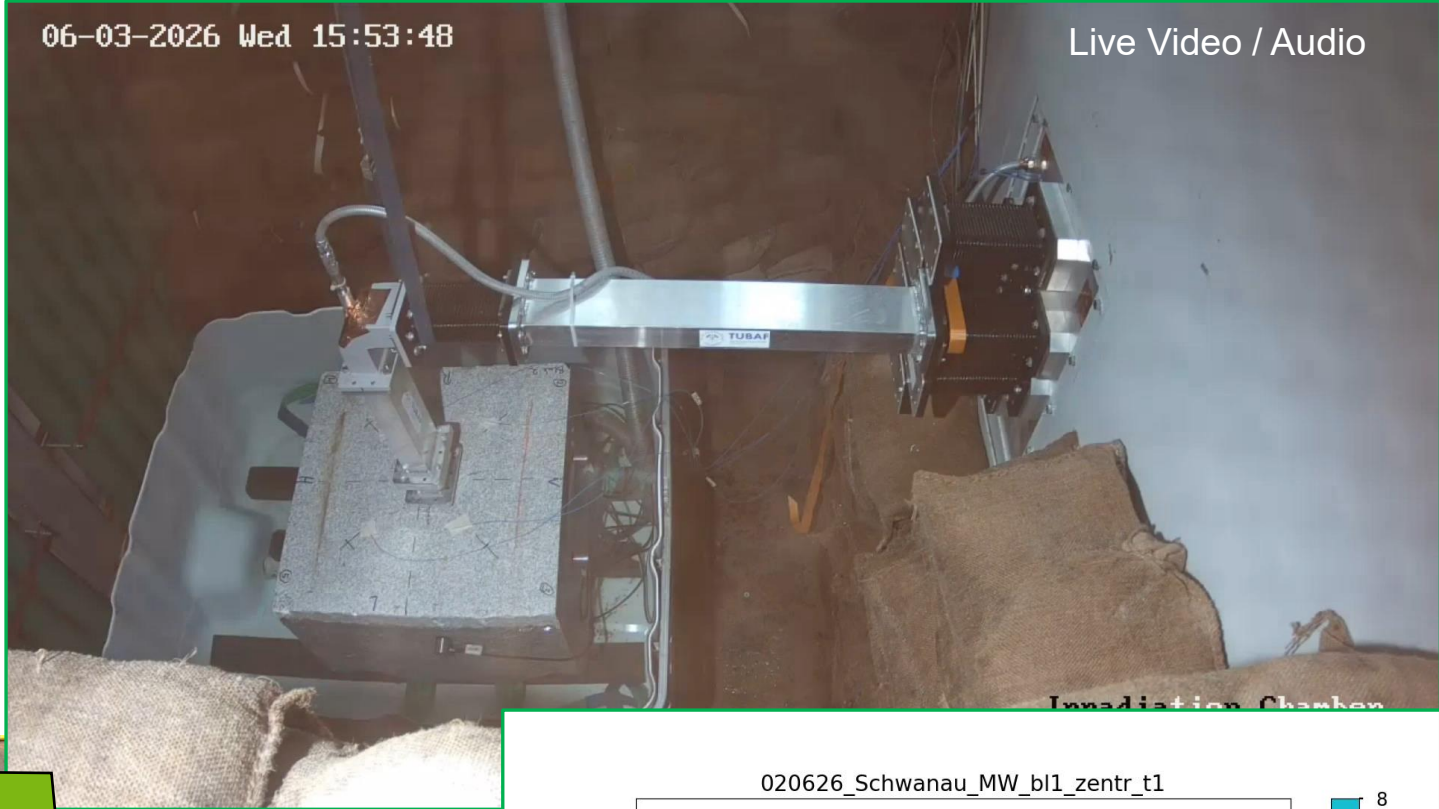
# TEST EXECUTION



Semi-Automatic  
Phased Array  
Focusing Control

06-03-2026 Wed 15:53:48

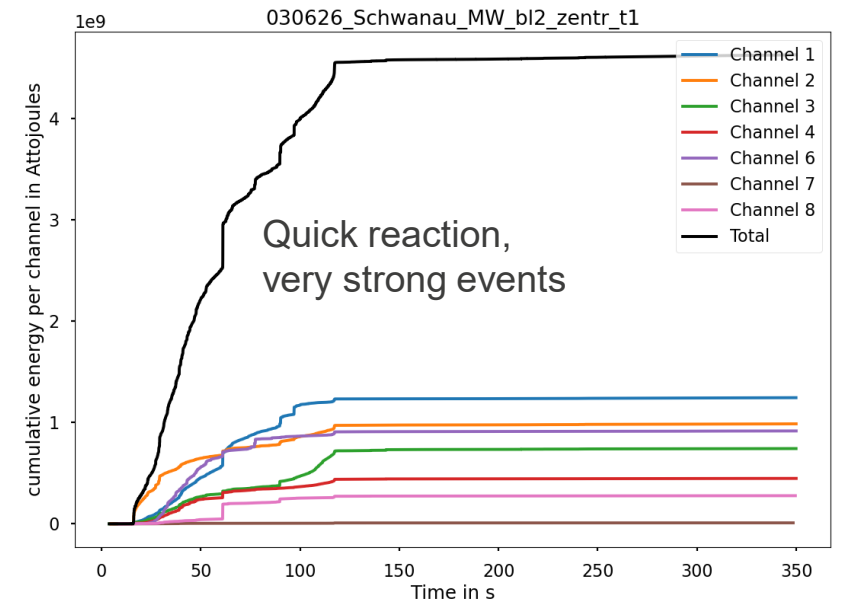
