Task 3.1

Task Title

Geo-energy technologies

Research Partners

Department of Mechanical and Process Engineering (D-MAVT) at ETHZ, Institute for Building Materials (IfB) at ETHZ, Lucerne University of Applied Sciences and Arts, University of Applied Sciences and Arts Western Switzerland (HES-SO), Laboratory for Hydraulic Machines (LMH) at EPFL

Current Projects (presented on the following pages)

Erosion Modelling in Centrifugal Pumps
E. Casartelli, S. Tosin, D.R. Launchbury

Impact of polymers in well cementing for geothermal wells
M. Palacios, R. K. Mishra, D. Sanz-Pont, R. J. Flatt

Deep Borehole Seismometer Demonstrator
C. Praplan, C. Cachelin, J. Moerschell

Extending Geophone Sensitivity for Induced Seismicity Recording
C. Praplan, J. Moerschell

Corrosion Challenges of Deep Geothermal Systems in Switzerland
A. Vallejo Vitaller, U. Angst, B. Elsener

Detecting Water Through Electric Impedance Measurements
G. Emery, A. Ganchinho, L. Mayencourt, J. Moerschell

Task Objectives

Five research groups are active in solving important technological problems in the application of geothermal energy. Without these technologies, geothermal energy would not become economically competitive.

- **Innovative drilling technologies**: highly important to reduce the so far excessively high costs for drilling the deep wells
- **Cementitious grouts for bore holes in geothermal wells**: concrete has to be pumped for up to 5 km down and should remain fluid, so cement hydration must be delayed
- **Heat Exchangers for geothermal applications**: the efficiency of heat exchangers will determine economic feasability
- **Sensors for harsh environments**: the main risk is that earthquakes will be initiated, the sensors are very sensitive and monitor seismic activities during the drilling process.
- **Long-term durable materials for geothermal plants**: Long-term operation of geothermal plants require durable materials without excessively high costs.

Interaction Between the Partners – Synthesis

- As the task group works on very different objectives, the research institutes exchange results in meetings at least two times a year. They have bilateral collaborations.

Highlights 2016

- Demonstrated for the first time that cement hydration can be delayed by specific dosages and structures of comb-copolymer superplasticizers. Established the key role of the curing temperature in the chemical composition of the cement pore solution and rheological properties of admixed pastes (Poster Flatt).
- A new sensor concept for seismometers based on magnetic suspension of an inertial spherical mass is developed and validated; it is now on the prototype level. New is that the force feedback loops of the system are implemented digitally (Poster Moerschell).
- Electrical impedance measurements have been studied as alternative technique to detect water in the rocks (Poster Moerschell)
- An high-temperature / high-pressure autoclave to study durability of metallic and inorganic materials in the geothermal brines is installed and the brines in the geothermal wells are determined by modeling (Poster Elsener)
- Numerical simulations can improve the understanding of the hydrothermal spallation drilling, provide more details than experiments (such as the temperature distribution in the whole field, velocity distribution, and also the effect of different structures), which will be helpful for designing and optimizing of the process.

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Erosion Modelling in Centrifugal Pumps

Ernesto Casartelli, Stefano Tosin, David Roos Launchbury

Introduction

Geothermal pumps are subjected to highly corrosive and erosive environments leading to significantly reduced life spans for impellers and components. Erosion not only leads to eventual material failure but a steady degradation of pump efficiency.

This work deals with the prediction of gradual erosive wear in centrifugal pumps and tries to provide a framework to estimate the effects of particle erosion on the long-term efficiency.

Fig. 1 – Depiction of an eroded open impeller (picture taken from [3])

Objectives

The proposed simulation procedure was developed to investigate particle erosion using a computational approach, as experimental erosion investigations are lengthy and expensive. The procedure should allow the investigations of high-erosion regions in pump impellers. Additionally, the actual geometrical erosion of the blades should be observable, as well as its influence on the pump performance characteristics. The goal is then to redesign existing pump impeller geometries in such a way that their performance is guaranteed over a longer period of time than is currently the case. This could be achieved by finding geometrical variations that reduce particle impacts by changing the flow structure or allow for more erosion resistance by material addition or localised coating. The influence on long-term performance of such modifications can be estimated using the present method.

Methods

- In-house modified OpenFOAM libraries are used for all calculations
- Lagrangian particle tracking used for the disperse phase
- Erosion modeling based on the Tabakoff & Grant model [1,2]

  $$E = f(\gamma)\left(\frac{V_p}{V_1}\right)^2 \cos\gamma\,(1-{R_T}^2)+f(V_{PN})$$

  where E is the eroded wall mass per mass of colliding particle, γ is the impact angle and V_p is the particle velocity at the time of impact. The other quantities are model functions based on the above quantities as well as constants that describe the material pairs of wall and particle.
- Iterative procedure for long term erosion calculations
  1) Calculate flow field using appropriate OpenFOAM solver
  2) Calculate particle tracking based on resulting flow field. Particles are calculated in the relative frame of reference using additional source terms for rotational forces.
  3) Wall collisions are recorded and erosion depth is calculated for each impacting particle. Particle impacts are monitored over a fixed period of time during which the geometry is assumed to remain constant.
  4) Resulting erosion depth is extrapolated to a selected duration (eg. 1 week of operating time)
  5) Erosion depth is used to deform the mesh in the wall face normal direction and mesh smoothing is performed.
  6) Restart from 1)
- Particle simulation duration and time of constant geometry can be varied to improve simulation results at the cost of increased calculation times.

Results

The following figures 2 and 3 show the degradation of the leading edge geometry over the course of two weeks using the present method.

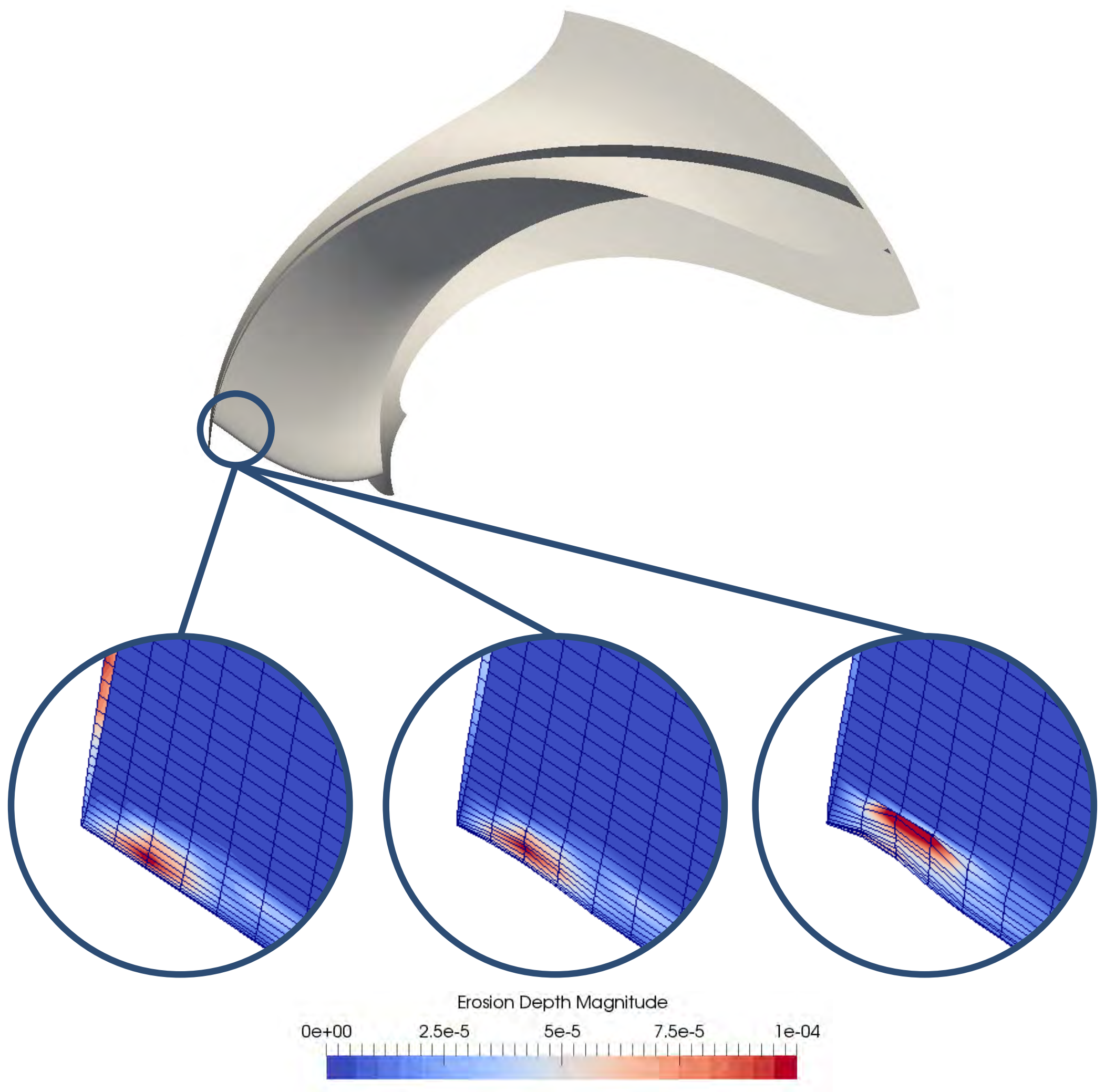

Fig. 2 – Closeup of leading edge erosion pattern

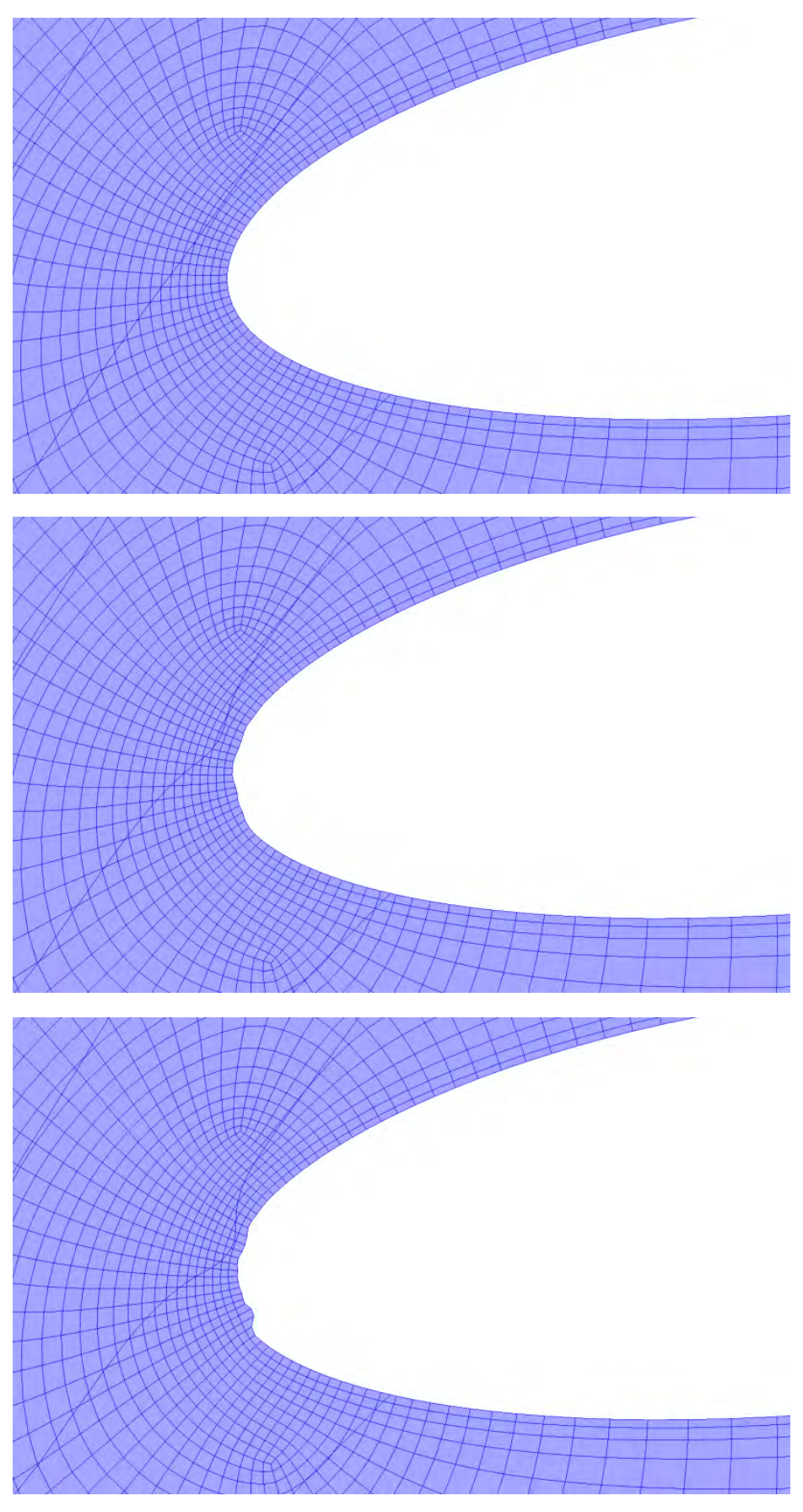

Fig. 3 – Constant-span slice

Figure 4 below shows a geometrical alternative of an impeller leading edge. The modified impeller performs at an overall lower efficiency compared to the original one, see figure 5, but particle erosion is significantly reduced. The goal will be to find an optimal trade-off between erosion reduction and long-term efficiency.

