Task 3.2

Task Title

Hydropower technologies

Research Partners

University of Applied Sciences Western Switzerland (HES-SO), École polytechnique fédérale de Lausanne (EPFL), Institute for Computational Science (ICS) at UZH

Current Projects (presented on the following pages)

Inline micro-hydropower production in water supply networks
I. Samora, P. Manso, M.J. Franca, A.J. Schleiss, H.M. Ramos

Understanding the unstable off-design operation of Francis turbines for large scale NRE integration
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Energy Recovery Station controller tuning based on water utility network simulation
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Experimental and numerical simulation investigations of the flow in a micro-turbine with counter-rotating runners
E. Vagnoni, S. Richard, L. Andolfatto, C. Münch, F. Avellan

Stability Analysis and Optimal Control of a Francis Turbine Vortex Rope
S. Pasche, F. Gallaire, F. Avellan

RANS computations for identification of 1-D cavitation model parameters Application to full load cavitation vortex rope
J. Decaix, S. Alligné, A. Müller, C. Nicolet, F. Avellan, C. Münch

Dynamic method for model testing hydraulic performance measurements
V. Hasmatuchi, A. Bosioc, S. Luisier, C. Münch-Alligné

Open-air laboratory for a new isokinetic turbine prototype
V. Hasmatuchi, A. Gaspoz, L. Rapillard, N. Brunner, S. Richard, S. Chevailler, C. Münch-Alligné

Experimental investigation of a pump-as-turbine (PAT) to recover the energy lost in drinking water networks
V. Hasmatuchi, S. Luisier, C. Cachelin, C. Münch-Alligné

DuoTurbo Prototype V0
D. Biner, V. Hasmatuchi, L. Andolfatto, F. Avellan, C. Münch-Alligné

Limnimeter for Mountain Streams
G. Emery, E. Bardou, C. Cachelin, J. Moerschell, E. Travaglini

PiezoEel: An Energy Harvester for Mountain Stream Monitoring
G. Emery, S. Richard, H. Keppner, J. Moerschell, C. Münch-Alligné, L. Rapillard

GPU-SPHEROS – Assessment of Constitutive Models for Silt Erosion Simulations

S. Leguizamón, E. Jahanbakhsh, A. Maertens, S. Alimirzazadeh, F. Avellan

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SismoRiv : An innovative system for bedload monitoring based on the measurement of seismic noise through river banks

E. Travaglini, P. Ornstein, L. Mayencourt, J. Moerschel, T. Schneider

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Prediction of Hydropower Plant stability with Francis turbines operating at partial load

J. Gomes, C. Landry, S. Alligné, C. Nicolet, F. Avellan

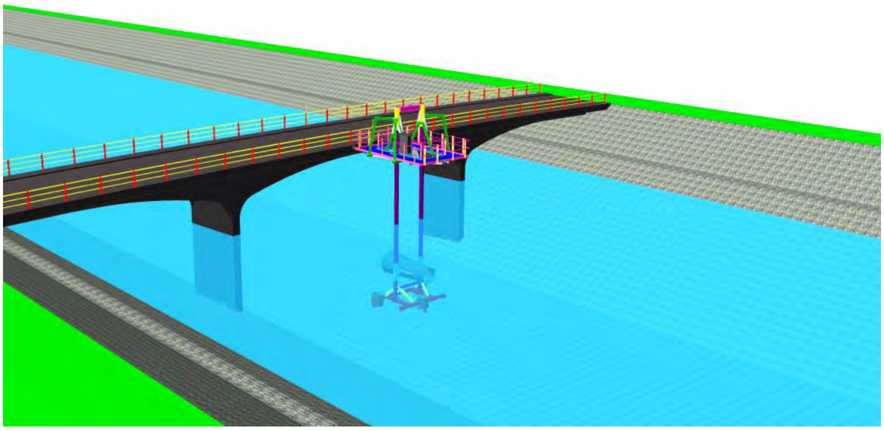
Task Objectives

This task focuses on innovative technologies for hydropower

- Expanding the operating range of hydraulic turbines and pump-turbines
- Modeling silt erosion in turbine components for large hydro
- New turbine design for harvesting energy from existing hydraulic Infrastructure fresh water network
- Uncertainty Quantification for fatigue in turbine blades

Highlights 2016

- GPU-SPHEROS
- Iso-kinetic turbine for artificial waterways: start of the SFOE/The Ark P+D project



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Inline micro-hydropower production in water supply networks

Irene Samora, P. Manso, M.J. Franca, A.J. Schleiss and H.M. Ramos*
**corresponding author: irene.almeidasamora@epfl.ch*

LABORATOIRE DE CONSTRUCTIONS HYDRAULIQUES
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Introduction

In the context of the Energy Strategy 2050, micro-hydropower can be a way of improving the energetic efficiency of existent infrastructure.

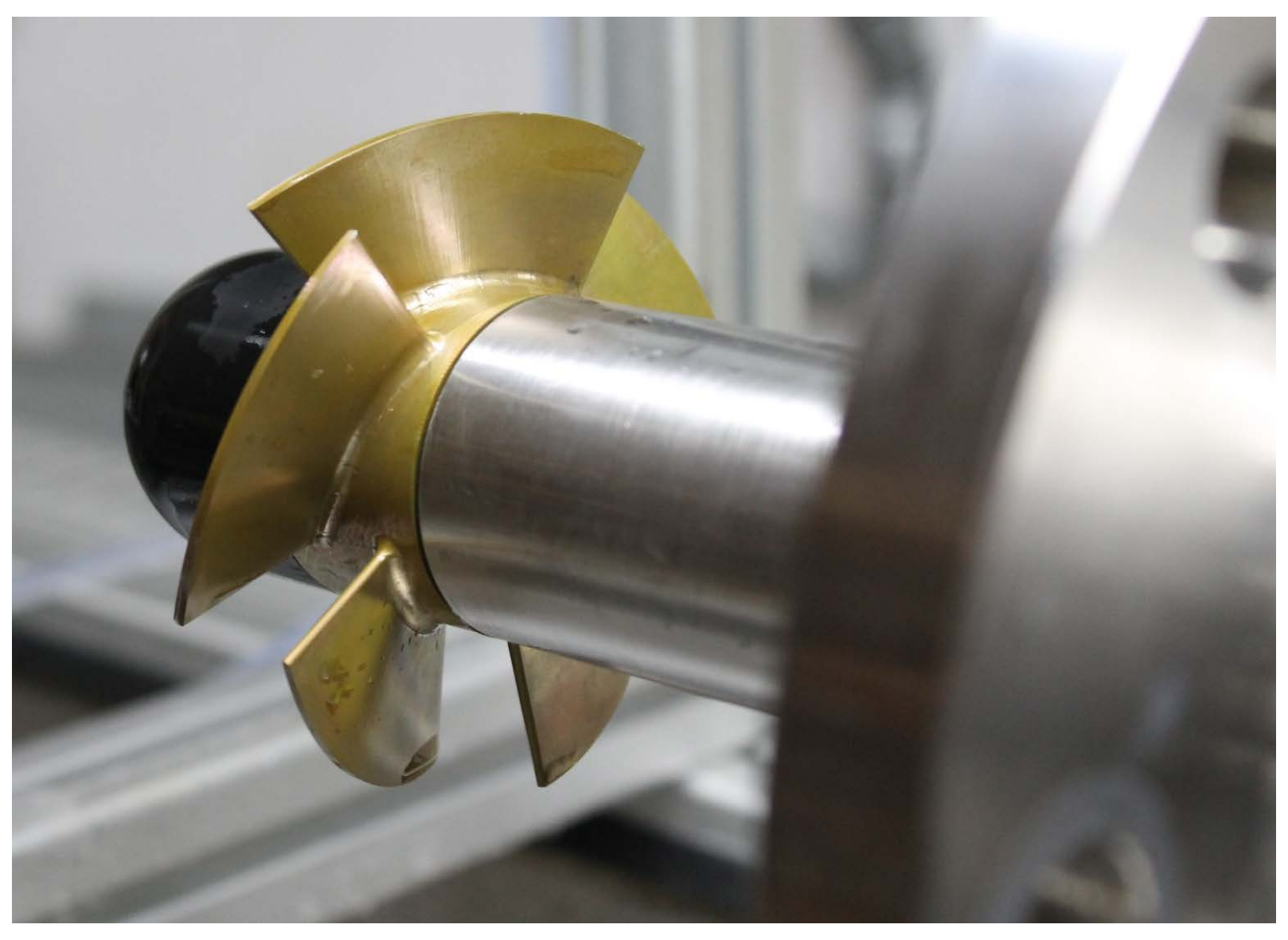
Within the identified man-made systems, the water supply systems present some advantages:
- These are pressurized systems, where the turbine operation can be done within the existing pipes with some modifications;
- The flow discharges are guaranteed during most of the hours of the day;
- The proximity of the installations to local consumers allows for a decentralized production, minimizing the transmission losses.