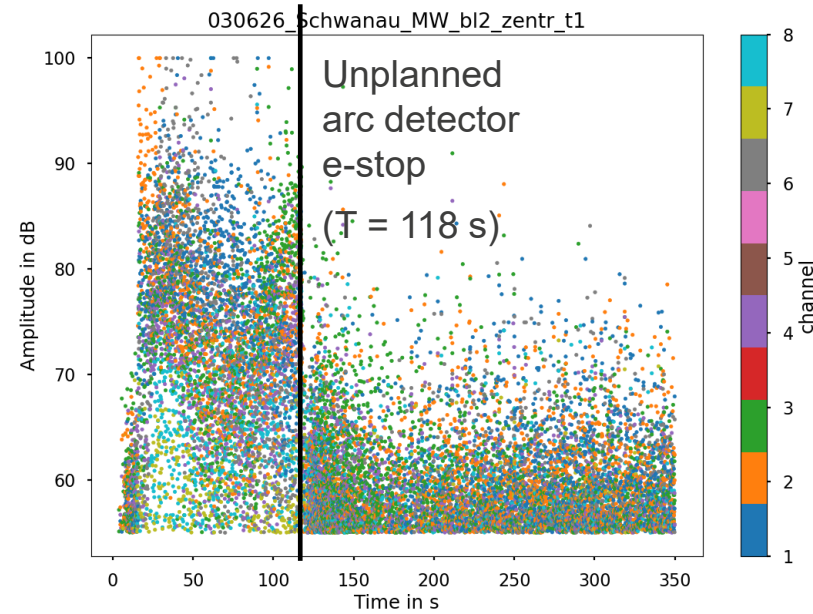
Live Video / Audio



# RESULTS: ACOUSTIC EMISSION

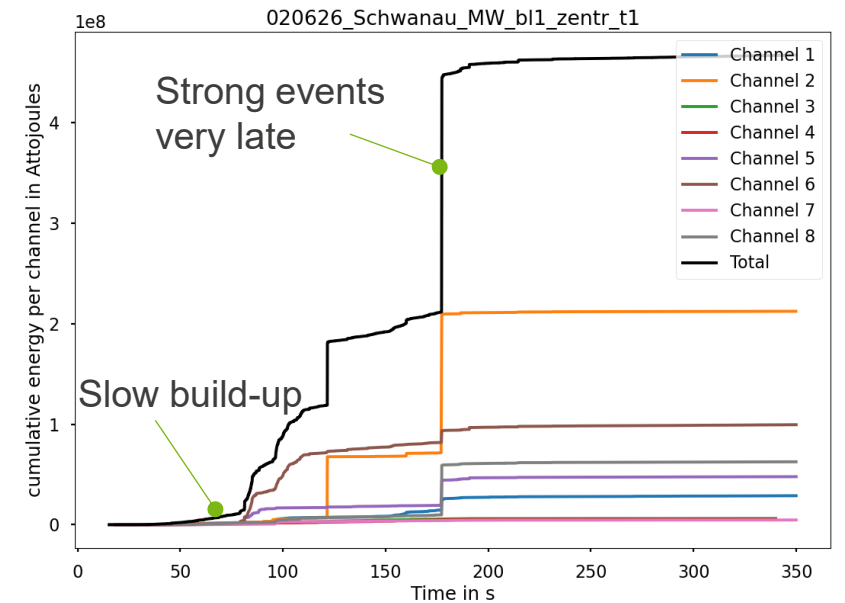
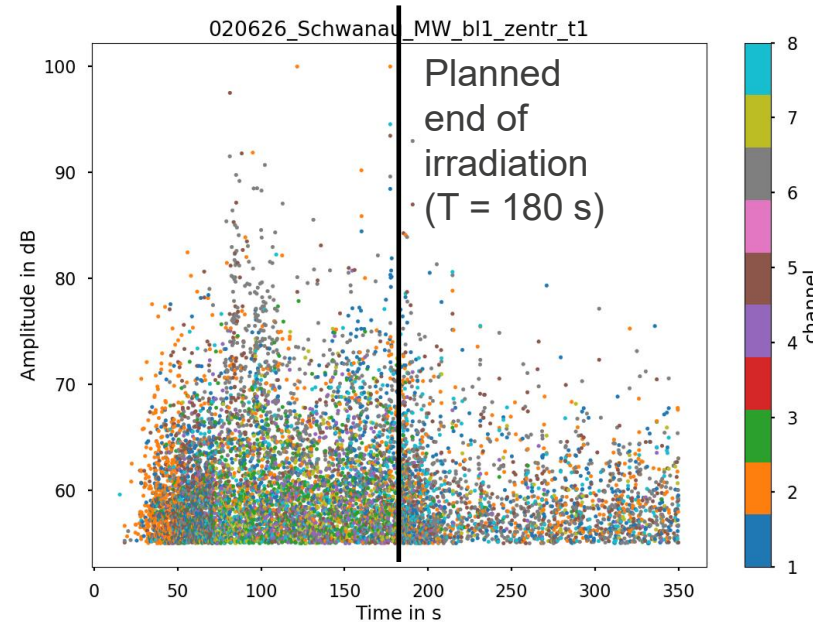
## Single Waveguide