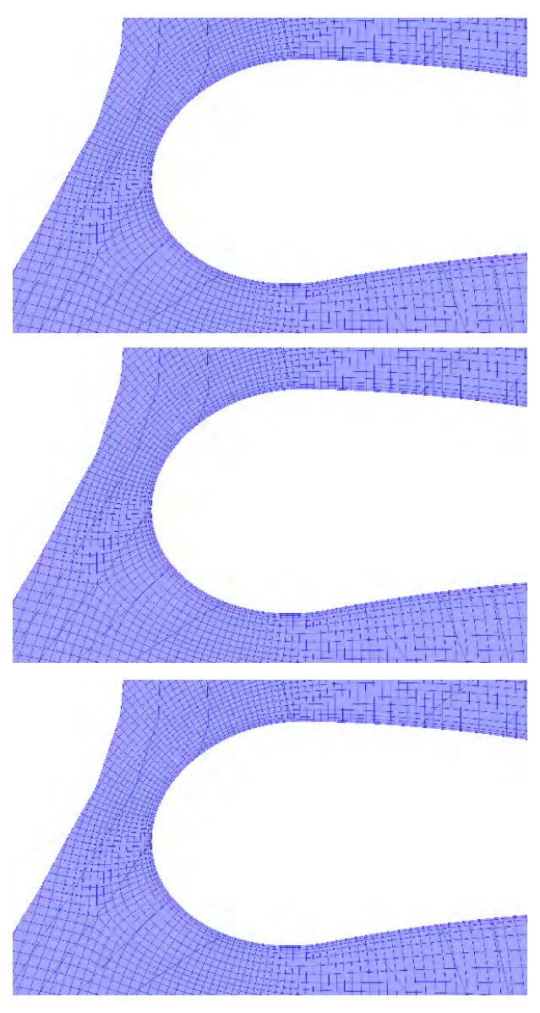

Fig. 4 – Leading edge alternative geometry. Erosion depth reduced.

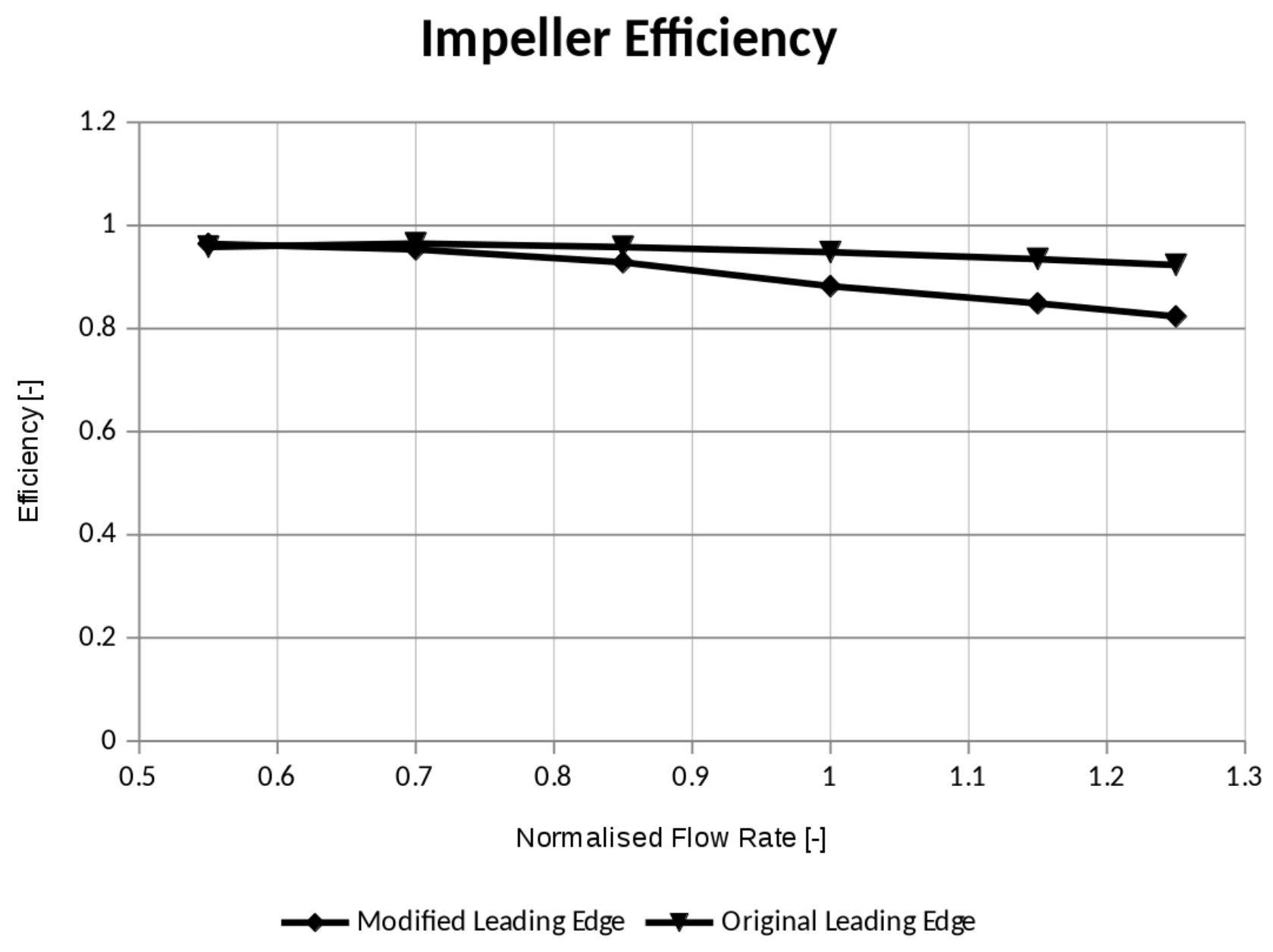

Fig. 5 – Impeller efficiency comparison

Conclusions

- Erosion prediction was succesfully implemented in the OpenFOAM framework for pump impeller applications
- OpenFOAM's Lagrangian particle libraries were improved for cases involving rotating frames of reference and cyclic mesh interfaces
- The iterative coupling of erosion rate and mesh deformation was implemented and shows promising results
- First geometrical variations were designed and investigated with respect to erosion resistance and efficiency

Outlook

- Currently, particle data and erosion model constants are based on past experiences and other authors (eg.[3]). Comparisons with actual eroded impeller geometries should be performed.
- Efficiency drop of eroded impeller geometries will be investigated
- Additional efforts need to be invested into improving the particle tracking capabilities of OpenFOAM

References

[1] G. Grant and W. Tabakoff, "Erosion prediction in turbomachinery due to environmental solid particles," in Proceedings of the 12th AIAA Aerospace Sciences Meeting, AIAA Paper no. 74-16,Washington, DC, USA, January-February 1974.
[2] G. Grant and W. Tabakoff, "Erosion prediction in turbomachinery resulting from nvironmental solid particles," AIAA Journal of Aircraft, vol. 12, no. 5, pp. 471–478, 1975.
[3] N. Martin S. Krüger and P. Dupont, "Assessment of wear erosion in pump impellers," in Proceedings of The Twenty-Sixth International Pump Users Symposium, 2010.

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Impact of polymers in well cementing for geothermal wells

*M. Palacios, R. K. Mishra, D. Sanz-Pont, R. J. Flatt**

1. Introduction

Backfilling with cementitious material is essential for mechanical stability of deep wells. However, with increasing depth temperature rises involving many technological challenges such as poor rheological properties and quick setting of cement slurries. On site, a combination of different chemical admixtures including dispersants, set retarders and accelerators are normally used although a loss of performance is often found.

In the Group of Physical Chemistry of Building Materials, in the frame of WP3 Task 3.1 “Geo-energy technologies”, we investigate the use of specific comb-copolymer superplasticizers to control cement hydration kinetics and rheological properties of cement slurries at the extreme conditions encountered in geothermal well. This will be done using an experimental and molecular modeling approach.

2. Methods

- **Isothermal calorimetry** to study the impact of polymer structure and dosage on cement reaction kinetics with the temperature.
- **Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES)** and **Dynamic Light Scattering (DLS)** to analyze cement pore solutions.
- **High-end rheometer** to investigate the rheological properties of the superplasticized retarded mixes.
- **Molecular modeling** to understand the interaction between organic admixtures and the chemical species present in solution.

3. Highlights of the project

It has been demonstrated for first time that cement hydration can be delayed at high temperatures by specific dosages and structures of comb-copolymer superplasticizers (**Figure 1**).

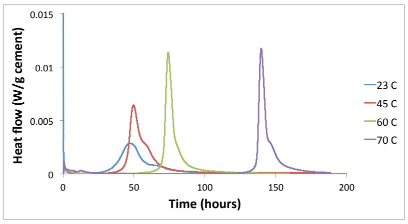


Figure 1. Calorimetry curves at different temperatures of cement pastes in presence of a specific comb-copolymer

The analysis of the chemical composition of the cement pore solution has proved a dramatic increase in the concentrations of Si, Al, Fe and Mg, in admixed cement pastes hydrated at 23 °C (**Figure 2a**). The formation of polymer aggregates involving intramolecular complexes between polymers and multivalent cations could explain the increase of these elements. In fact, nanoparticles with a size around 700 nm have been identified in the pore solution (**Figure 2b**). In contrast, these nanoparticles are only marginally formed in admixed pastes hydrated at 70 °C.

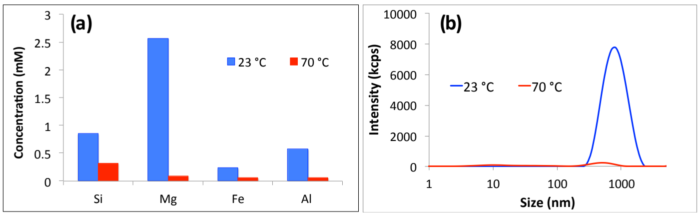


Figure 2. (a) Analysis of pore solutions of admixed pastes by ICP-OES and (b) Intensity size distribution of pore solutions by DLS.

The presence of nanoparticles in the pore solution at 23 °C would explain the shear-thickening behavior of the cement pastes in contrast with the Bingham behavior of those hydrated at higher temperatures (**Figure 3**).

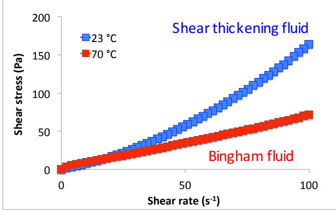


Figure 3. Flow curves of admixed cement pastes hydrated during 1h at 23 °C and 70 °C

The mechanisms behind molecular interactions between tricalcium silicate (C_3S) and aluminate ions has been firstly studied by molecular dynamics (MD) simulations using all-atom accurate force field models (**Figure 4**). Furthermore, the interactions between the aluminate ions and PCE comb-copolymers have been investigated (**Figure 5**).

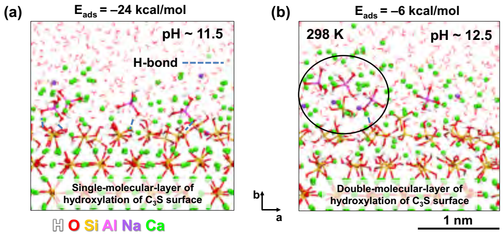
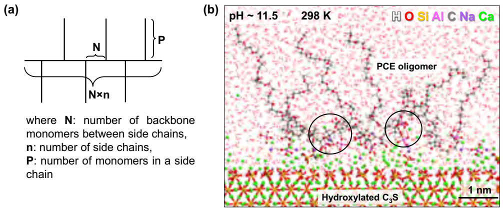


Figure 4. Binding of aluminate ions with the hydroxylated (hyd.) C_3S surface. (a) Interactions of aluminate ions with hyd. C_3S surface at pH ~ 11.5 involve strong ionic interactions to calcium ions on the surface as well as interfacial hydrogen bonds (Al–OH···O–Si and Al–OH···OH–Si). (b) Interactions of aluminate ions with hyd. C_3S surface at pH ~12.5 are weaker. Dissolution of silicate ions and formation of ionic complexes between aluminate and calcium ions, aluminate ions and silicate ions are shown using circular highlight.



where **N**: number of backbone monomers between side chains,
n: number of side chains,
P: number of monomers in a side chain

Figure 5. (a) Structure notation shown with an example of PCE with six side chains. Used PCE is composed of anionic backbone (polyacrylate) with side chains of polyethylene oxides.(b) MD snapshot of interaction between aluminate ions and polycarboxylate ether (PCE) on the hyd. C_3S surface. Complex formations happen between carboxylate group and aluminate ions (circular highlight). Very weak interactions of PCE oligomer with hyd. C_3S can be seen.

4. Future research

The following studies will give new insights into the design of more robust cement grouts:

- Role of the nanoparticles on the delay of cement hydration.
- Influence of the temperature on the adsorption of the polymer.
- Impact of organic admixtures in presence of Mg and Fe ions by molecular modeling.

5. Acknowledgements

Francesco Caruso and Sara Mantellato (IfB-ETHZ) for the ICP-OES analysis and Eric Fisher (ICB – ETHZ) for providing access to the DLS.

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Deep Borehole Seismometer Demonstrator

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1. What is the problem ?

Environmental sensors are currently not well suited for DGE monitoring:

- scientific sensors are too costly or not available for deep boreholes.
- fracture motion detection puts particular requirements on sensors.
- commercial equipment (e.g. for oil/gas reservoir exploration and monitoring) is not always adequate for water reservoir monitoring

.

