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# Geo-Energy Magnetic Resonance Imaging (GEM) Facility at ETH Zurich: MRI as a Probe for Geofluids in Porous and Fractured Media

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## INTRODUCTION

The geosciences demand non-invasive imaging and quantification techniques to investigate the coupled thermal-hydraulic-mechanical-chemical-biological (THMCB) processes that govern subsurface systems in geothermal energy applications, subsurface energy storage, and $CO_2$, $H_2$, and other fluid storage and extraction applications. In these complex and often fractured porous media, direct access is limited, and traditional invasive methods can disturb the very processes under study. Accurate, volumetric, and non-destructive imaging is essential to resolve key parameters including fluid flow velocity, temperature distribution, rock deformation, solute transport, and microbial activity. These measurements are critical for understanding system behavior, improving predictive models, and guiding the safe and sustainable use of the subsurface.

Magnetic resonance imaging (MRI) is a non-destructive, elementally-specific, and volumetric technique that can probe complex systems in a spatially-temporally-resolved manner. Over the past five decades, the development of MRI has been accelerated primarily by the medical industry. MRI technologies are still being continuously developed, with improvements in hardware, data processing, and real-time monitoring. MRI primarily operates with non-invasive radiofrequency (RF) irradiation and is well-suited for penetrating different geofluids and rock species. MRI has previously been used for 3D velocity field mapping in rock cores (Romanenko, Xiao and Balcom, 2012; Karlsons *et al.*, 2021) and for temperature measurements in porous media (Serial *et al.*, 2023).

In this contribution, we present the design, objectives, and key technical details of MRI systems currently under development in the GEG group, which are scheduled for commissioning within the next year. Herein, we focus on outlining the design principles and the anticipated scientific contributions of the systems, as well as some preliminary test results.

## 1 METHODS

### 1.1 High-Field MRI

A custom high-field MRI device will be implemented using several commercial components (**Figure 1**). The vertically oriented superconducting magnet from Superconducting System Inc. has a maximum field of 5.6 T. The magnet has gradient inserts from Tesla Engineering that provide a maximum 270 mT/m gradient field with a clear bore of 27 cm, which are powered by IECO gradient amplifiers. The homogenous field of view is over a sphere of 20 cm in diameter. The system uses a Tecmag Redstone spectrometer, with four transmitters and sixteen receivers. Four 2 KW broadband RF amplifiers from TOMCO Technologies are used. Multichannel RF coils are homebuilt and sourced from different vendors.