- Block 2, Position 1 (First irradiation on the virgin block)
- Air gap ~ 10 mm
- **E-Stop due to arcing**
- 87 s, 32 kW ~ 0.78 kWh



## Phased Array

- Block 1, Position 1 (First irradiation on the virgin block)
- Air gap ~ 45 mm
- 180 s, 35 kW ~ 1.73 kWh

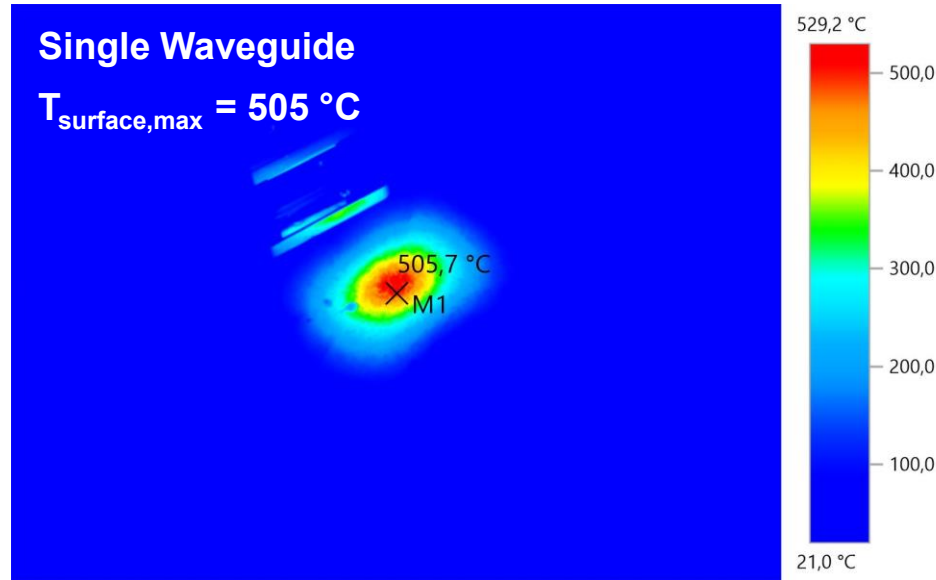


# RESULTS: TEMPERATURE AND FOCUS

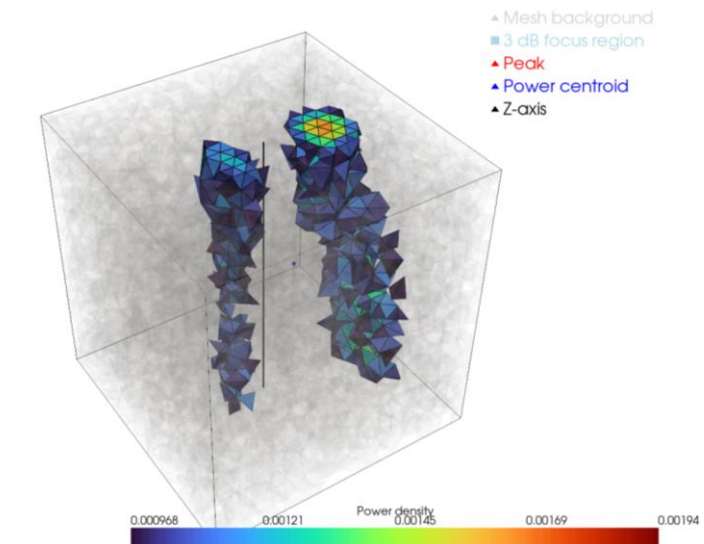
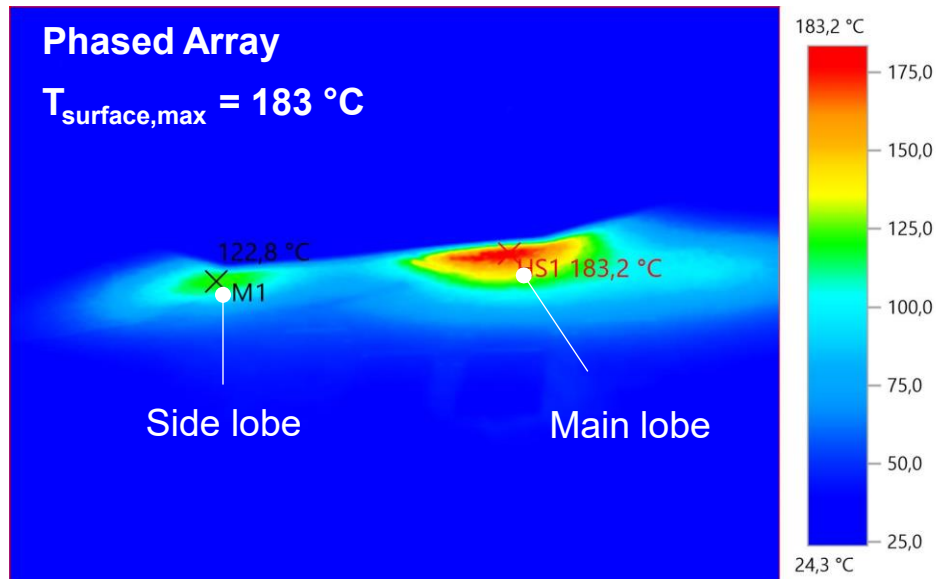
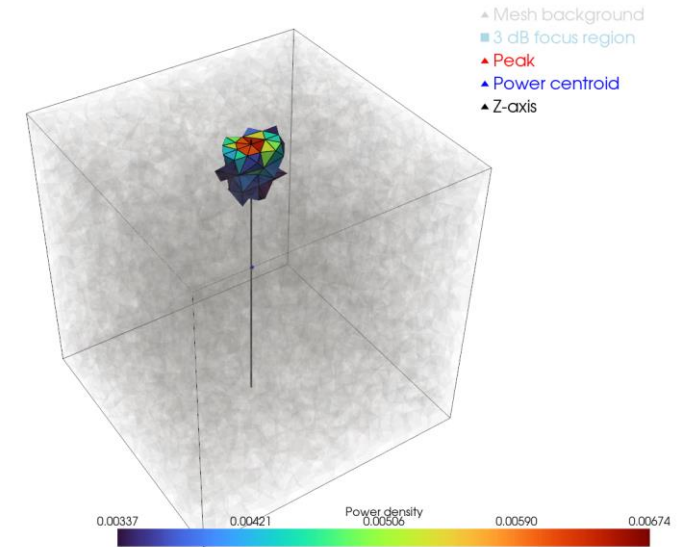
Color Photo