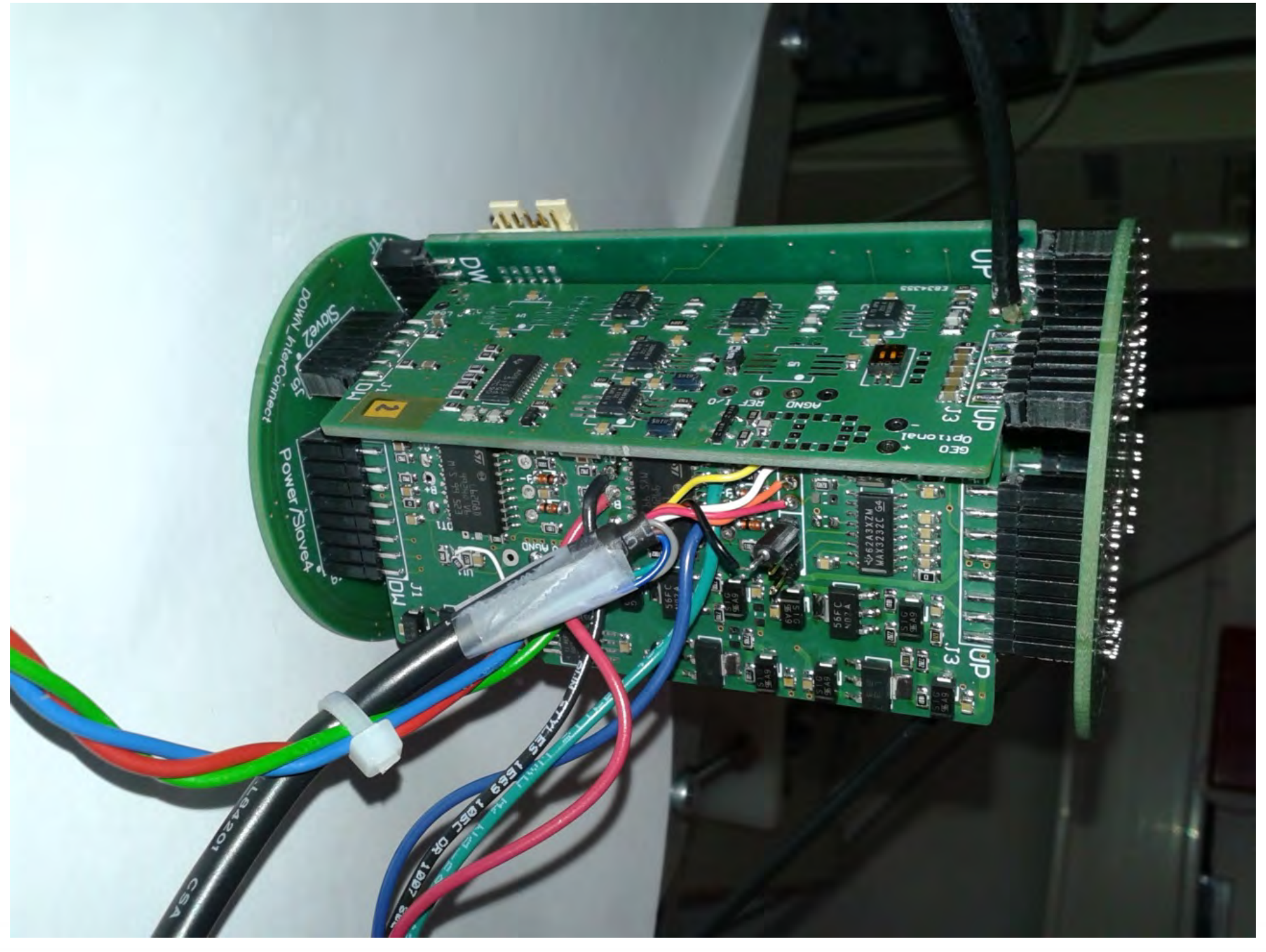
2. New deep borehole seismometer

- Monitor induced seismicity close to it's origin
- Performance target: sense microseismic events related to rock fracturing and pressurized water flow
- Extreme environment: 200bar+, 150°C, highly corrosive materials
- High temperature tolerant sensor front end with acquisition electronics
- Geophone sensors in three axes
- Capability to measure inside up to 30° inclination borehole
- Mechanically stiff mounting for large bandwidth acquisition up to 400sps.
- Electronic sensitivity enhancement by active termination (negative impedance conversion)

3. Electronics compartment

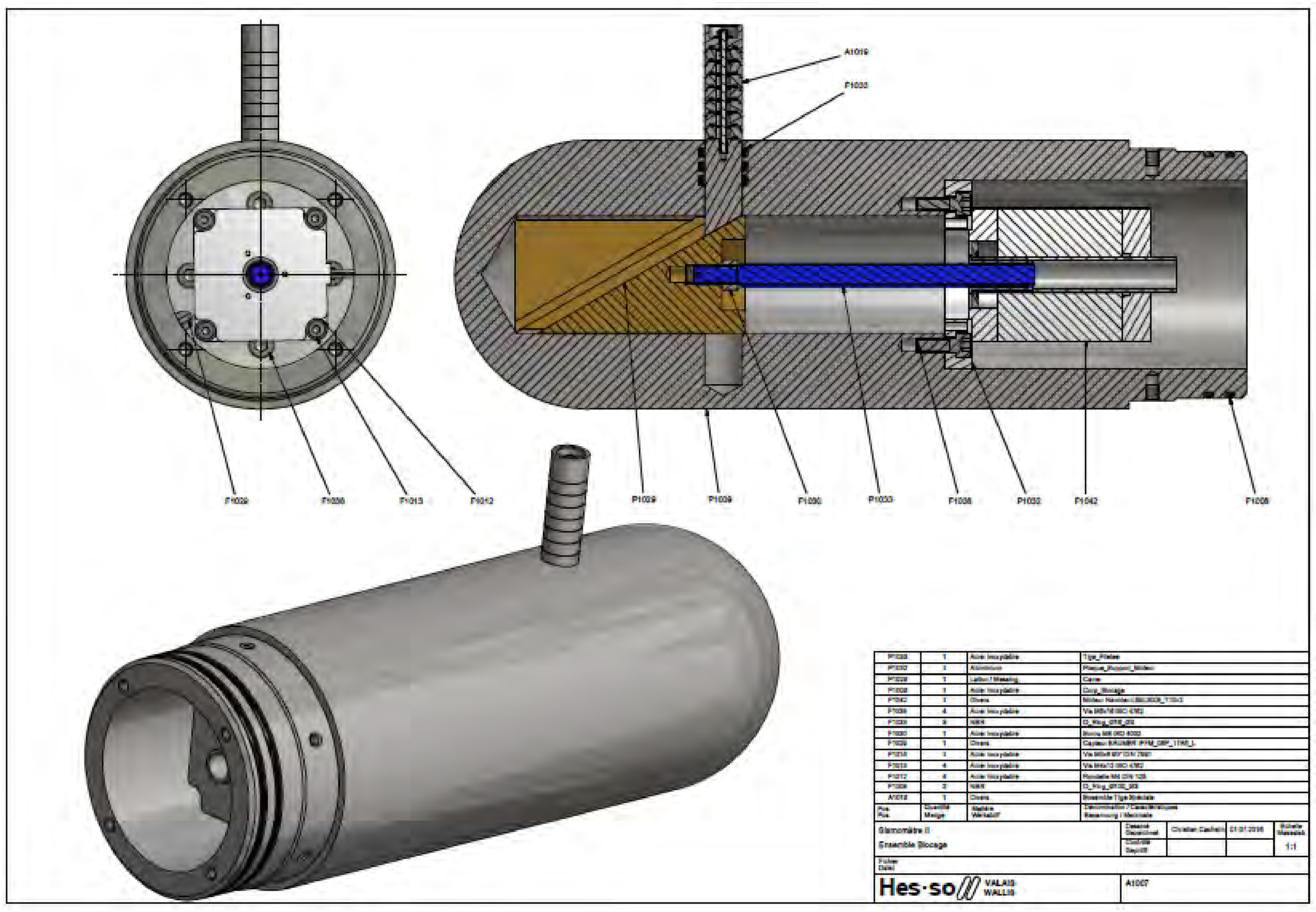
The electronics of the seismometer comprise

- Three channel active termination circuits and A/D conversion
- Preprocessing of data (filtering) implemented in an FPGA
- Serial communication interface to the cable, capable of transmitting over long distance.
- Power supply circuits and housekeeping sensors
- Two motor controllers for the blocking devices