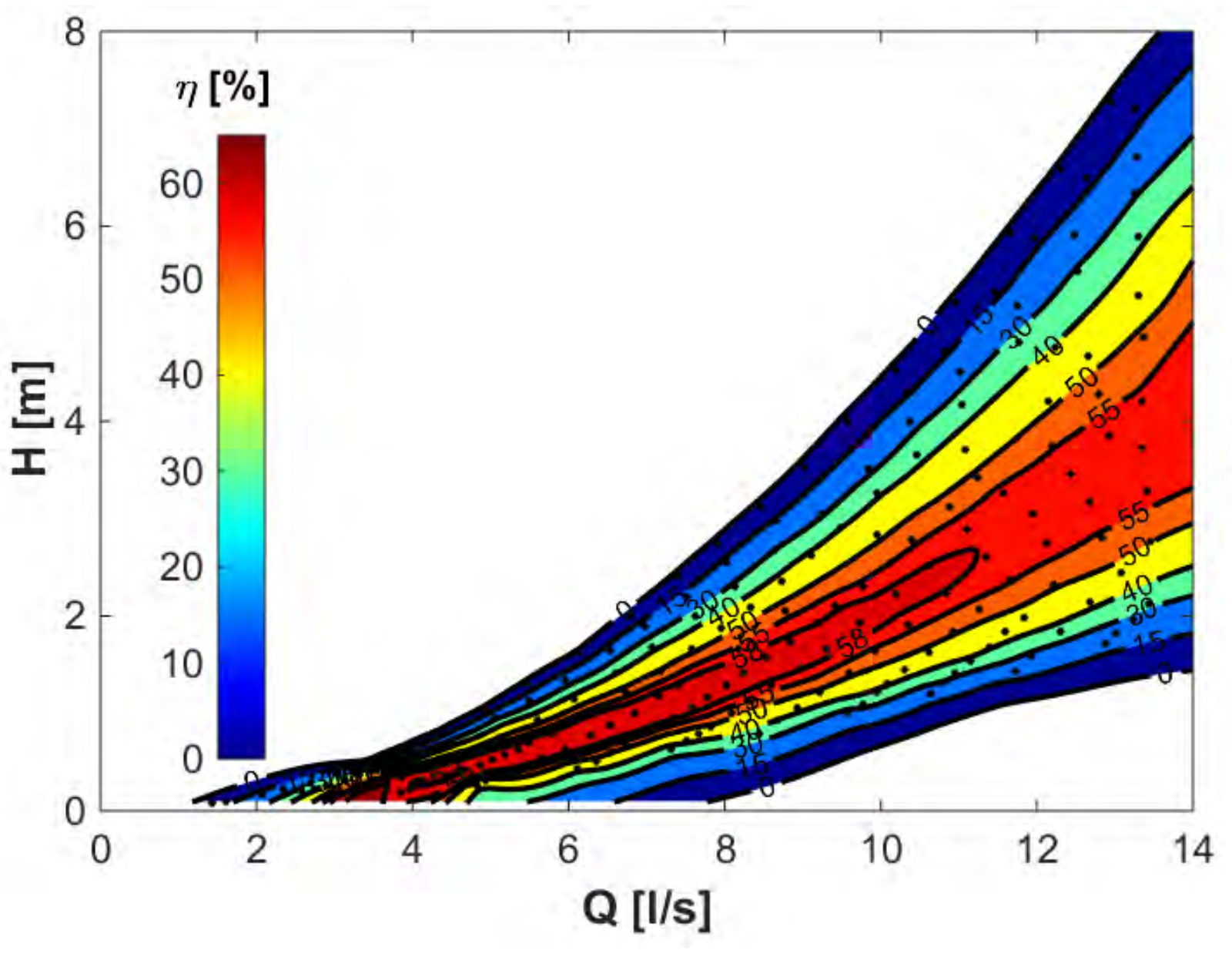
In this project, the following objectives were aimed at:
- Developing a turbine for inline installation;
- Conceiving a compact all-included micro-hydropower plant;
- Establishing a methodology to identify the ideal locations for energy recovery within water supply networks (WSN).
- Quantifying the excess energy available in WSN and the share that can be recovered with the micro-hydropower concept

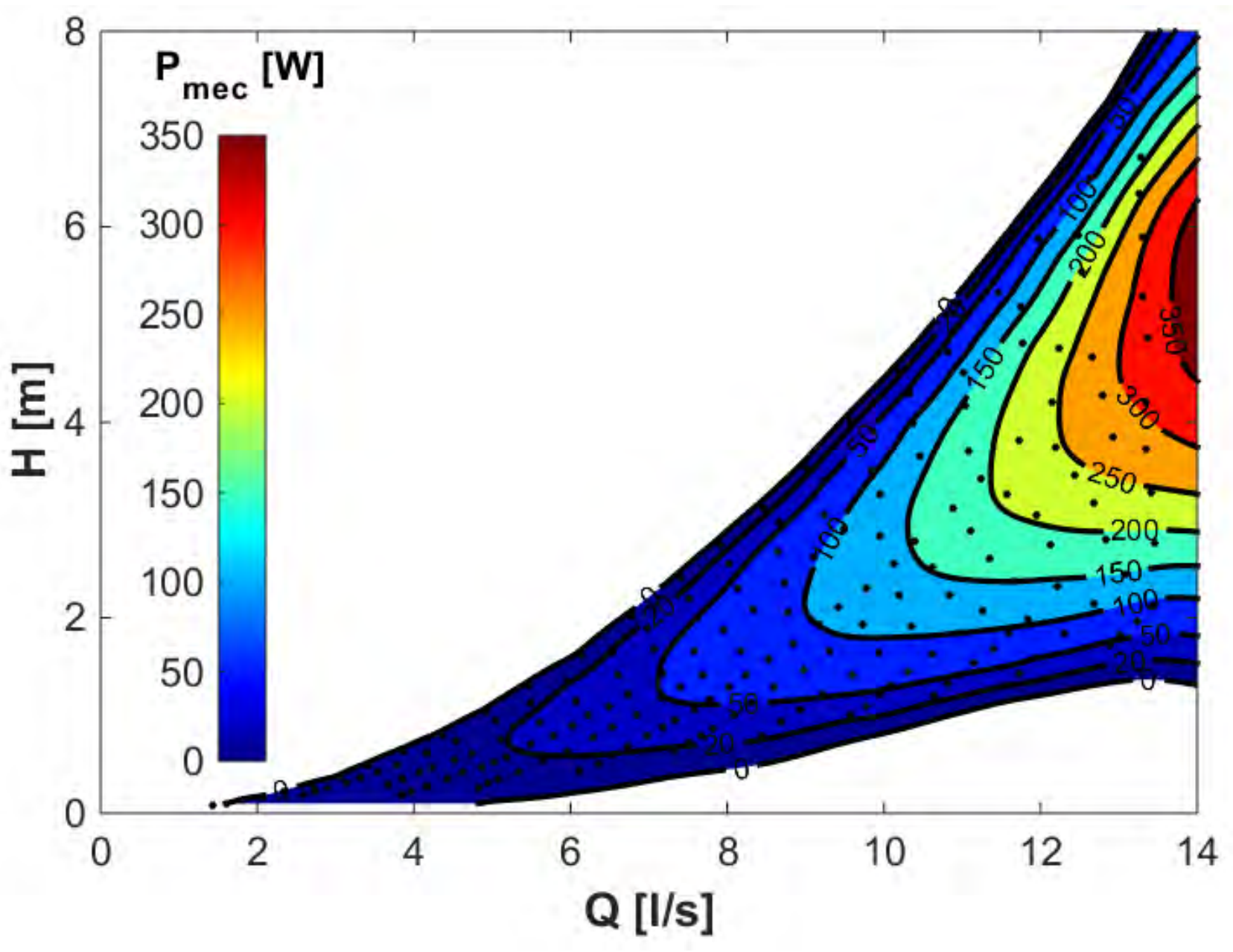
The five blades tubular propeller turbine (5BTP)

Initially developed in IST (Lisbon), this turbine was recently tested in HES SO Valais.

The prototype:
- diameter of 85 mm
- maximum output power of 300 W with an efficiency of 51%
- Best efficiency point at 64% with 1500 rpm.