Thermal Image



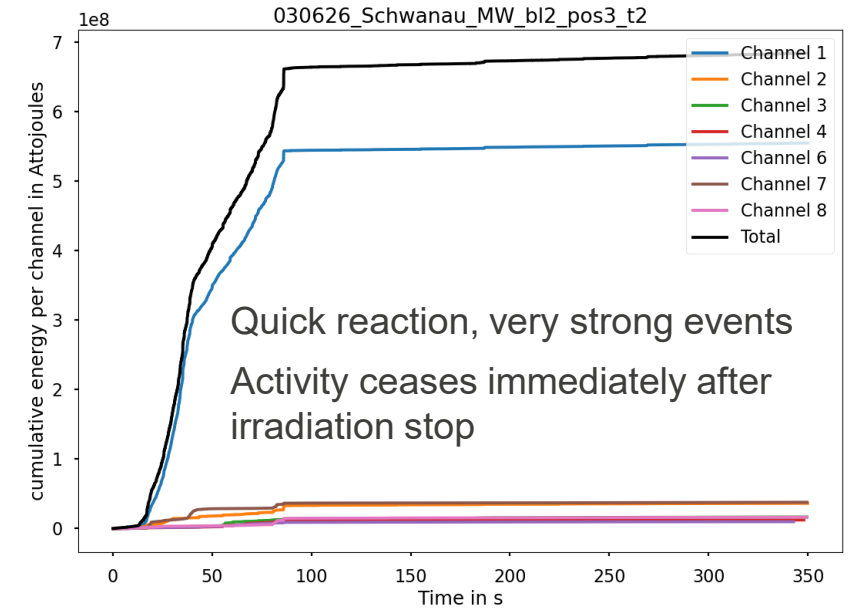
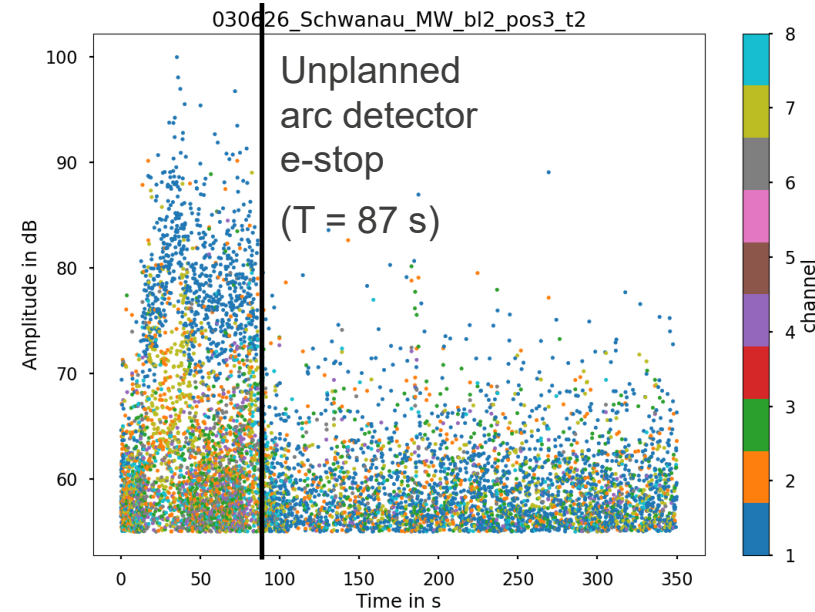
Simulated 3 dB Lobe