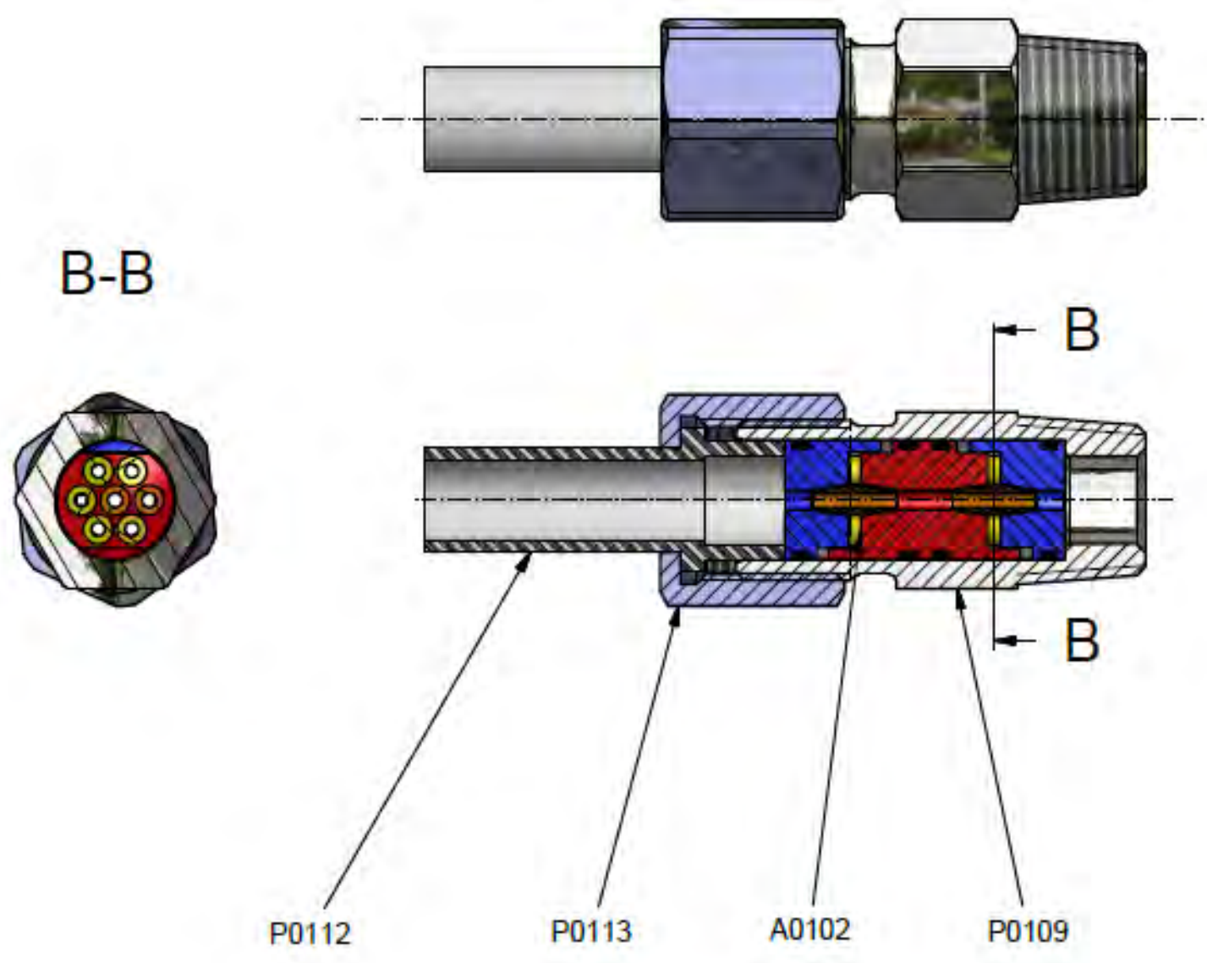
4. Seismometer blocking device

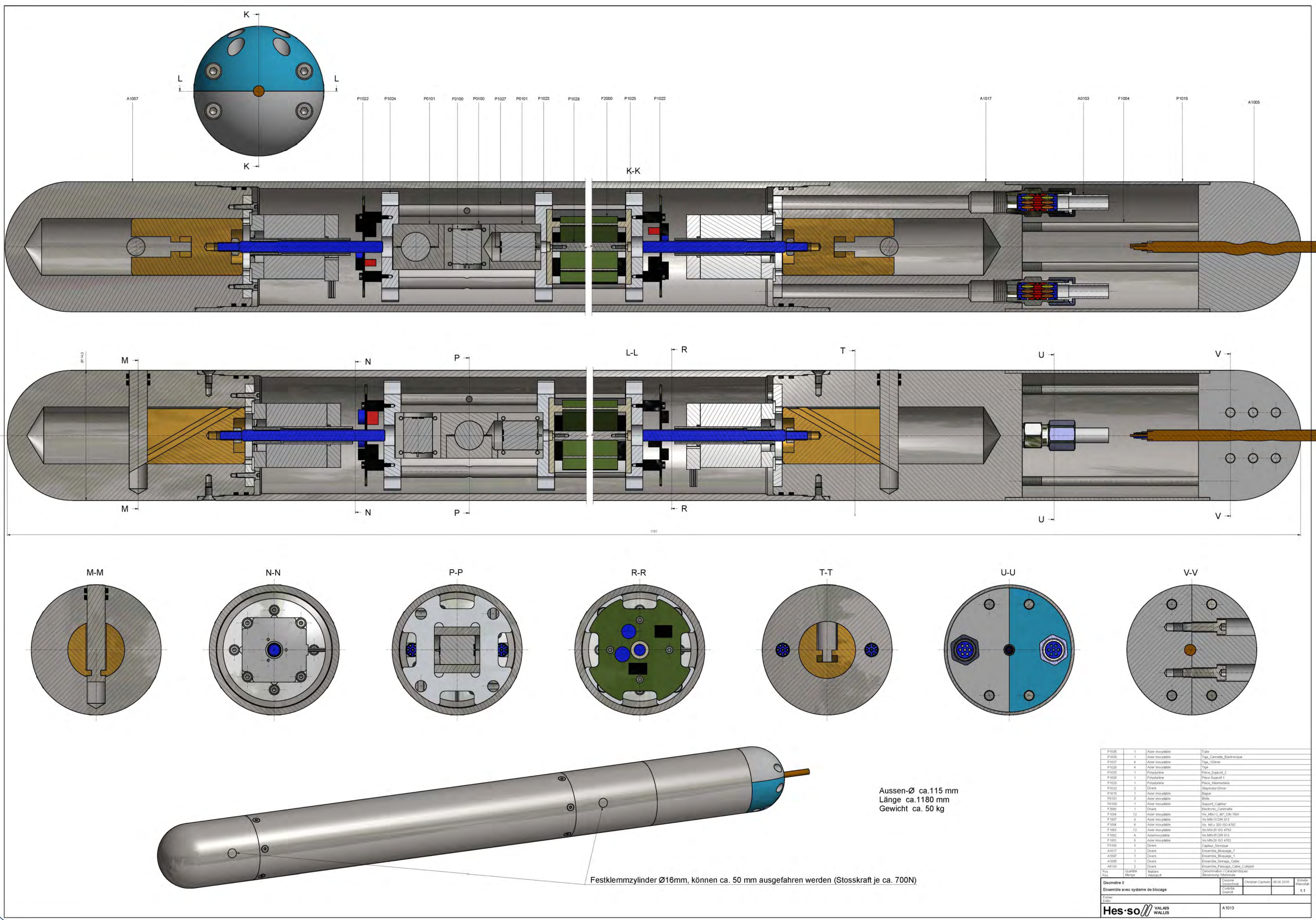
The seismometer is blocked inside the borehole using two deployable fingers that press the steel casing laterally against the borehole. The design is such that the risk of getting stuck in mud or small stones is minimized. Also, a predefined breaking point is foreseen, so that the seismometer can be withdrawn from the borehole by strongly pulling its suspension cable.



5. High pressure compatibility

The seismometer casing withstands high pressures by its circular form. Inside, ambiant pressure as on surface is maintained in the sensor and electronics compartments. Cable pass-throughs are specifically designed to accommodate the pressure difference and are water proof.





6. Installation tripod

The seismometer is deployed using a tripod hoisting assembly that can be rapidly installed and removed from the borehole.

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Extending Geophone Sensitivity for Induced Seismicity Recording

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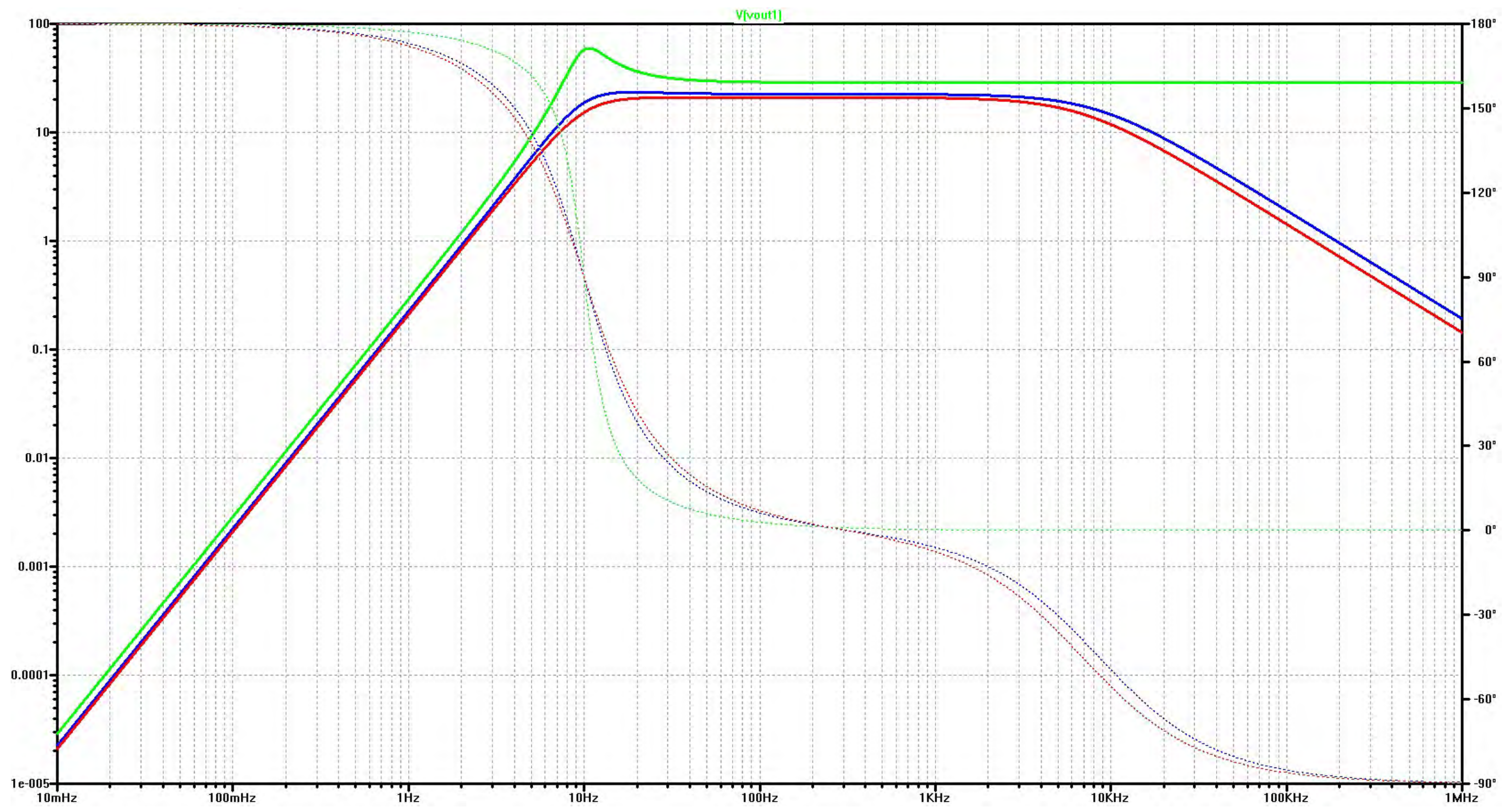
1. What is the problem ?

Geophone sensors are compact, and their package is compatible with a downhole sensing application. However:

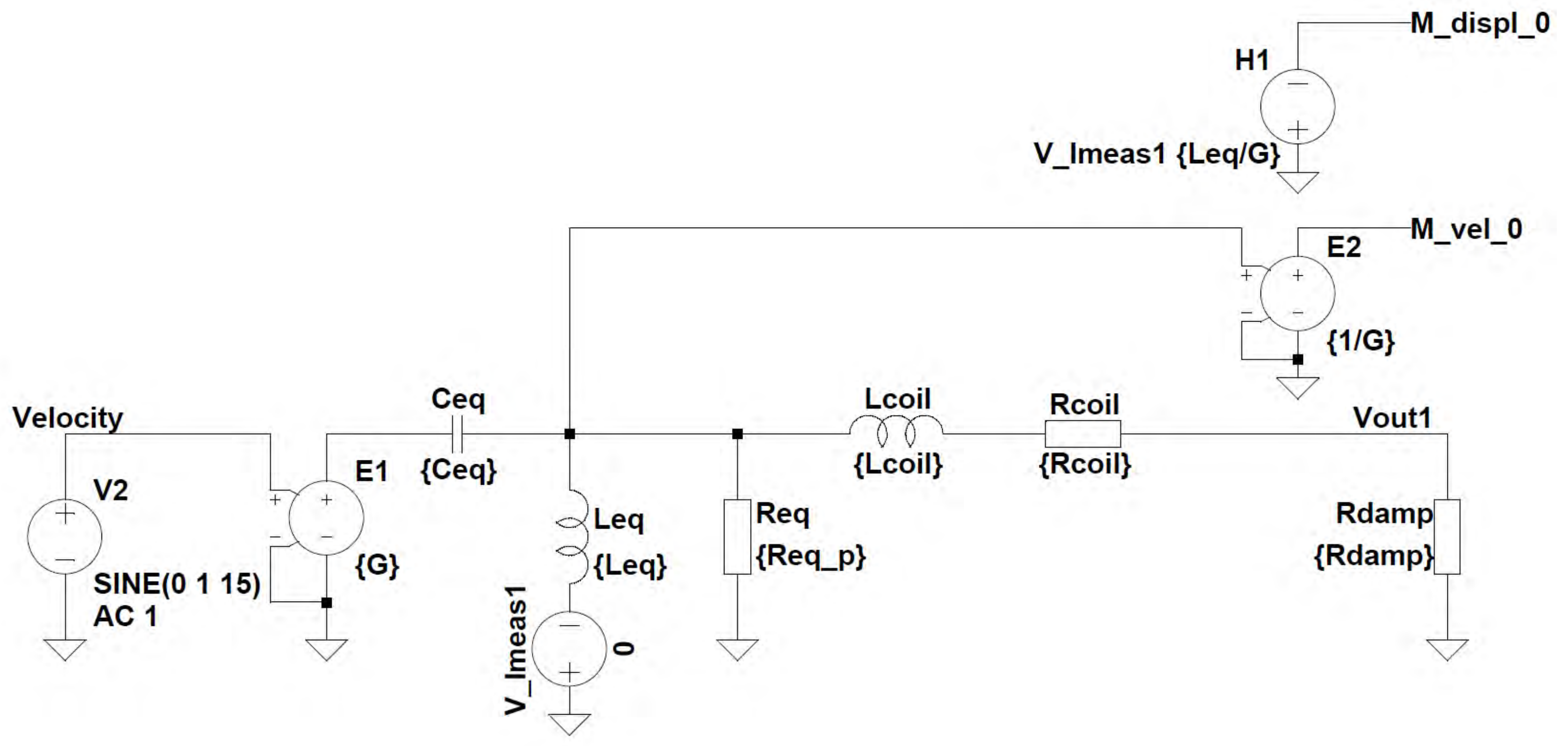
- Bandwidth is limited towards small frequencies by the suspension resonance, which may be weakly damped
- Below this resonance the frequency response falls off with 40dB/dec, thereby strongly reducing sensitivity and thus resolution .

Standard geophone frequency response curve:



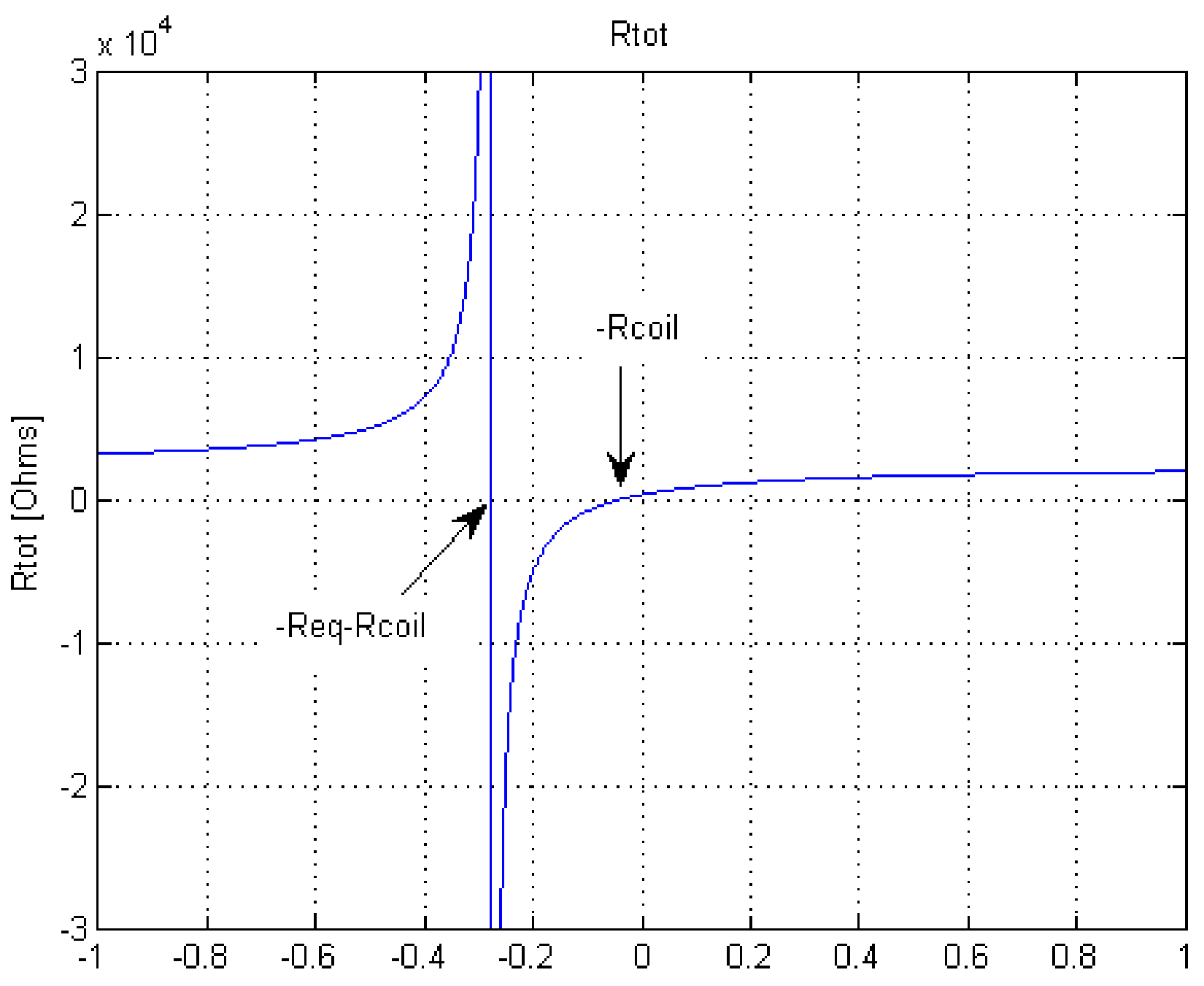
2. Geophone equivalent electric circuit model