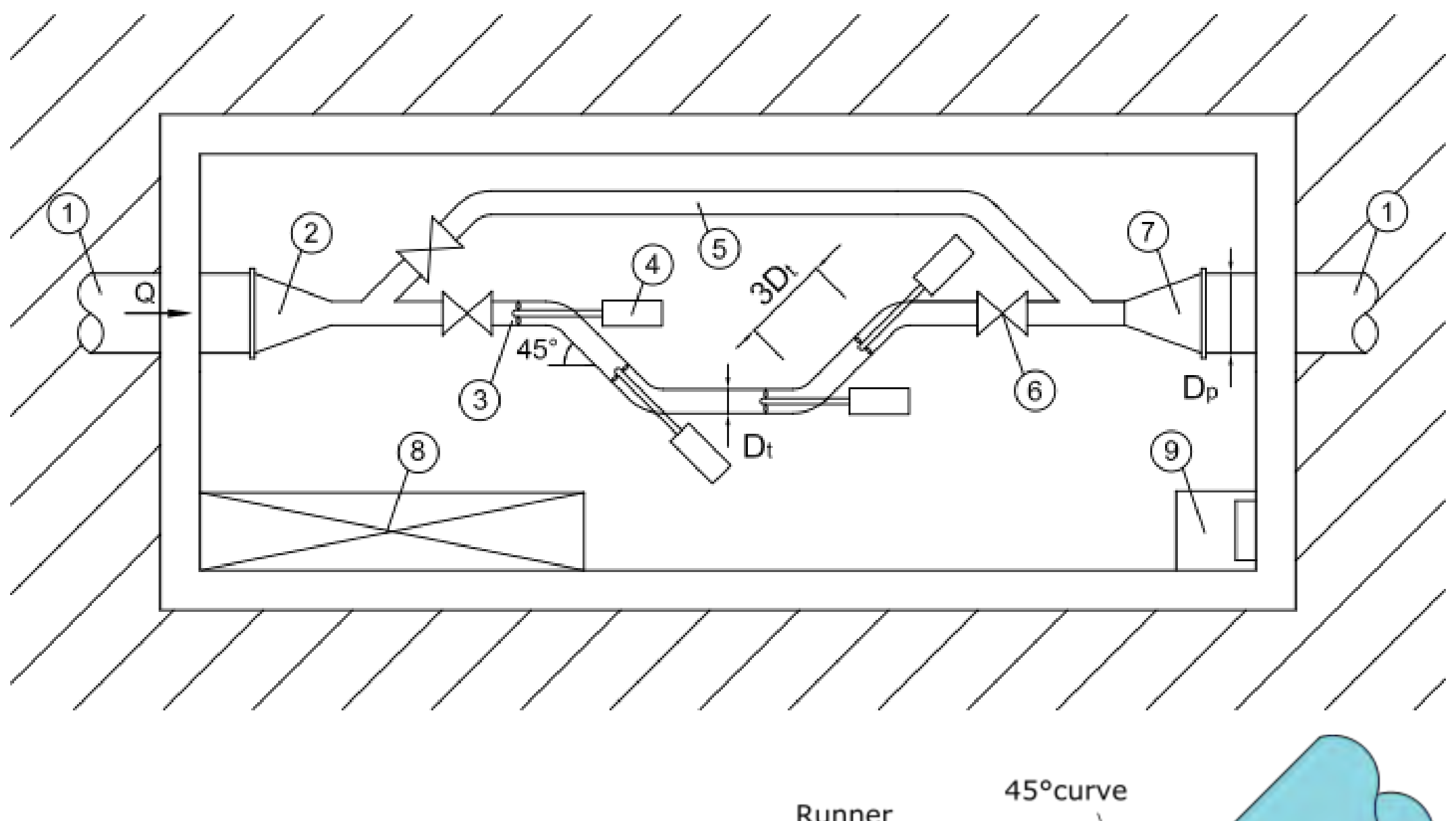




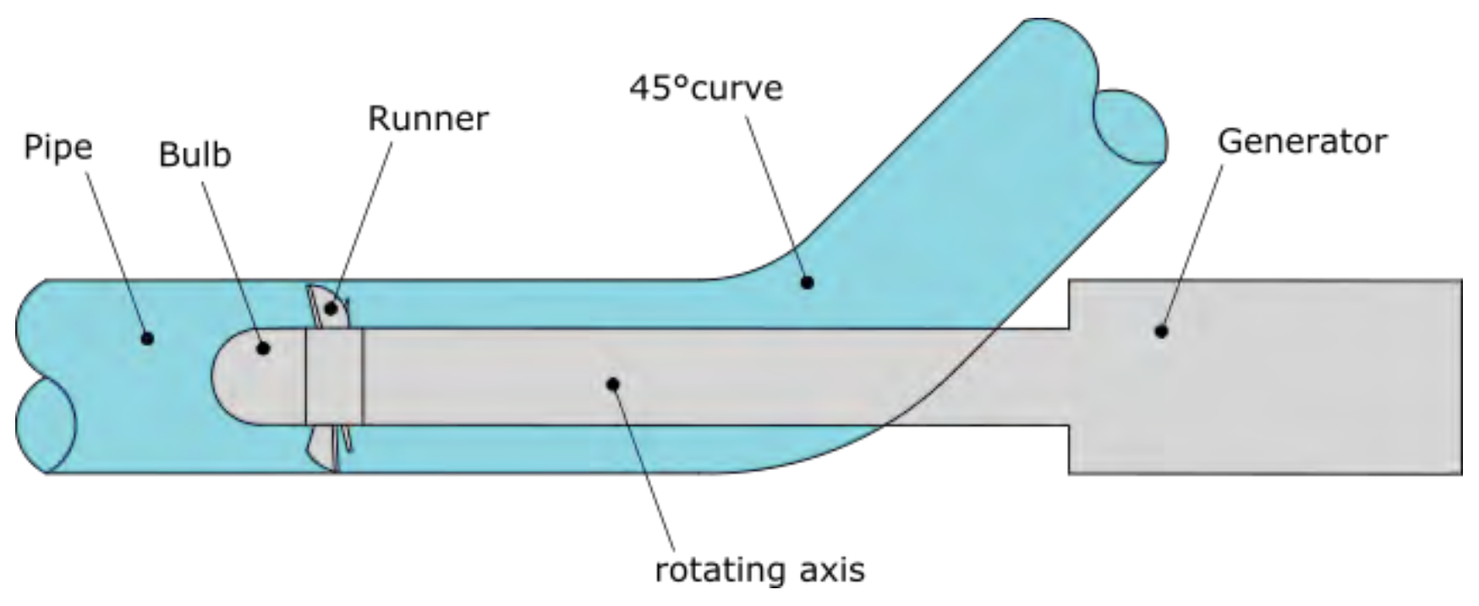


Micro-hydropower plant

Based on the 5BTP a conceptual micro-hydropower plant is proposed, composed of a buried concrete chamber built around an existing pipe. Up to four turbines can be installed in the same chamber. The dimensions depend on the turbine runner and pipe.



1 – Existing pipe
2 – Contraction taper
3 – Turbine runner
4 – Generator
5 – By-pass
6 – Isolation valve
7 – Enlargement pipe
8 – Electric cubicle
9 – Access manhole
10 – Concrete chamber wall