# RESULTS: ACOUSTIC EMISSION

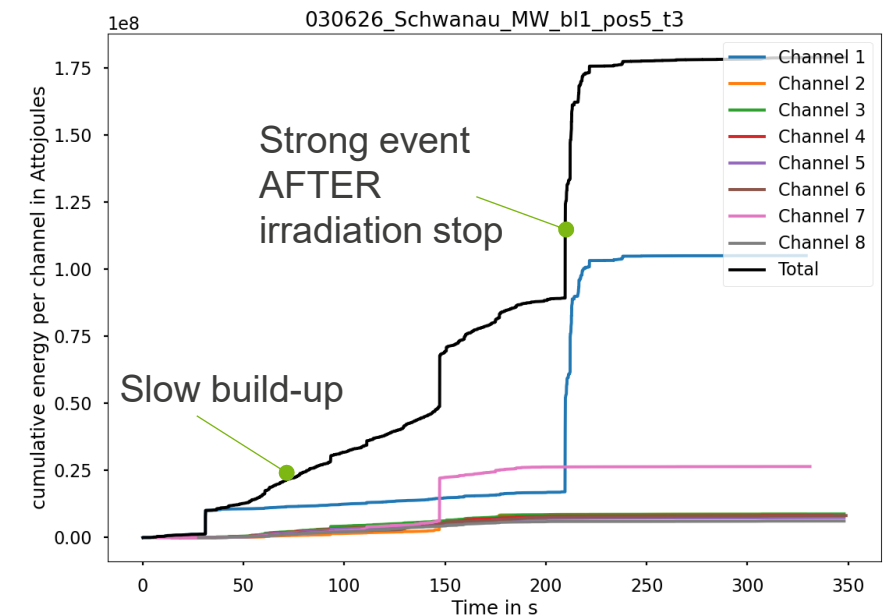
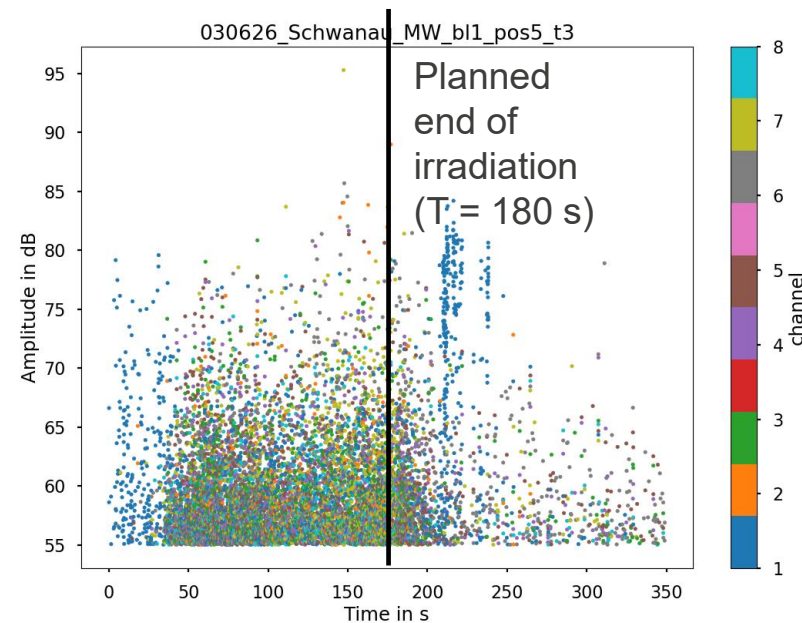
## Single Waveguide