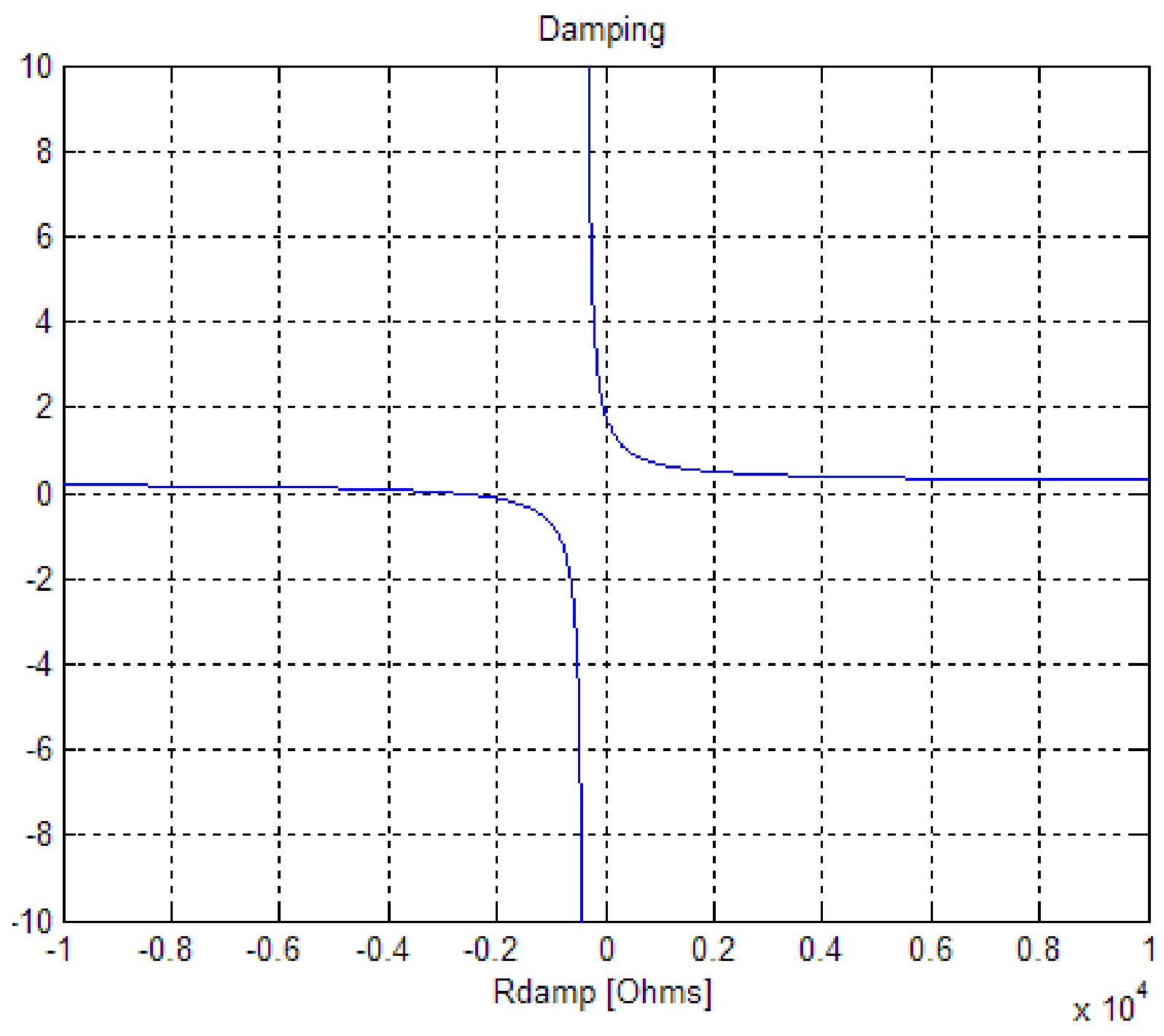
The circuit model proposed hereunder comprises as well the electric circuit part, and the mechanical suspension part. Also, the couplings between them are included as controlled sources.



3. Damping and overdamping

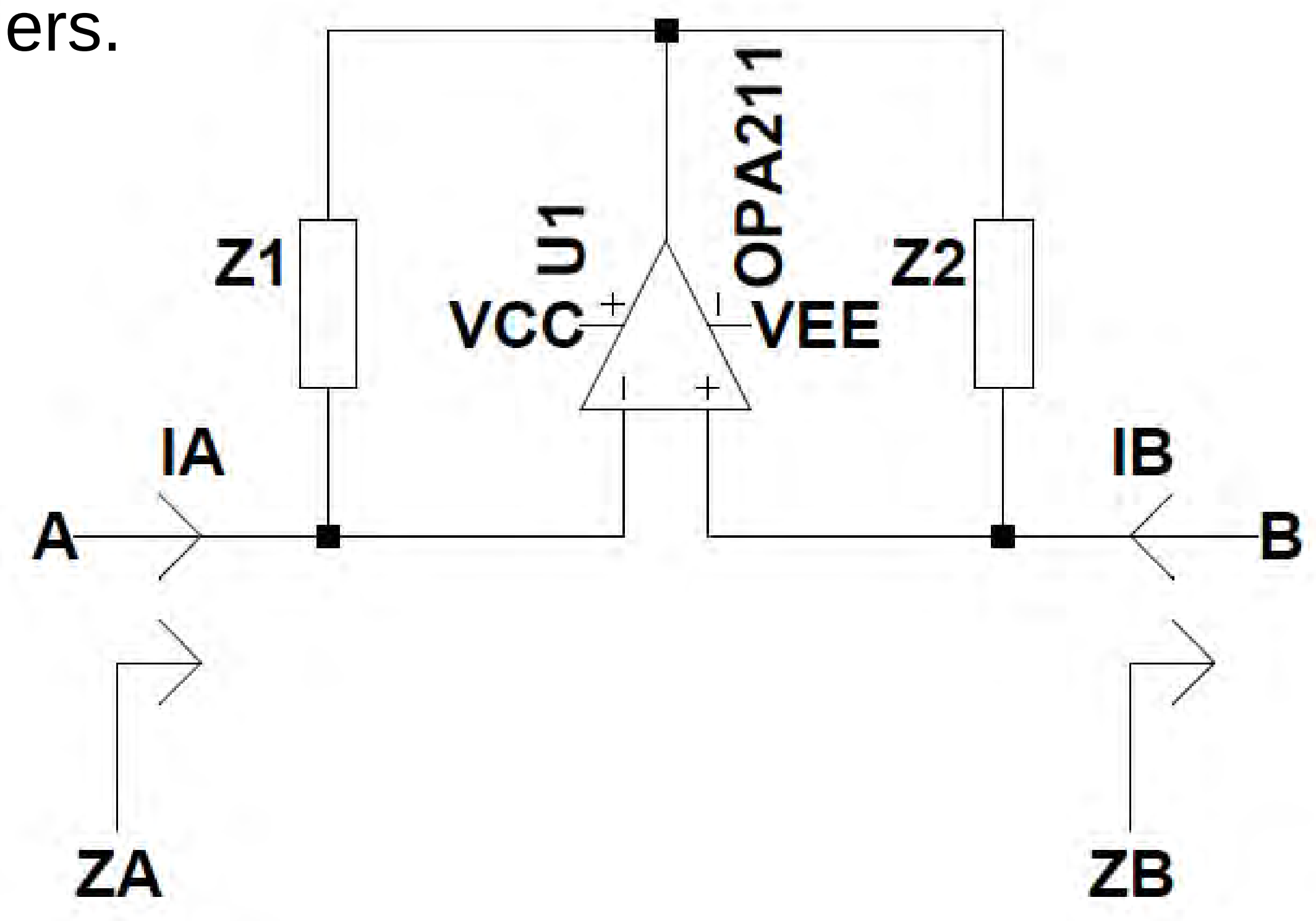
- To modify the mechanical damping characteristic of a geophone, the standard approach is to terminate it with a load resistor. The smaller the resistor value, the stronger the damping effect becomes.
- If the resistance is made zero (short circuit), the strongest passive damping is achieved. The output short circuit current represents then the measured signal.
- By making the resistance value negative, overdamping is realized. In this case, a roll-off of 20dB/dec of the geophone frequency response can be achieved, thus reducing its loss of sensitivity at low frequencies.





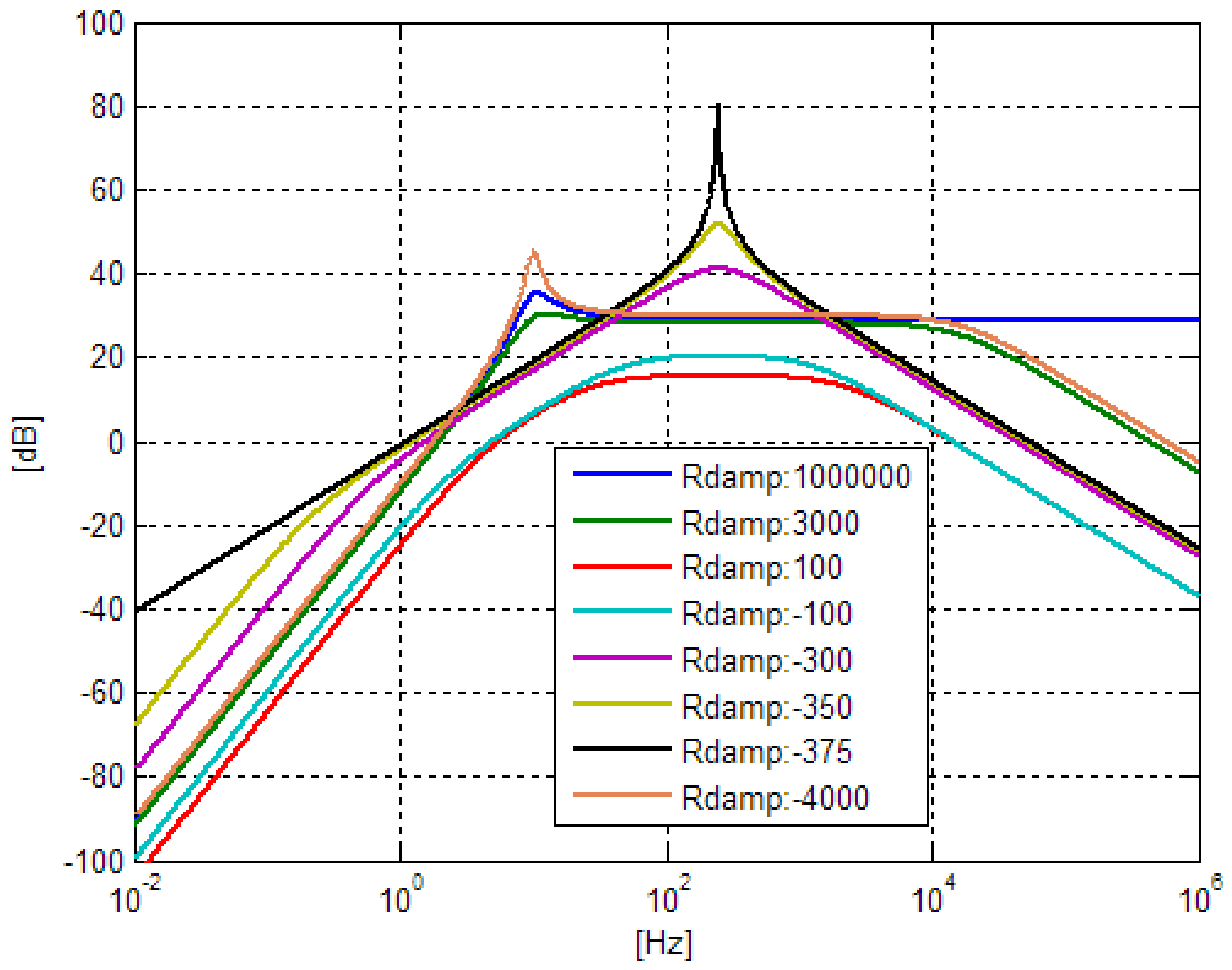
4. Negative impedance converter

- A negative impedance converter (NIC) is an electronic circuit realizing a negative resistance or impedance value. It is an active circuit.
- The NIC can be thought of as being composed by gyrators, a theoretical circuit element realized with an operational amplifiers.