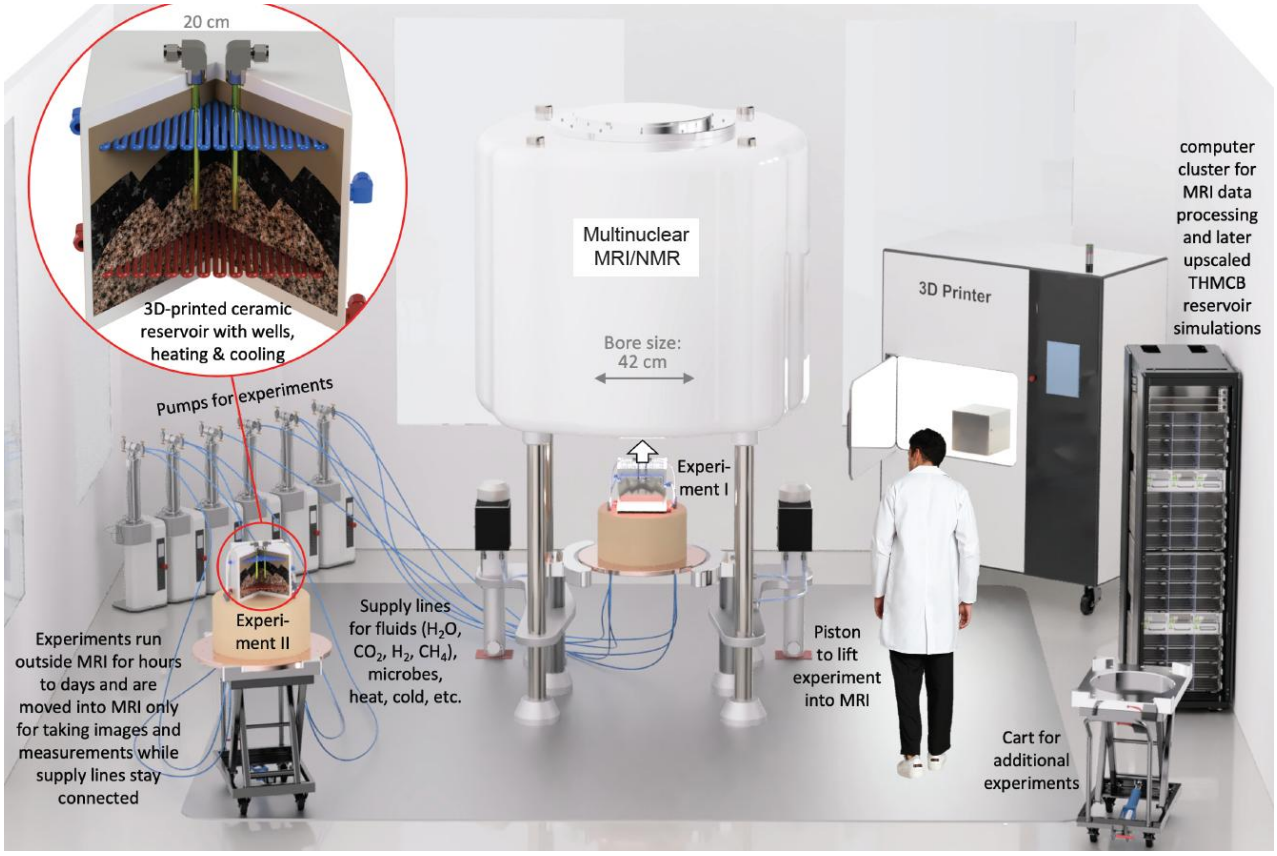



**Figure 1: Render of the GEM facility. Included is an MRI magnet (centre) with a 42 cm inner-diameter bore. Experiments are contained within 3D-printed ceramics and connected to pumps and supply lines for the various geofluids and to supply the necessary heat and pressures for experimental conditions.**

### 1.2 Low-Field MRI

Parallel to the high-field MRI, a fully custom low-field MRI system will be implemented for portable and fieldable studies as well as electron paramagnetic resonance (EPR) studies. The system will use a resistive solenoid magnet and 3-axis gradient system from Resonance Research Inc. with gradient amplifiers from AE Techron. This system also uses a Tecmag Redstone spectrometer and a 500 W low-frequency RF amplifier from TOMCO Technologies. Initial prototypes of a low-field system use ceramic ferrite magnets based on the CLAM design (Morin *et al.*, 2024).

The low-field MRI system includes dynamic nuclear polarization (DNP) and EPR capabilities. Microwave sources include both a Signalhound VSG25A and a Qblox Quibit Readout and Control (QRC), where the latter is also used for receiving signals. A 500 W EPR amplifier from TOMCO Technologies is used to amplify microwave transmission signals.

## 2 DISCUSSION

### 2.1 High-Field MRI

Our GEG laboratory currently hosts two advanced non-intrusive imaging systems tailored to investigate coupled THMCB processes in porous and fractured media. The first is an *in-situ* X-ray Computed Tomography (CT) system that enables four-dimensional (three spatial dimensions and time) imaging of rock microstructures. It allows us to visualize structural deformation, multiphase fluid distribution, and solute concentration—when enhanced with suitable contrast agents—under reactive and mechanical loading. However, X-ray CT does not provide direct measurements of fluid flow velocity or temperature fields, and it is inherently limited to small sample sizes due to resolution and beam penetration constraints. The second is an optical laser-based system used for analogue studies, where fluid velocity fields are quantified employing particle image velocimetry (PIV), while solute and temperature distributions are captured using laser-induced fluorescence (LIF) techniques. While PIV offers high spatial and temporal resolution, it requires optically- transparent media and simplified experimental conditions, which limits its applicability to representative geological materials. Further, velocities are measured with tracer particles rather than in the fluids directly. These complementary systems form the foundation of our

current THMCB imaging capabilities, while also highlighting the need for new approaches to overcome their respective limitations.

To overcome the limitations of current imaging platforms and advance our ability to observe and quantify THMCB-coupled processes in porous media, we are developing a custom multinuclear MRI facility—**Geo-Energy Magnetic Resonance Imaging (GEM)**—within the GEG group's laboratory. GEM will incorporate advanced MRI technology to enable fully non-invasive, real-time, three-dimensional (3D) visualization and quantification of multiphase, multicomponent fluid and energy transfer, as well as (reactive) biogeochemical processes within porous structures. These time-resolved 3D (4D) measurements will capture variables such as fluid velocity, temperature, pressure, and microbe or biofilm distributions.

The GEM facility is depicted in **Figure 1**. The facility is cantered around the high-field vertical MRI magnet, which uses cryogen-free technology; this enables the magnet to be operated at any magnetic field strength up to 5.6 T. This is particularly beneficial as many non-clinical MRI experiments perform better at lower fields (*e.g.*, 1 T) due to porous media exhibiting unique magnetic properties (Enjilela *et al.*, 2019; Bagnall *et al.*, 2020, 2022). GEM's MRI capabilities include multinuclear operation ($^{1/2}$H, $^{13}$C, $^{19}$F, $^{23}$Na, $^{29}$Si, $^{31}$P, $^{129}$Xe, *etc*.), which is critical for analyzing multicomponent fluids such as $H_2O$, $H_2$, $CH_4$, $CO_2$, brine *etc*.