- Block 2, Position 3 (2nd irradiation)
- Air gap ~ 10 mm
- E-Stop due to arcing**
- 87 s, 32 kW ~ 0.78 kWh



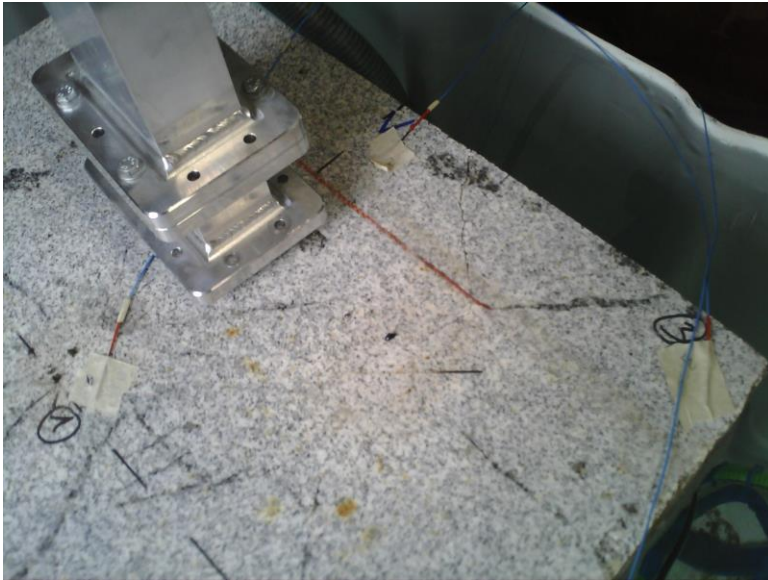
## Phased Array

- Block 1, Position 5 (3rd irradiation)
- Air gap ~ 45 mm
- 180 s, 35 kW ~ 1.73 kWh