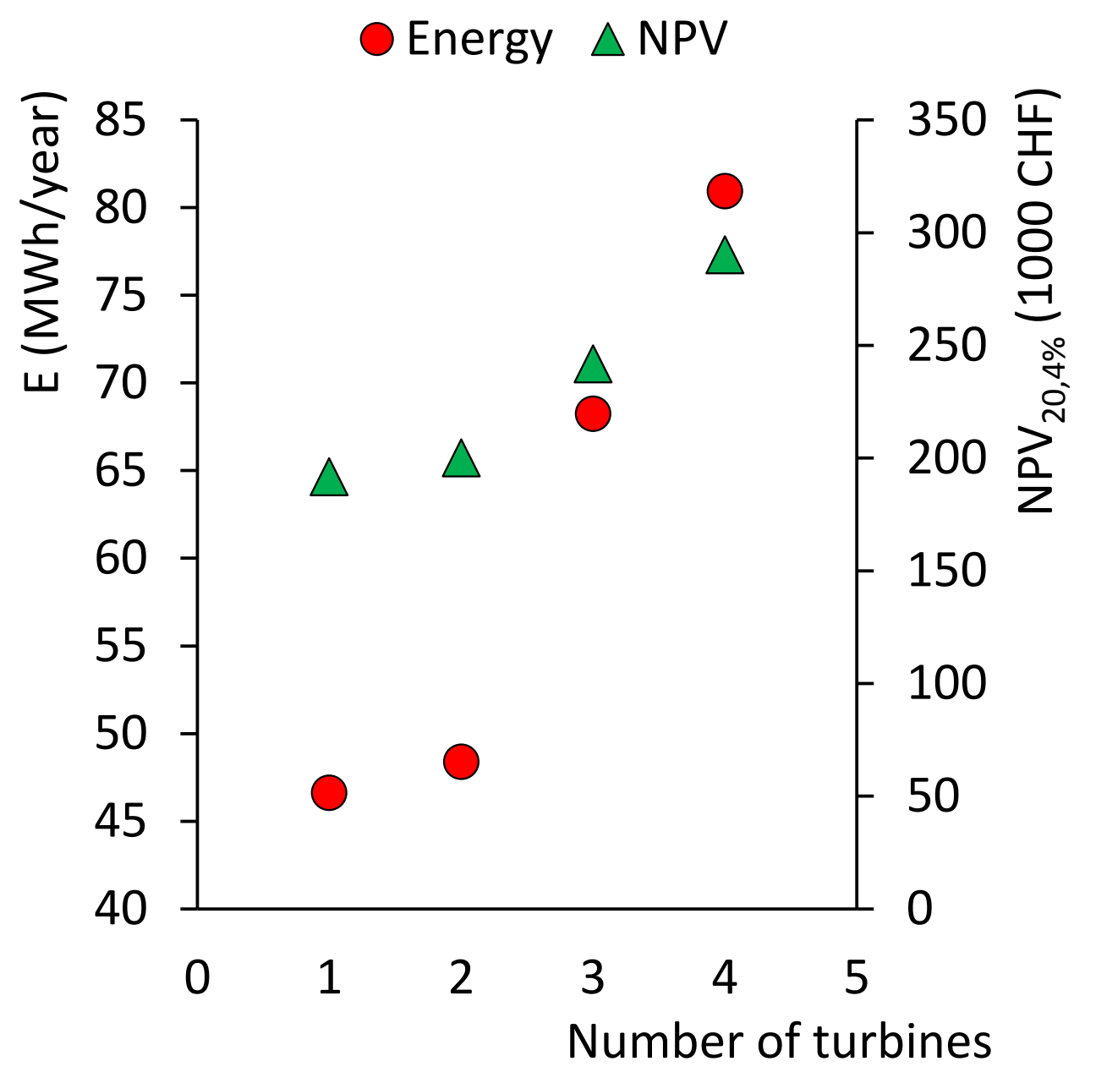
Identification of ideal locations

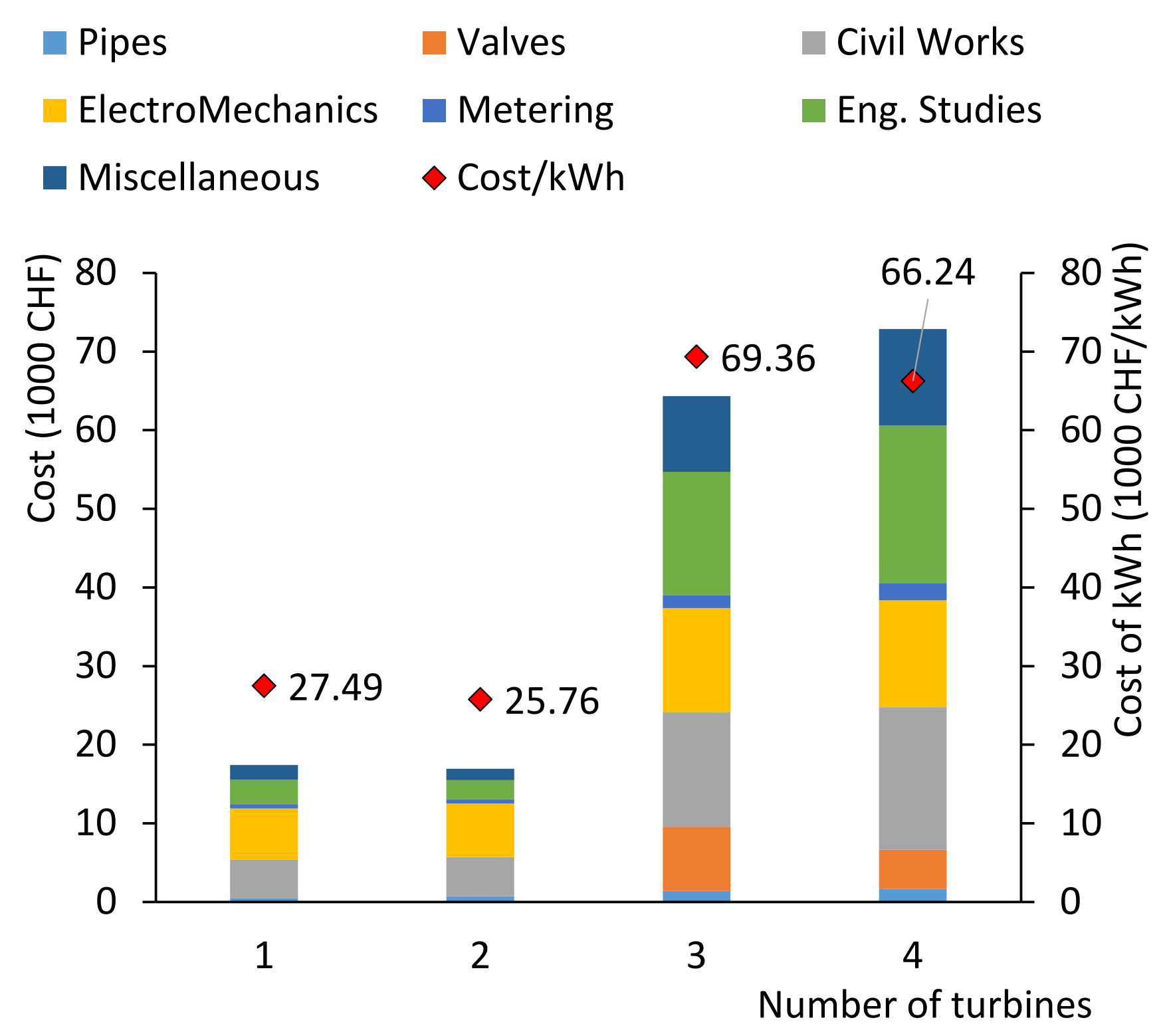
The optimal location of the turbines is not ~~be~~ a straightforward problem in most cases: highly variable flow discharges and pressures; network complexity; minimum service pressure. A search algorithm was developed to optimize the economic value of the installation of micro-hydropower plants in WSNs based on:

- simulated annealing technique
- maximization of net present value after 20 years of operation
- characteristic and efficiency curves of a turbine;
- turbine upscaling based on similarity laws
- database of hourly flow demand;
- hydraulic simulations in EPANET 2.0
- feed-in-tariff in Switzerland
- database of typical unit costs in Switzerland

Case study: Lausanne sub-grid

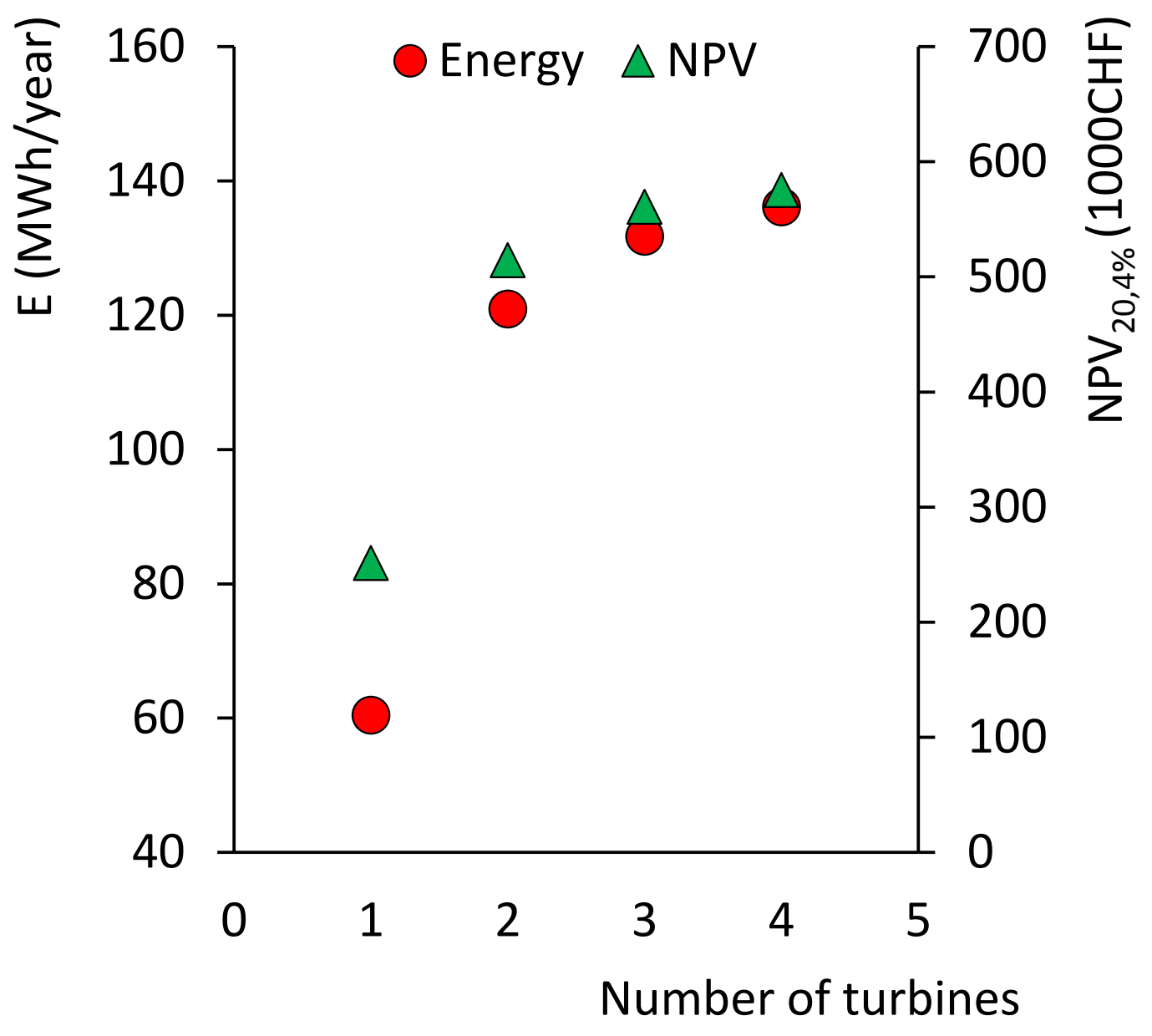
335 links and 312 nodes

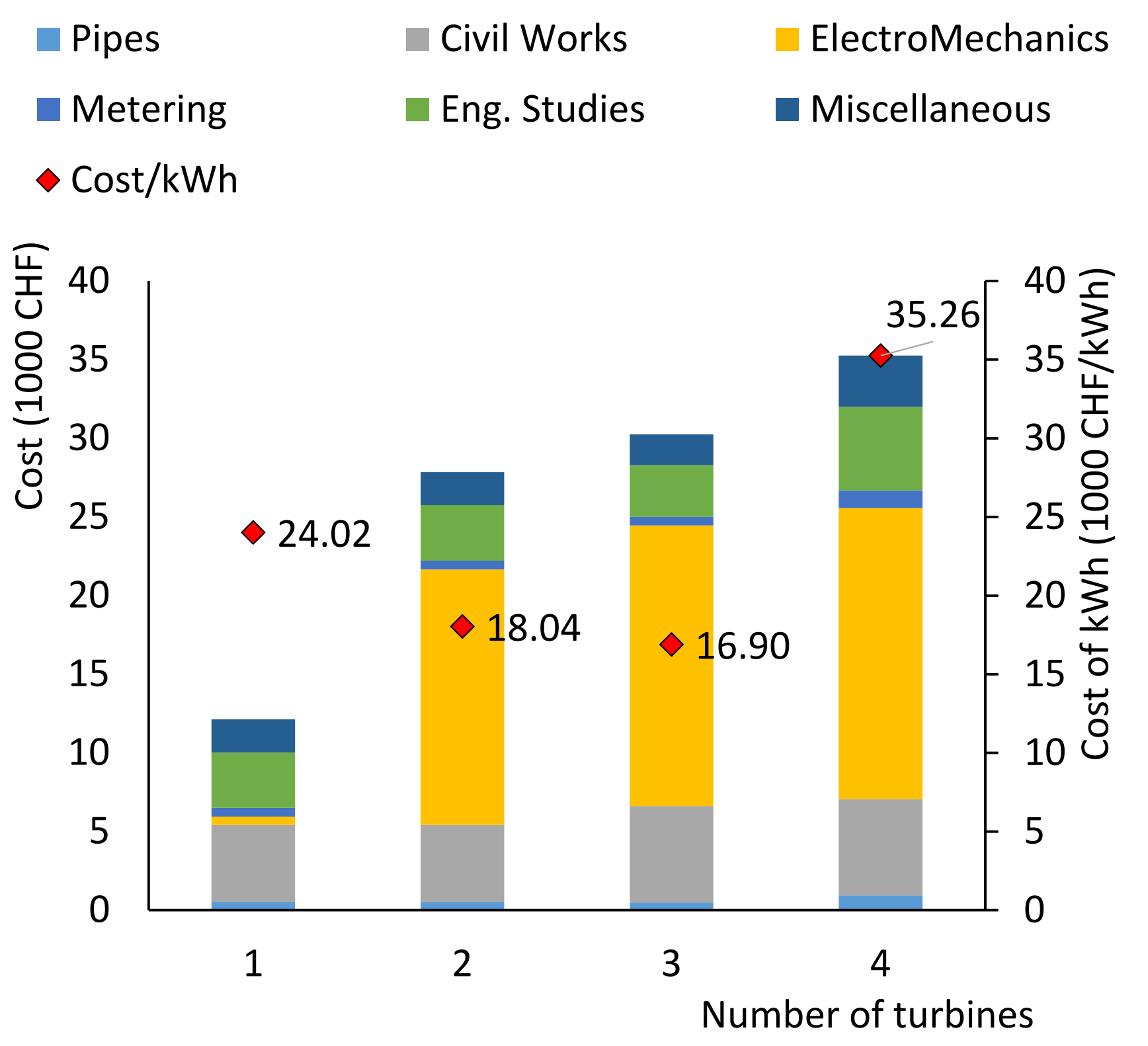




Case study: Fribourg WSN

2972 links and 2805 nodes





Conclusions

The installation of micro-hydropower plants in urban WSNs is economically feasible.Two turbines is often the most reasonable solution. Sensibility analysis to the demand should be considered to verify its impact in the energy production. The by-pass (specially supplementary valves) can have an important impact on the investment wherever there is no redundancy in supply.