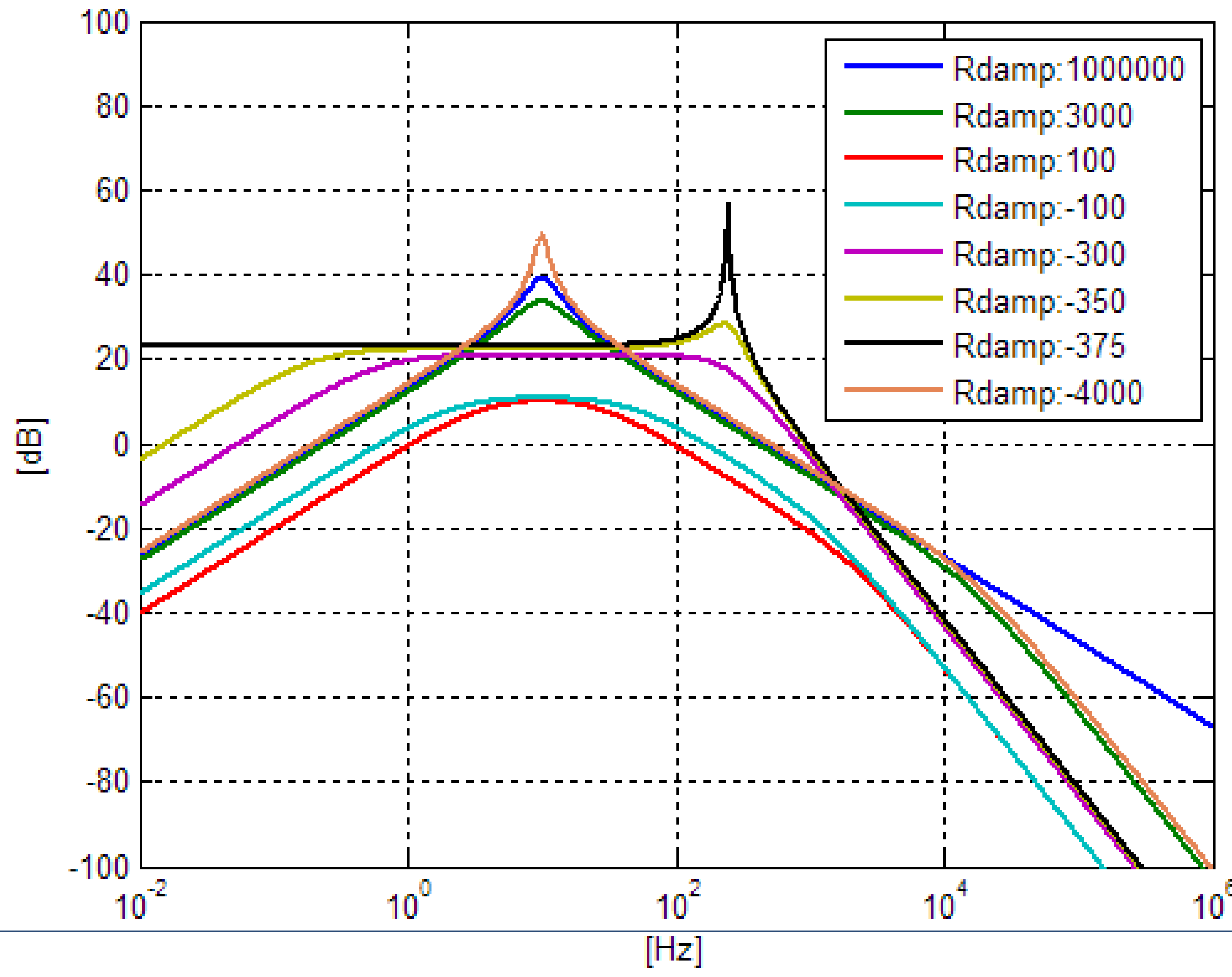
5. Modified geophone frequency response

As a function of damping resistances, positive and negative, modified geophone frequency responses are shown below.



6. Integration of the frequency response

- To further improve the low frequency sensitivity, the output of the geophone can be integrated before digitization, as shown below.
- Alternatively, a first order low-pass or second order band-pass filter can be used.
- A similar high-pass effect is obtained if the NIC is used to compensate not only the resistance, but also the inductance of the coil.



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Corrosion Challenges of Deep Geothermal Systems in Switzerland

A. Vallejo Vitaller, U. Angst, B. Elsener

Introduction

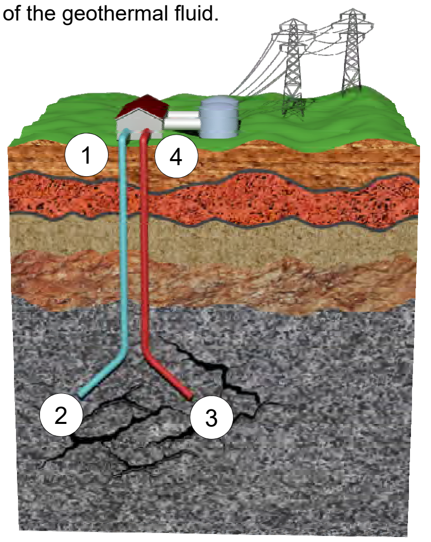
The co-generation of electric power and heat from deep geothermal resources is gaining further attention. However, corrosion and scaling are determining phenomena for the reliable and long-term operation of geothermal power plants. The direct contact of the metallic materials with corrosive fluids at high temperatures leads to premature deterioration of fundamental components, such as wells, pumps, or heat exchangers.

In Switzerland, the expertise in operational issues of geothermal power plants is limited, as no electrical energy from deep geothermal resources is produced nowadays. Similarly, literature shows that there is a lack of knowledge of chemical properties of deep geothermal fluids (at depths of 4-5 km) [1].

Therefore, the objective of this project is to contribute to a more detailed understanding of the characteristics of deep geothermal fluids that could be found in Switzerland and their potential corrosiveness in geothermal power plants. A geochemical model has been developed in Phreeqc [2] to simulate the water-rock interaction during the hydraulic stimulation process and the evolution of the chemical composition of the fluid.

Modelling approach

The following approach has been used to develop a model in Phreeqc in order to simulate the hydraulic stimulation of the reservoir and the production of the geothermal fluid.



	Temp. (°C)	Pressure (bar)	Simulation
1	15	50	Injection of fresh water
2	35	500	Hydraulic stimulation
3	200	500	Production of hot fluid
4	180	20	Exchange of heat at surface

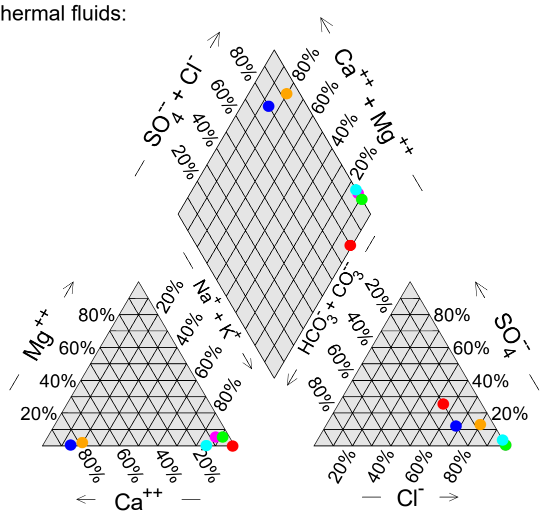
Metallic materials used in geothermal power plants

Low-alloyed steels are common metallic materials used for the casing, tubes, and heat exchanger. Typical steel grades are:

	%C	%Si	%Mn	%Cr	%Mo	%Ni	Microstructure
K55	0.37	0.19	1.32	0.05	0.01	0.05	Ferrite-pearlite
L80	0.25	0.19	1.02	0.45	0.16	0.04	"
C110	0.33	0.29	0.35	0.94	0.82	0.03	"
Q125	0.33	0.30	0.35	0.95	0.80	0.03	"

Composition of deep geothermal fluids

The injected fresh water is subjected to temperature and pressure changes and interacts with the host rocks of the reservoir. The following Piper diagram presents different chemical compositions of geothermal fluids:



● Magmatic rock – River water (pH=7.2)
● Magmatic rock – Sea water (pH=4.5)
● Sedimentary rock – River water (pH=7.1)
● Sedimentary rock – Sea water (pH=5.0)
● Metamorphic rock – River water (pH=6.5)
● Metamorphic rock – Sea water (pH=6.0)

Potential corrosion challenges

The main environmental factors affecting corrosion phenomena are chemical species, such as Cl^-, H^+, CO_2, H_2S, or O_2. For example:

- Cl^- is known for promoting localized corrosion. In the considered scenarios, its concentration can reach up to 0.45 mol/kg. Higher temperature and [Cl^-] contents increase the susceptibility to pitting corrosion.
- At high concentrations of H^+ (i.e. low pH), the corrosion rate of the material increases (especially, if pH<6 and [Cl-]>2%). When sea water is injected for the hydraulic stimulation, the obtained pH is usually lower than 6.

On the other hand, the steel microstructure might play a significant role on corrosion issues. A ferrite-pearlite microstructure shows worse performance against localized corrosion, in comparison to a ferrite or tempered martensite microstructure. This is because the non-uniform distribution of cementite (Fe_3C) leads to a lower adhesion of the corrosion products and a higher risk of spallation of the oxide layer.

Further work

- To perform simulations that consider shallow fluids from Switzerland and obtain a more approximated composition of deep geothermal fluids.
- To conduct electrochemical experiments in an autoclave (high T and P) and analyse the behaviour of different available commercial steels.
- Develop new metallic materials that can withstand the special geothermal environments (especially Cl^-, O_2, ..).

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Detecting Water through Electric Impedance Measurements

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In cooperation with the CTI
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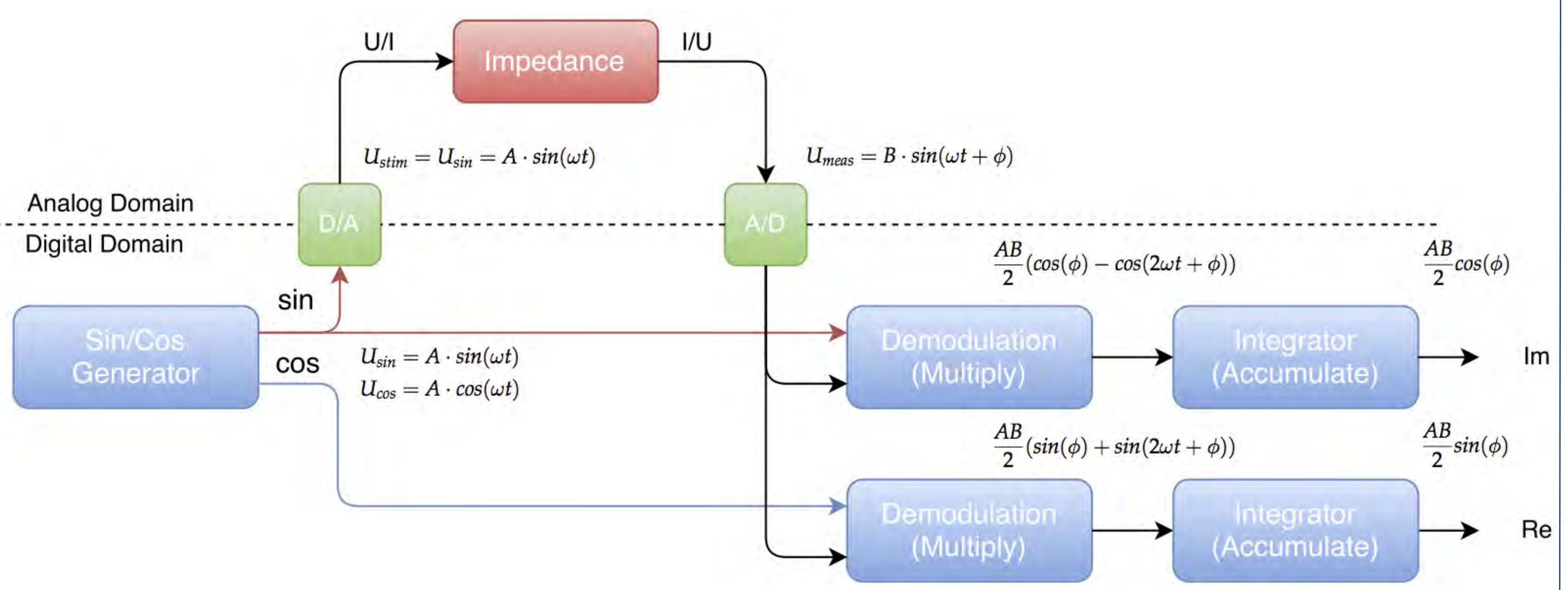
1. What is the problem ?