In addition to rock cores, 3D printing technology will be used, enabling the iterative creation of different reservoir replicas to be used in experiments inside the MRI, enabling scenario testing, identification of uncertainties and parameter sensitivities, as well as optimization of geothermal reservoir utilization strategies. Additive manufacture not only allows desired reservoirs and caprocks, but also enables the printing of injection and production wells to conduct injection and production experiments. Combined with numerical modelling, GEM experiments can be used to pre-test, simulate and optimize the conditions for cost- and time-extensive underground laboratory experiments (*e.g.* in the Bedretto, Mont Terri, and Grimsel underground laboratories in Switzerland and other such facilities globally).

The high-field MRI device enables visualization and quantification of coupled THMCB processes in natural rock cores and in 3D geologic reservoir replicas at elevated temperatures (> 100 °C) and pressures (> 100 bar), including temporal resolution, resulting in a 4D analysis. Decimetre-sized reservoir replicas, manufactured using advanced additive manufacturing techniques, represent downscaled geological reservoirs, which are typically tens of kilometres in size. With high-resolution printing (< 50 µm) and special material properties, these 3D-printed replicas allow for realistic experiments under high reservoir fluid pressures and temperatures inside the multinuclear MRI system.

NMR/MRI under elevated temperatures and pressures has been thoroughly demonstrated to date. NMR probes for safe operation over ranges of 240 – 1050 °C have been used in permanent and superconducting magnets (Adler, Michaels and Reimer, 1990; Fabich *et al.*, 2020). High-pressure containments for 1 – 2 kbar experiments for use in MRI magnets are also commercially available (Fu *et al.*, 2012). These solutions, including novel containments developed in our laboratory, will be used for high-temperature and pressure experiments in GEM's MRI devices.

MRI has demonstrated the capability to non-invasively quantify key variables such as fluid velocity, temperature, pressure, and biofilm distribution in three-dimensional porous media. Among these, accurate knowledge of fluid velocity is fundamental for determining mass and energy transfer rates involving fluids, solutes, and microbes. Well-established phase-encoding MRI techniques enable 3D mapping of fluid velocity fields by exploiting the MR signal phase shift by pulsed field gradients. This phase shift is proportional to the velocity of moving nuclei, allowing quantitative velocity measurements.

Furthermore, simultaneous multinuclear MRI, including imaging with $^{19}$F, extends these capabilities to multiphase flow systems and enables tracking of solutes and microbial populations. These advanced imaging techniques are essential for investigating reactive transport processes in complex, multiphase porous systems with high volumetric resolution.

Quantifying temperature distributions in 3D-printed porous media is essential for understanding geothermal processes and thermal contributions from geochemical and biological reactions. In MRI, temperature can influence resonance frequencies, longitudinal relaxation times ($T_1$), transverse relaxation times ($T_2$), and molecular diffusion rates. By monitoring these temperature-sensitive MR signal characteristics, it becomes possible to reconstruct the three-dimensional temperature field of fluids that contain MR-active nuclei. This enables real-time, non-invasive imaging of temperature-dependent phenomena, such as buoyancy-driven flow,

within pressurized porous media, offering valuable insights into subsurface thermal processes in geothermal and reactive environments.

### 2.2 Low-Field MRI

A custom low-field (40 mT) MRI device will be implemented that is capable of traditional MRI experiments, but in a far more economic and potentially portable modality. This device offers the unique capability to directly image paramagnetic organic radical species (*e.g.*, quartz radicals) using electron paramagnetic resonance (EPR)-MRI with a FOV over a sphere of 5 cm in diameter. In situations where radicals cannot be imaged, then dynamic nuclear polarization (DNP) can be used to enhance the signals of $^{1}H$ and $^{13}C$ by a theoretical maximum of 660- and 2600-fold, respectively, offering signal strengths that can exceed those measured at 5.6 T. This also offers a concomitant time savings of five and six orders of magnitude, respectively.

An initial prototype of a low-field MRI device was built using inexpensive ceramic ferrite permanent magnets and custom RF probes (< $100 USD). For a porous medium filled with $H_2O$, the pore size is proportional to the characteristic $T_2$ of the $^{1}H$ nuclei in the pore space.(Yan *et al.*, 2023) The $^{1}H$ $T_2$ can be measured with the Carr-Purcell/Meiboom-Gill (CPMG) pulse sequence using the ceramic magnet system in a highly portable and fieldable modality. With knowledge of the surface relaxivity, $\rho$, for different porous media the absolute pore size can be determined.

## 3 CONCLUSIONS

The GEM facility will be a world unique laboratory for MRI-based studies of geological fluids and materials under realistic reservoir conditions. Researchers from other laboratories and institutions are encouraged to inquire about using the facility for their unique experiments. The primary high-field instrument enables multinuclear studies at a strong field, with a large bore, and without the constraints of clinical or *in-vivo* scanners. The low-field instrument offers the ability to probe paramagnetic radical species and potentially operate in a low-cost and portable modality.

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