Peer-reviewed publications

Samora, I.; Manso, P.; Franca, M. J.; Schleiss, A. J.; Ramos, H. M.; 2016. Energy Recovery Using Micro-Hydropower Technology in Water Supply Systems: The Case Study of the City of Fribourg, Water, 8(8), 344.

Samora, I.; Manso, P.; Franca, M. J.; Schleiss, A. J.; Ramos, H. M.; 2016. Opportunity and economic feasibility of inline micro-hydropower units in water supply networks. Journal of Water Resources Planning and Management.

Samora, I.; Hasmatuchi, V.; Münch-Alligné, C.; Franca, M. J.; Schleiss, A. J.; Ramos H. M.; 2016. Experimental characterization of a five blade tubular propeller turbine for pipe inline installation. Renewable Energy, 95, 356-366

Acknowledgments

This research project was developed in the scope of the Ph.D. Thesis by Irene Samora under the joint IST-EPFL doctoral initiative. It was funded by the Portuguese Foundation for Science and Technology and LCH-EPFL. The laboratorial experiments carried out at the HES-SO were co-funded by the SFOE.

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Understanding the unstable off-design operation of Francis turbines for large scale NRE integration

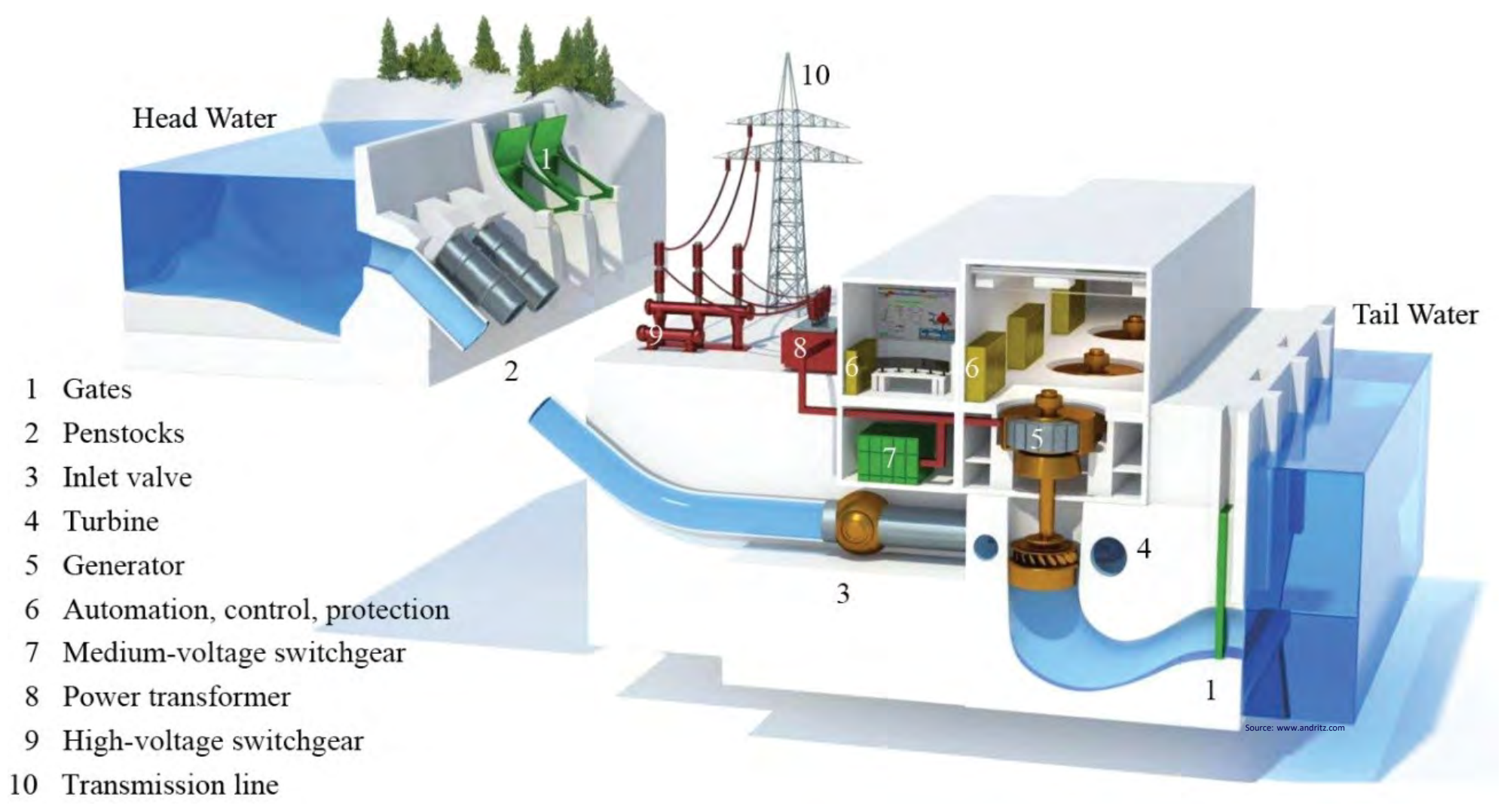
A. Favrel, K. Yamamoto, A. Müller, C. Landry and F. Avellan

Context

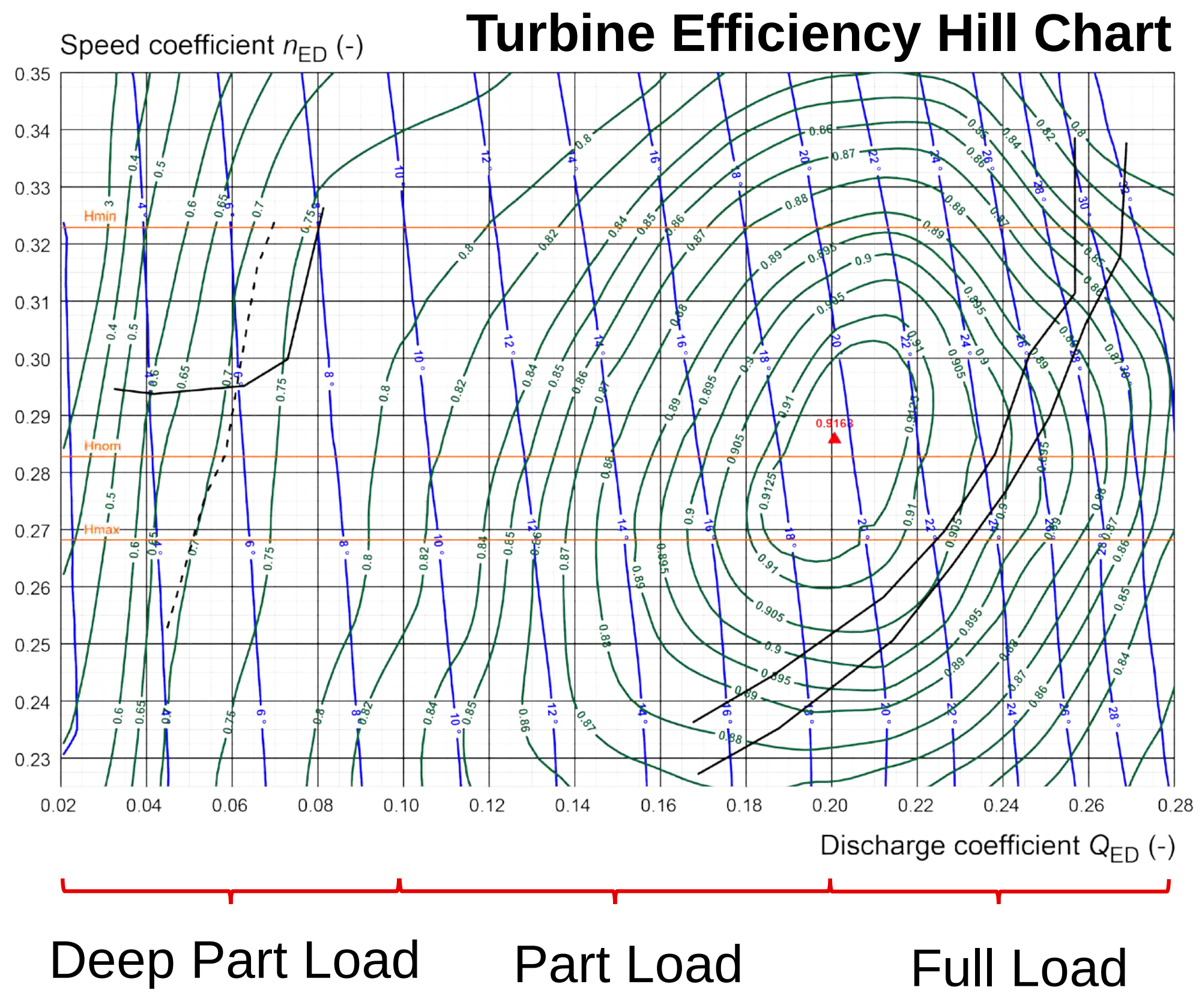
In order to guarantee the electrical grid stability in the course of the integration of New and Renewable Energies (NRE), the operating range of conventional and pumped-storage hydropower plants is continuously extended. The off-design operation however induces unfavourable flow patterns and instabilities in hydraulic machines, causing a variety of problems, from cavitation erosion to dangerous power swings.