Sensors for deep water reservoir monitoring have to face several challenges:

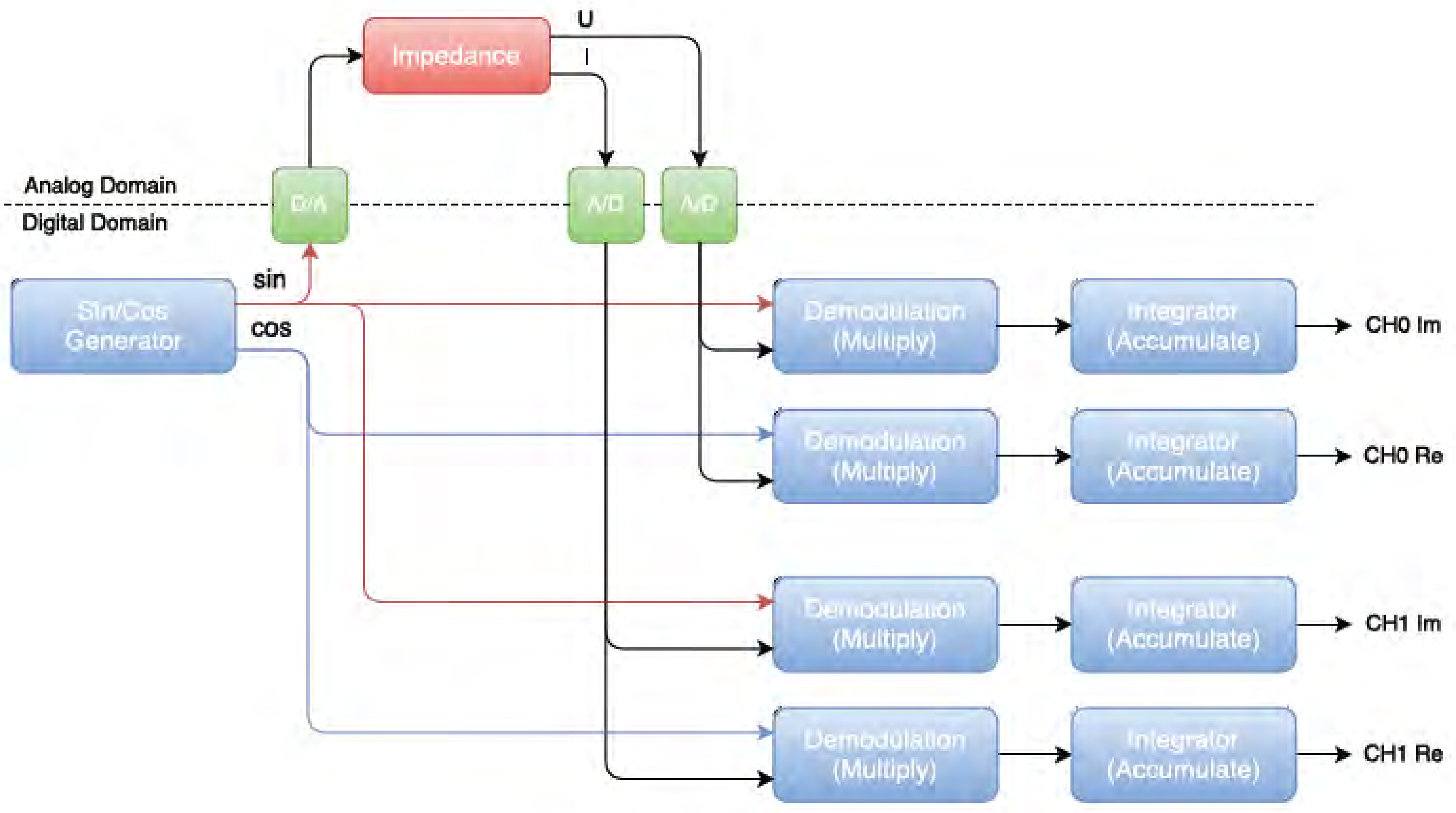
- important depth of aquifer location.
- need to detect small signals with high signal-to-noise-ratio.
- unknown absolute values of conductance of water.

2. Digital lock-in technique for impedance measurement

To reach high SNR, impedance measurement is based on a digital lock-in technique.

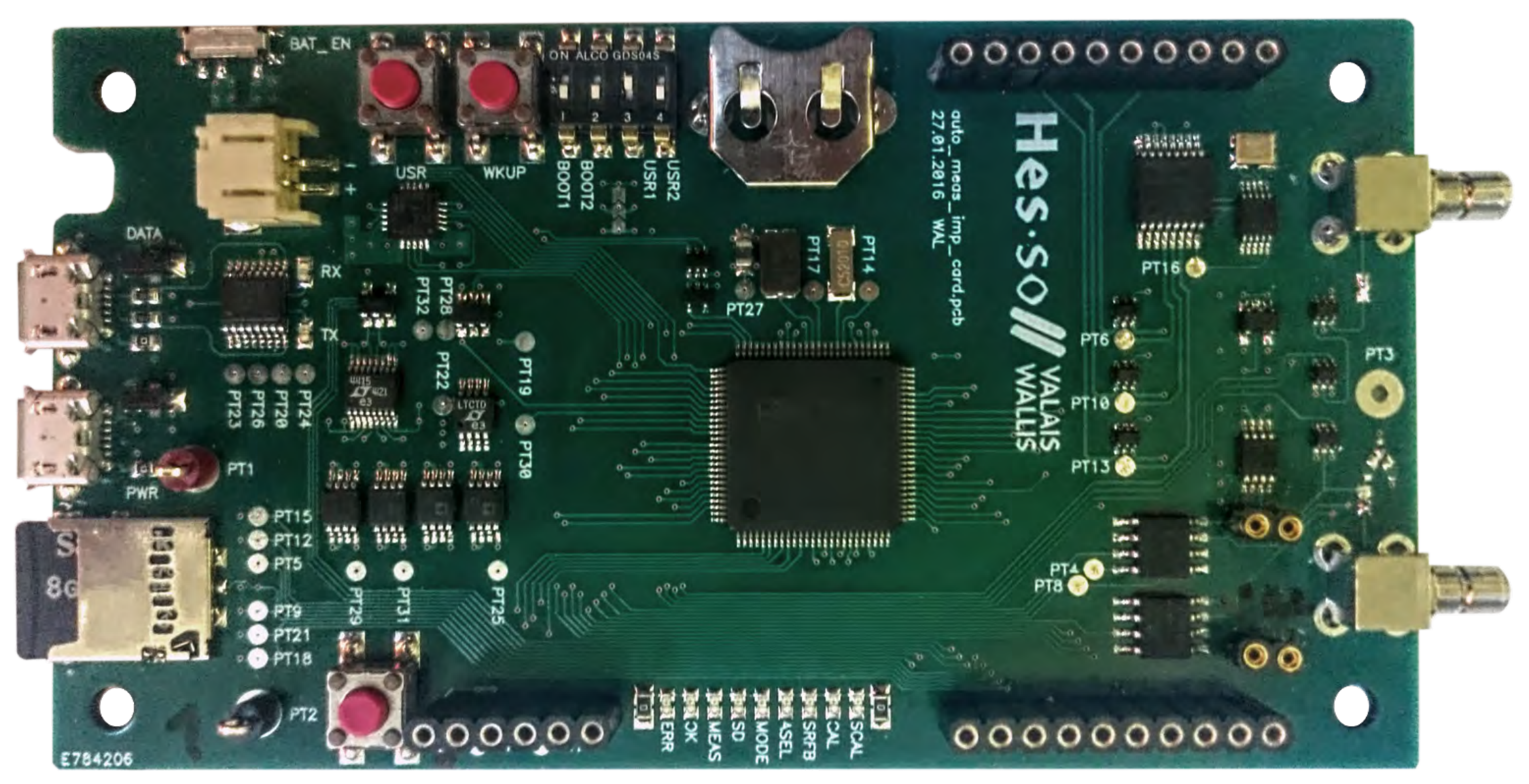


By sweeping the excitation frequency, impedance frequency spectra can be acquired. Current and voltage outputs can be digitized:



3. Low-to-medium bandwidth implementation

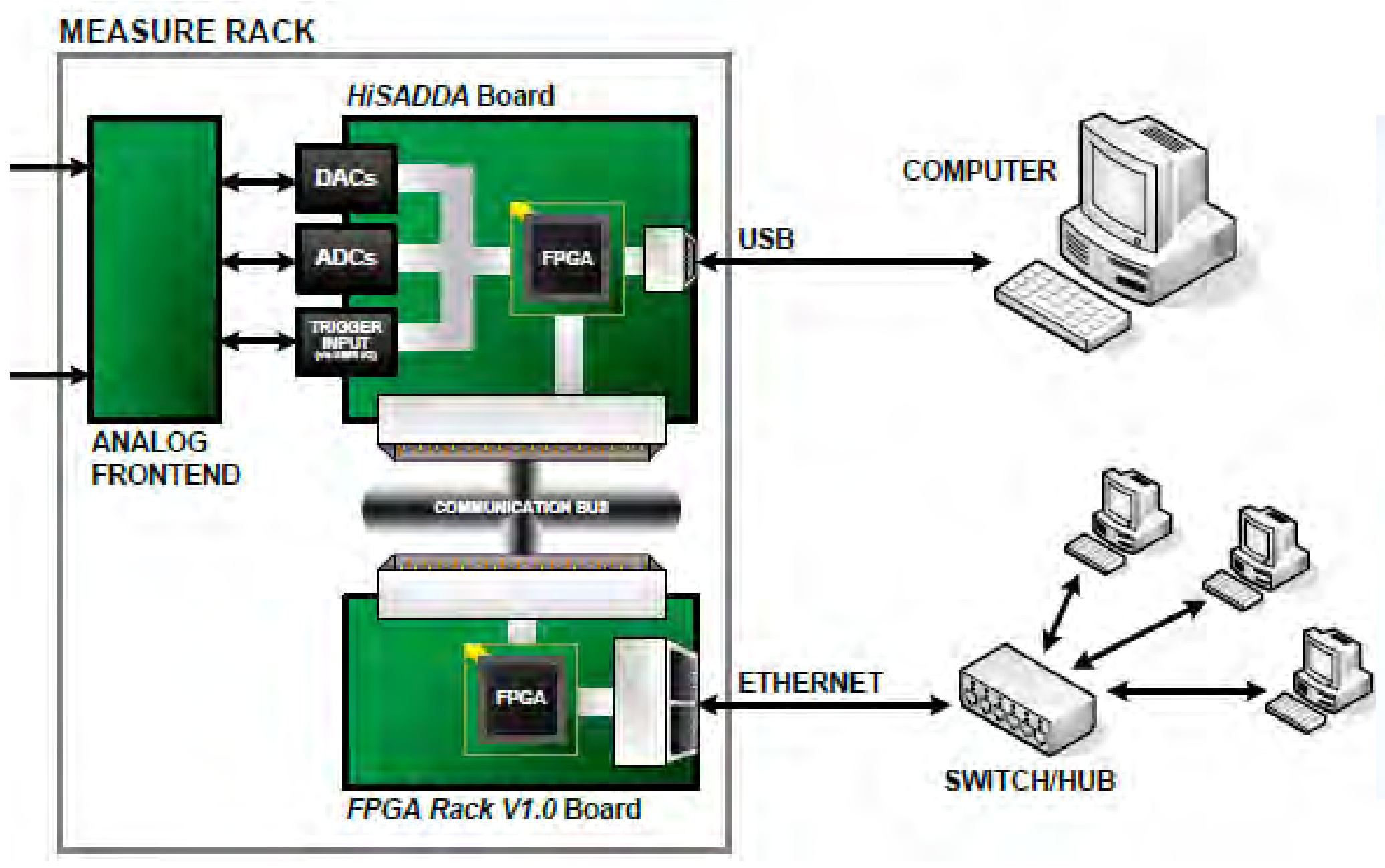
- Based on commercial single-chip implementation of lock-in technique, AD5933
- 100Hz to 100kHz excitation and measurement bandwidth

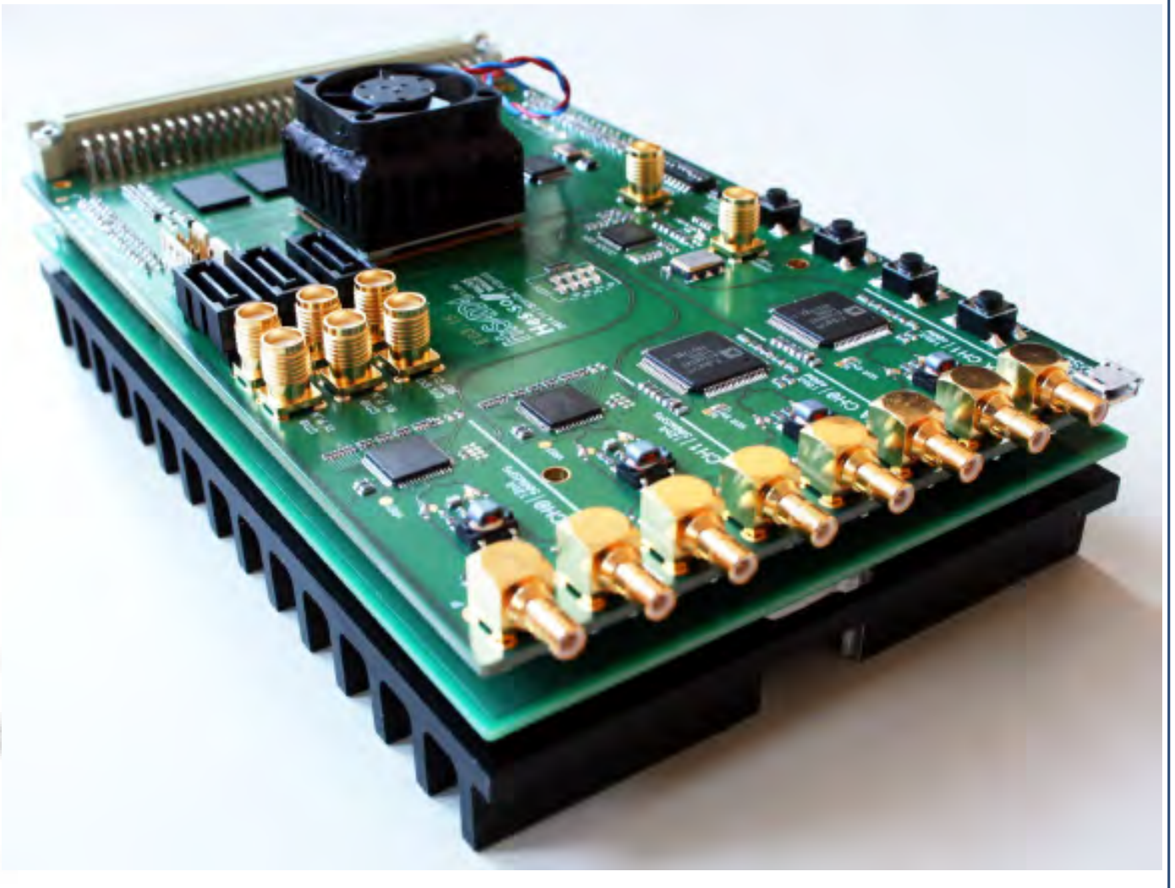


4. Large bandwidth implementation

Large bandwidth lock-in detection can serve as well for impedance spectroscopy via contactt electrodes, as for ground penetrating radar signal processing..