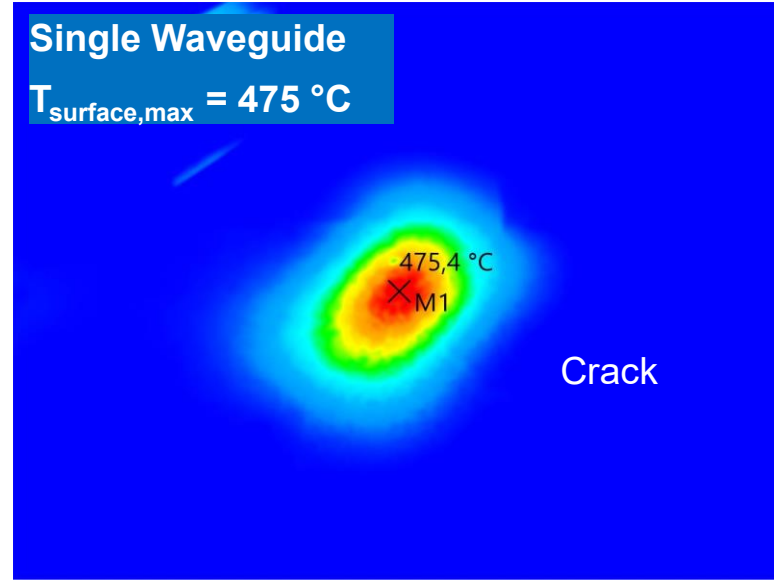


# RESULTS: TEMPERATURE AND FOCUS

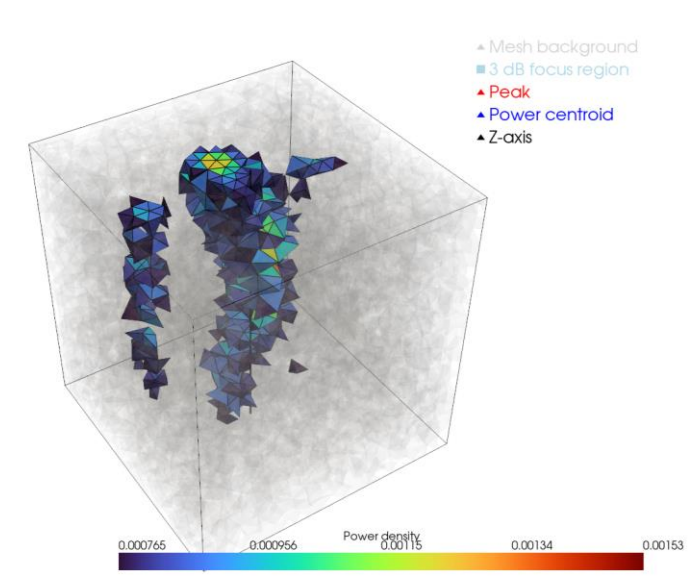
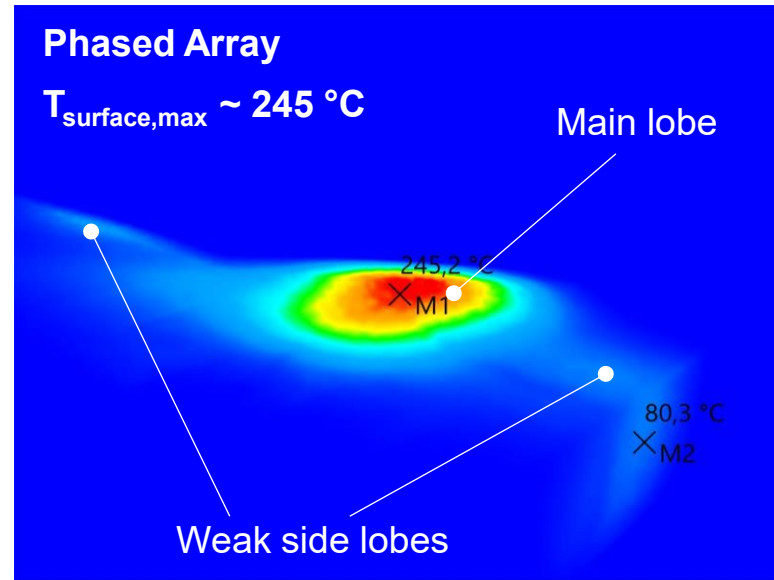
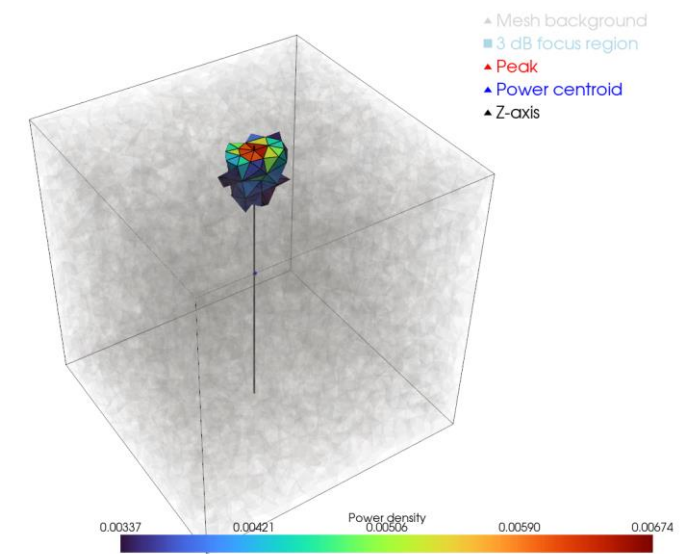
Color Photo