The HYPERBOLE research project (ERC/FP7- ENERGY-2013-1-Grant 608532), consisting of leading European universities and turbine manufacturers, aims at making a decisive contribution towards the smooth integration of NRE. An important objective thereof is to reach a profound understanding of the underlying physical mechanisms leading to an unstable behaviour of the unit, by performing tests on reduced scale models as well as numerical simulations. The resulting data serves to enhance the accuracy of existing models for a comprehensive simulation of hydroelectric power plants over their whole operating range.

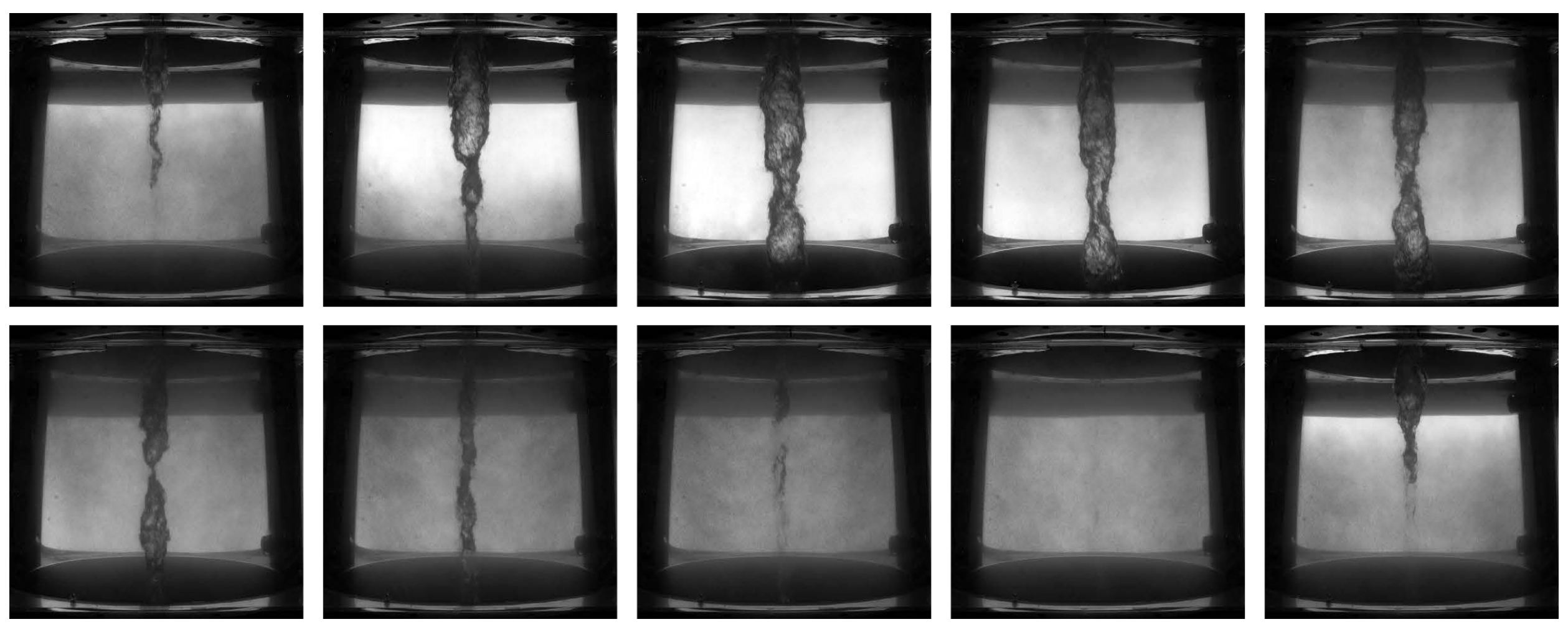
Extension of the operating range of hydropower plants for electrical grid regulation in the course of NRE integration.



Turbine Efficiency Hill Chart



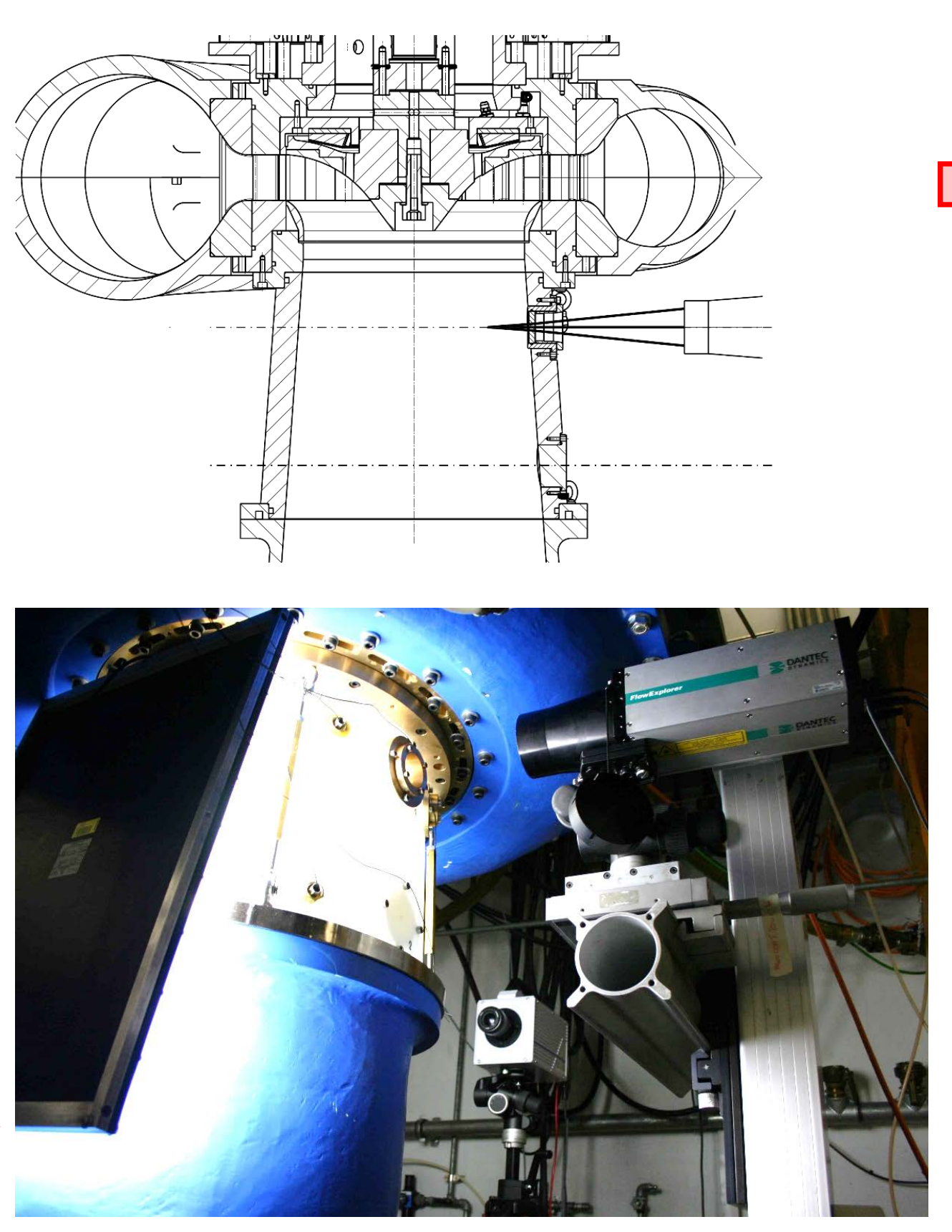
FULL LOAD



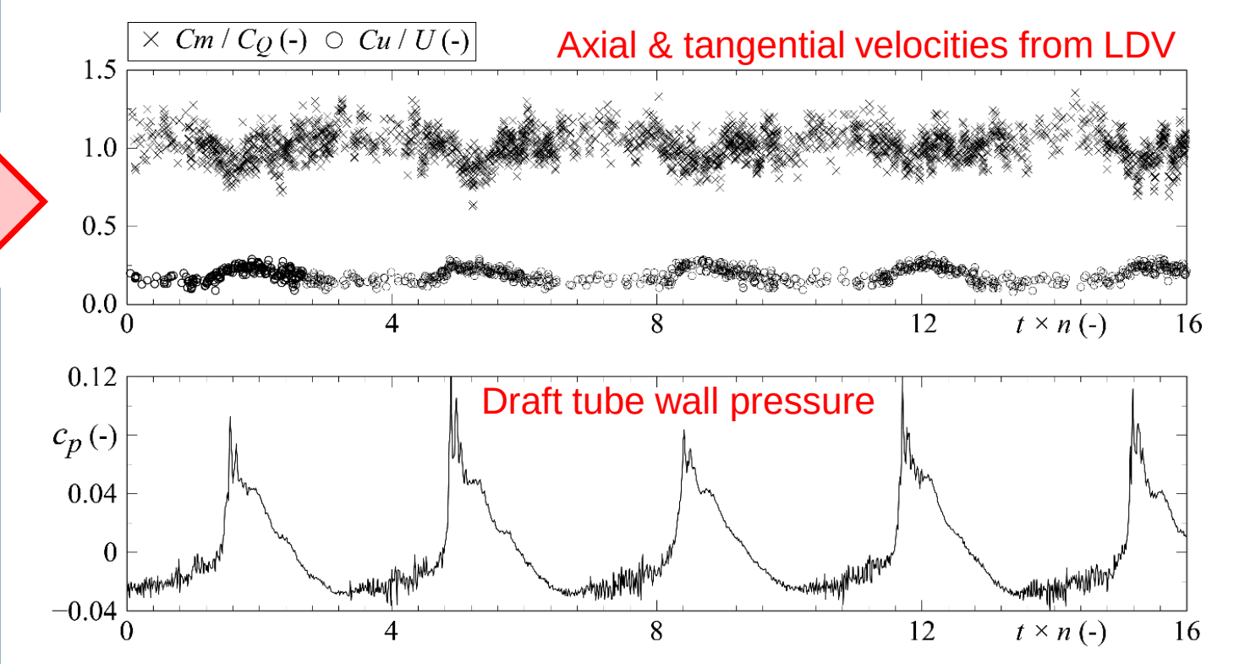
Problem: Self-excited oscillation of an axisymmetric cavitation vortex rope in the draft tube cone and of the hydro-electric system (wall pressure, mechanical torque on the runner shaft, electrical power).