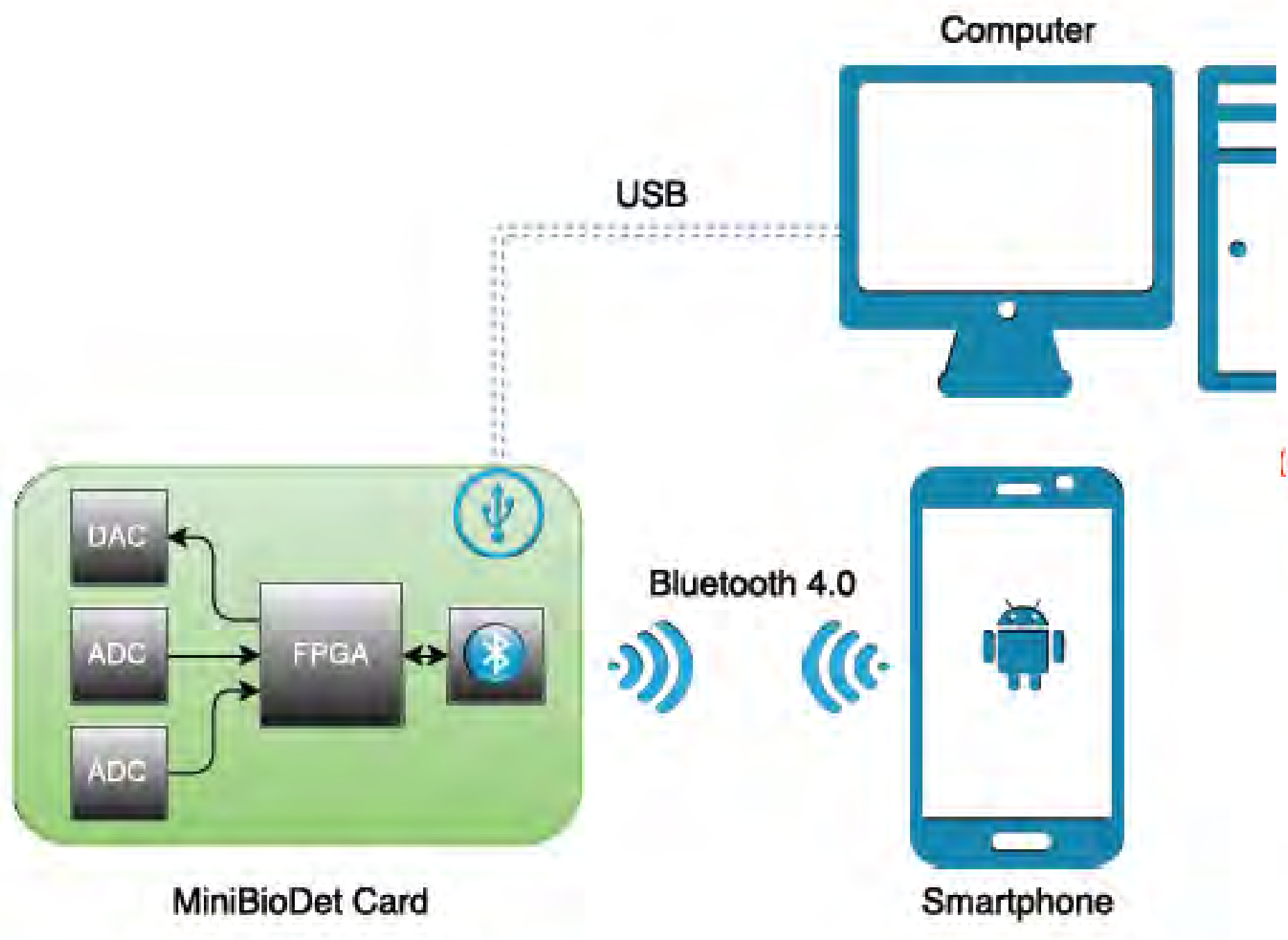
- mHz to 200MHz excitation and measurement bandwidth
- 12bit A/D and D/A conversion
- Direct digital sampling of excitation signal generation and acquisition
- Possibility to digitize high speed polarization processes as e.g. accompanying rock fracture

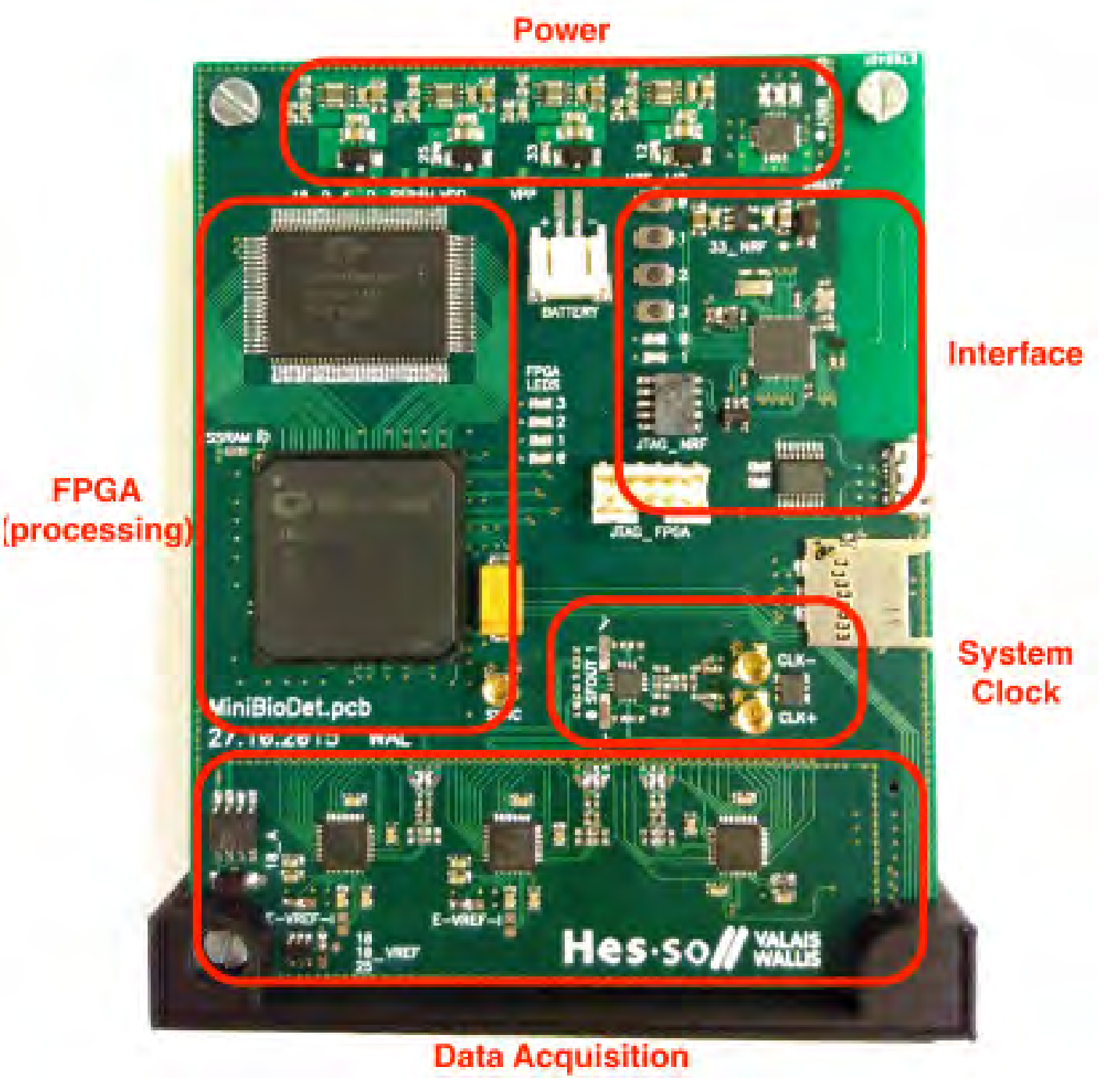




5. Battery powered lock-in amplifier

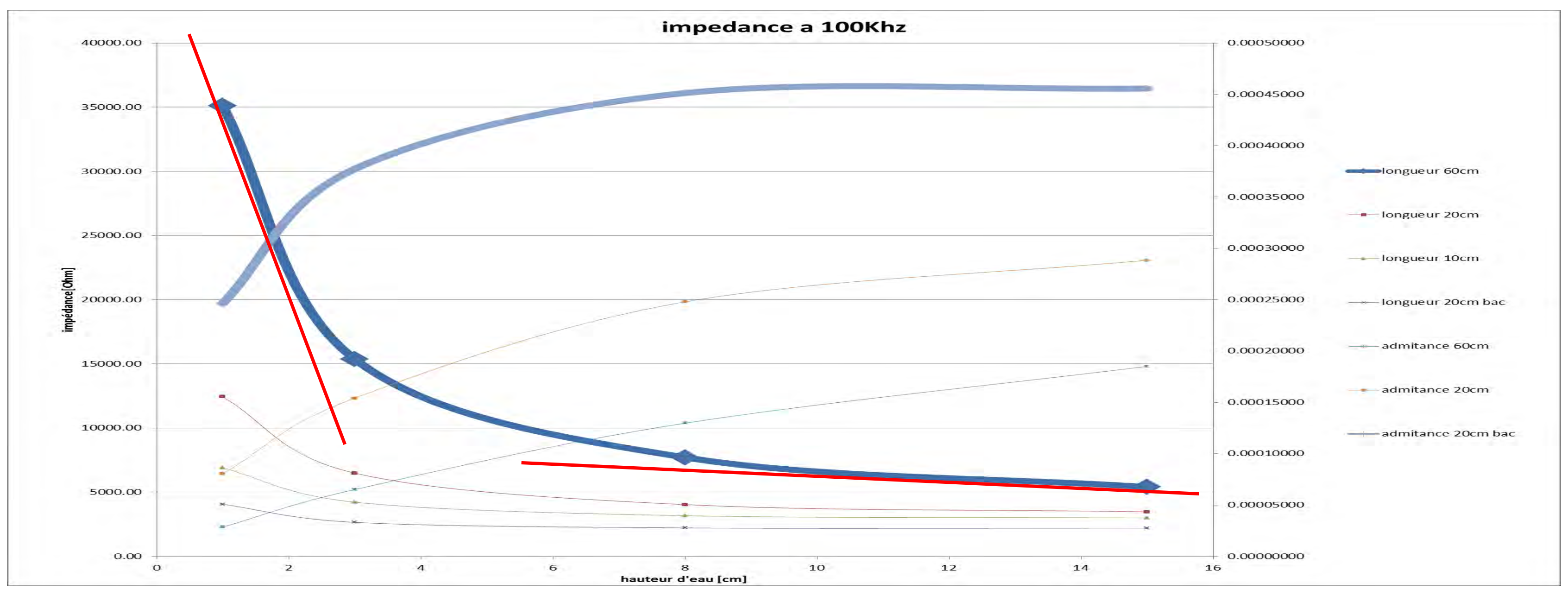
- For continuous monitoring applications at locations where public grid is not available, the impedance measurement equipment must be solar powered with battery buffering.
- 14bit D/A, 16bit A/D conversion, mHz to 20MHz excitation and measurement bandwidth
- Bluetooth communication with a smart phone as local user interface.





6. Small scale tests in water

- Digital excitation and synchronous demodulation.
- Frequency seep range 1mHz…1MHz.
- Custom H/W and S/W development by HES-SO Valais.
- Different linearization possibilities depending on electrode spacing vs. depth and on the use of impedance or admittance



7. Small scale tests in snow

- Validation of measurement principle through a snow layer measurement
- Electrodes disposed on ground, facing upward
- Distance between electrodes not constant, allowing differential and common mode measurements
- Objective: estimation of snow layer thickness and characteristics