Thermal Image



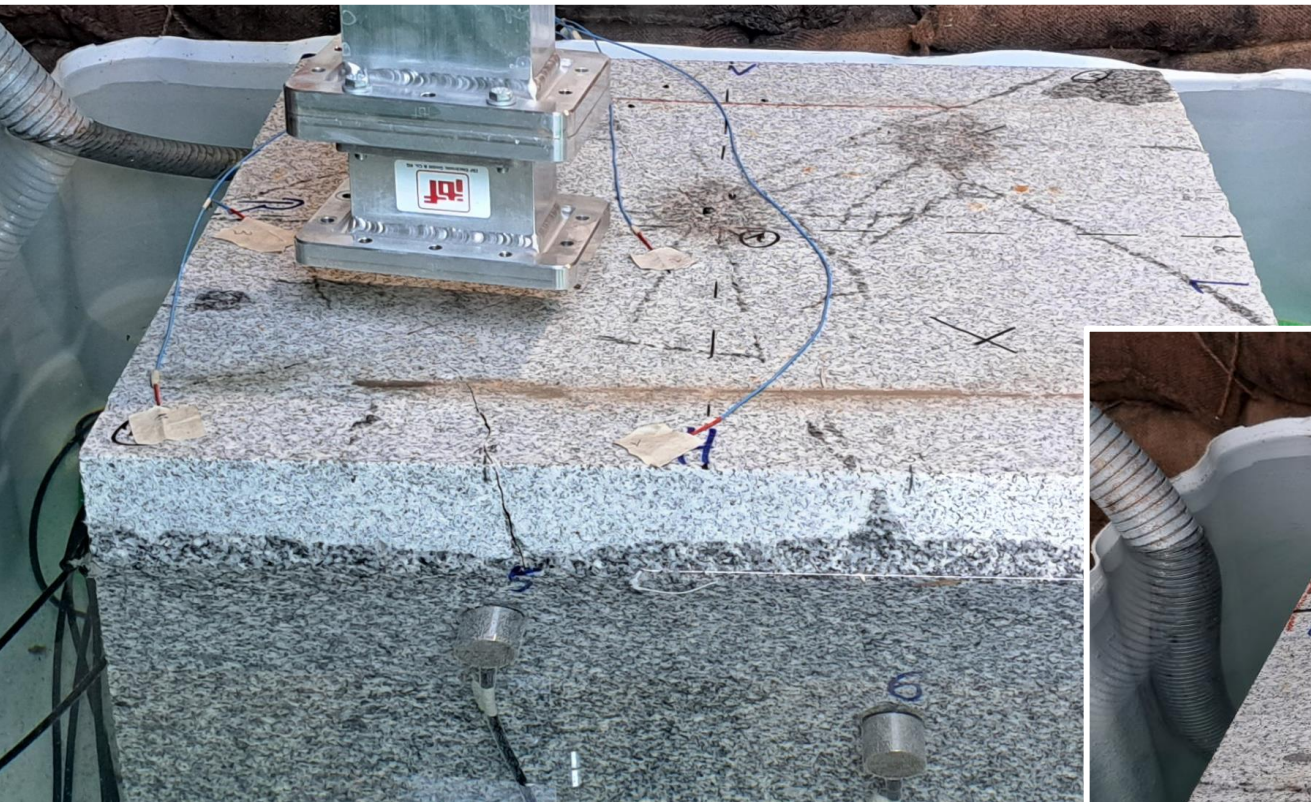
Simulated 3 dB Lobe



Experimental Validation

# PICTURES

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# CONCLUSION

## Summary

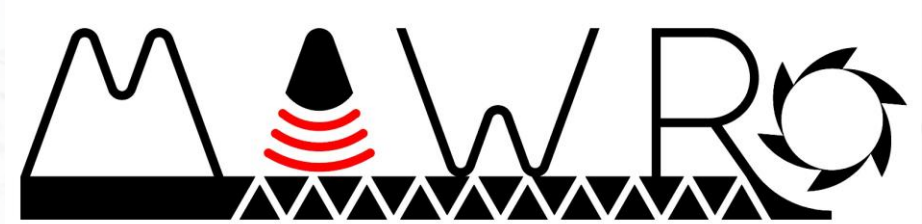
- › Irradiation trials with simultaneous AE monitoring on granite blocks in two configurations (single waveguide and 6-port phased array) were performed
- › Key assumptions on the phased array approach confirmed
- › Sophisticated phased array control strategies applied and refined

## Next Steps

- › Partial face cutting tests on virgin and irradiated rock by July 2026
- › Detailed evaluation of AE results (localization, damage assessment)
- › Further optimization of the phased array focus control
- › Preparation of TRL6 underground trials for MW-assisted cutting (MAWRo)

## Acknowledgements

- › Parts of this work were supported by the German Federal Ministry of Research, Technology and Space (BMFTR) under the “EGARoh” funding program within the MAWRo research project



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