Experimental approach: Study of the interaction mechanisms between flow and system through LDV and high-speed visualizations, synchronized with pressure and mechanical torque measurements.

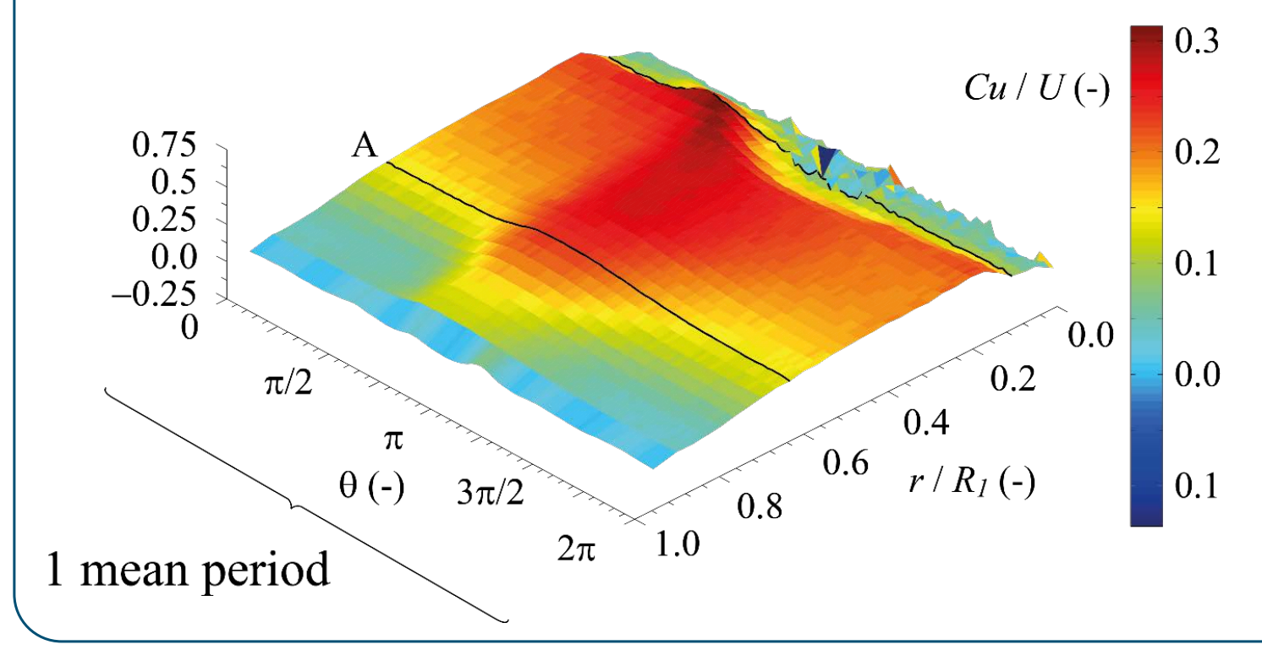
2-D LDV in the draft tube cone



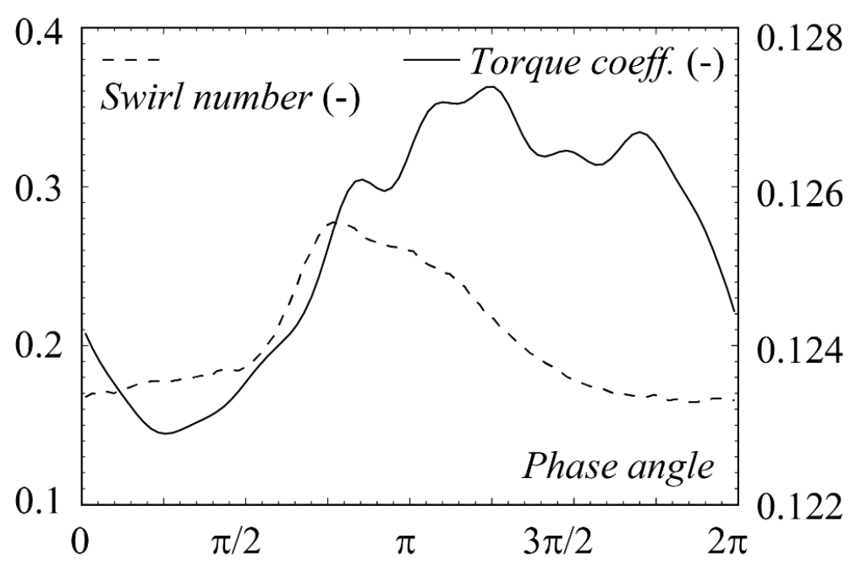
Pressure phase averaged velocity, flow swirl and torque



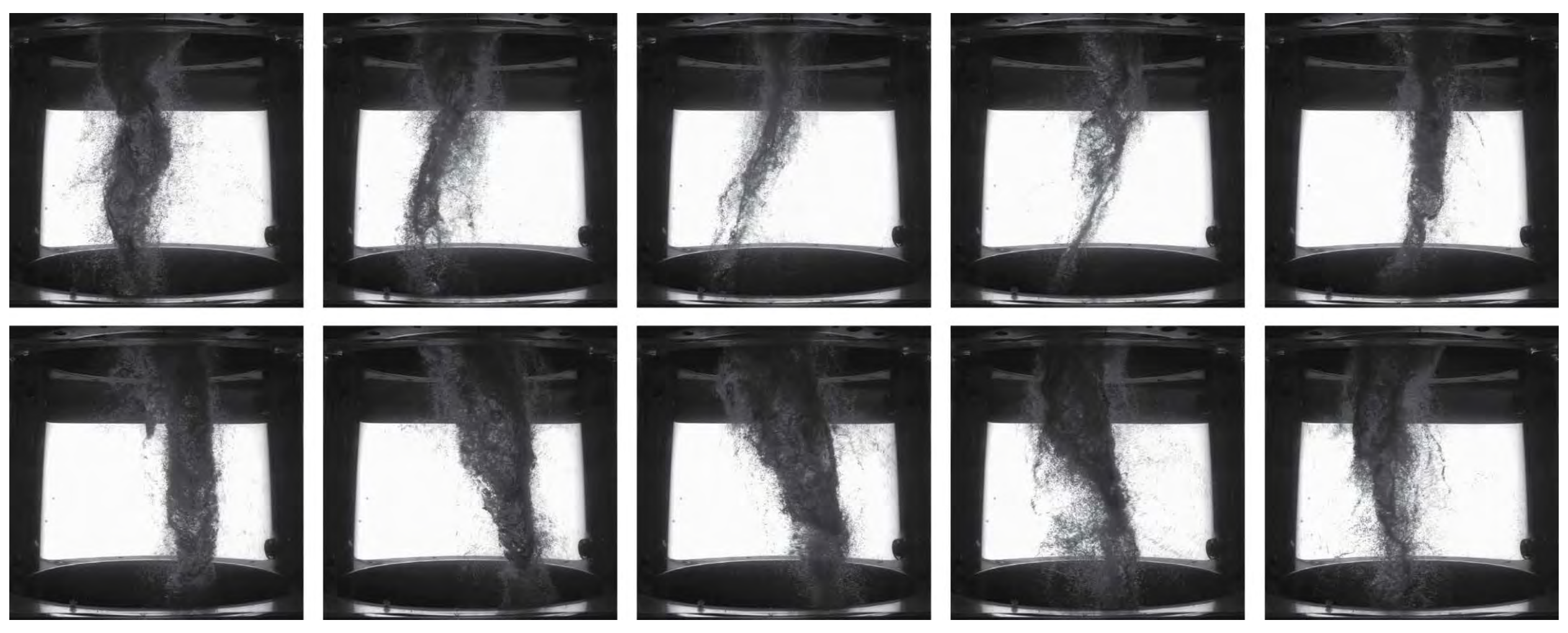
>> Pressure mean phase averaged velocity profiles at 30 radial positions



- ✓ Comprehensive description of hydro-mechanical system behaviour.
- ✓ First time identification of the mechanisms of unstable fluid-structure interaction.
- ✓ Ongoing development and validation of hydro-acoustic models for stability analysis.



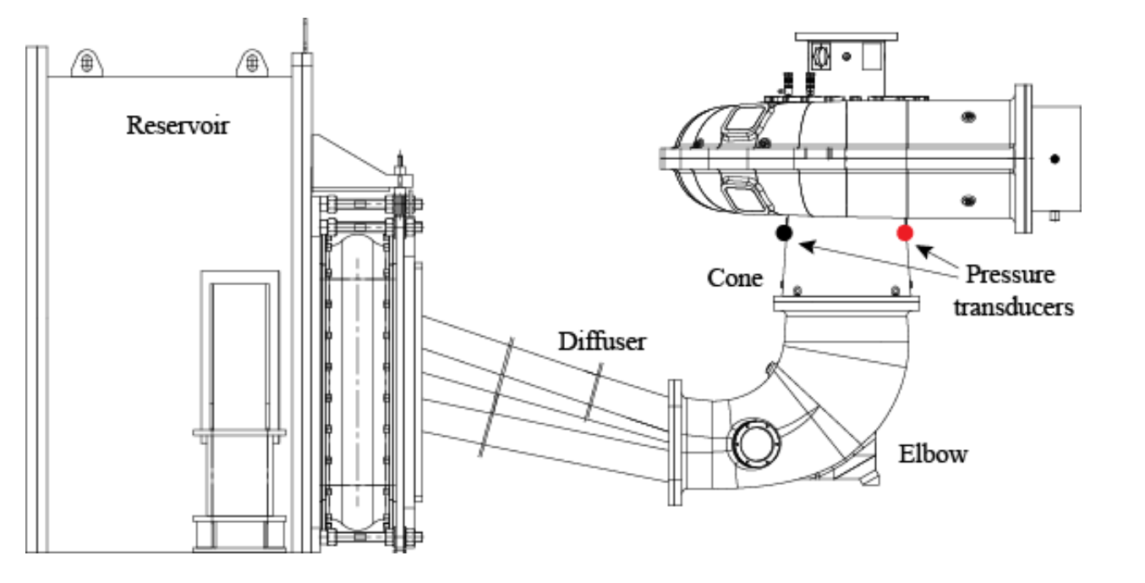
PART LOAD

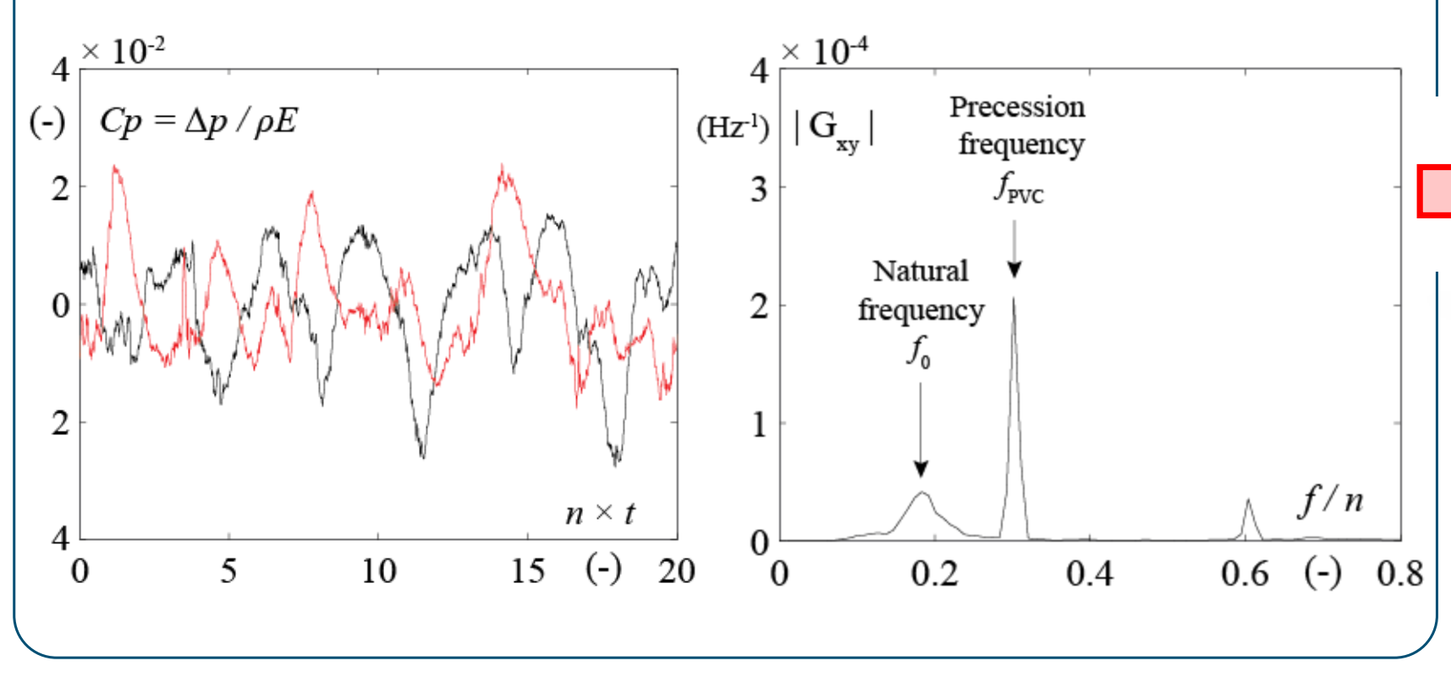


Problem: Development of a cavitation precessing vortex rope in the draft tube cone acting as an excitation source for the hydro-mechanical system >> risk of resonance jeopardizing the system stability.

Investigative approach: Establishment of dimensionless laws linking both precession and natural frequencies with the operating parameters to predict resonance occurrence on the complete hillchart.

Identification of both the precession and natural frequencies by pressure measurements

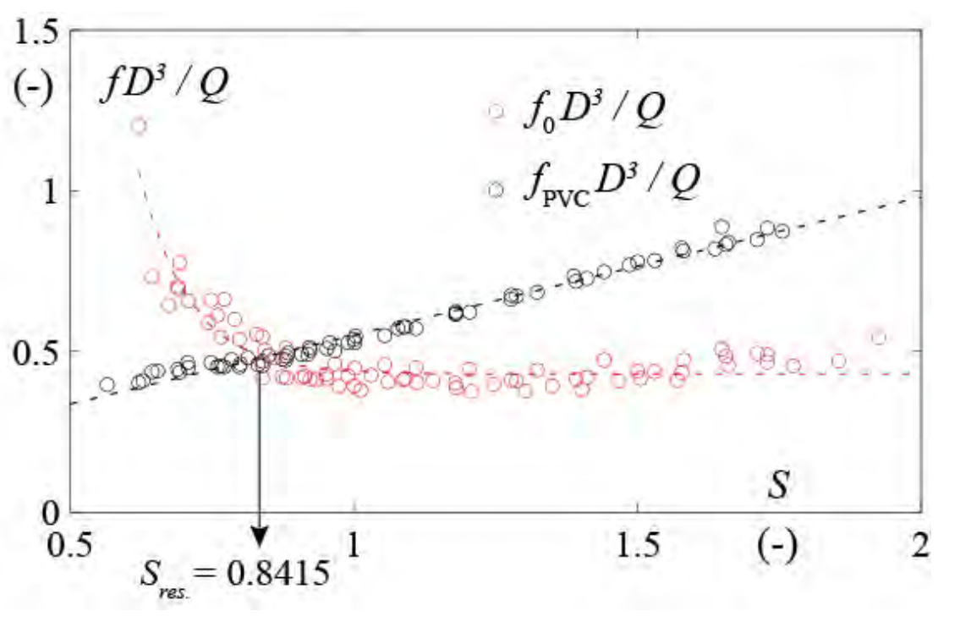




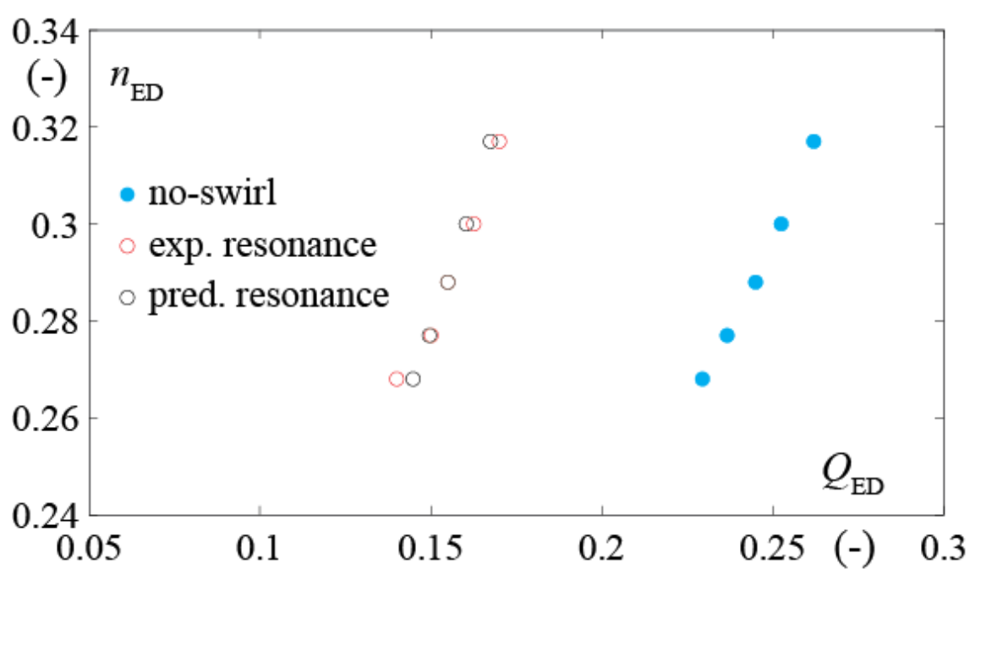
Prediction of resonance conditions on the complete turbine hill chart at the model scale

- ✓ Derivation of an analytical expression of the swirl number *S* as a function of the speed and discharge factors
- ✓ Empirical dimensionless relations linking the swirl number and the precession and natural frequencies

Empirical dimensionless relations between frequency and swirl

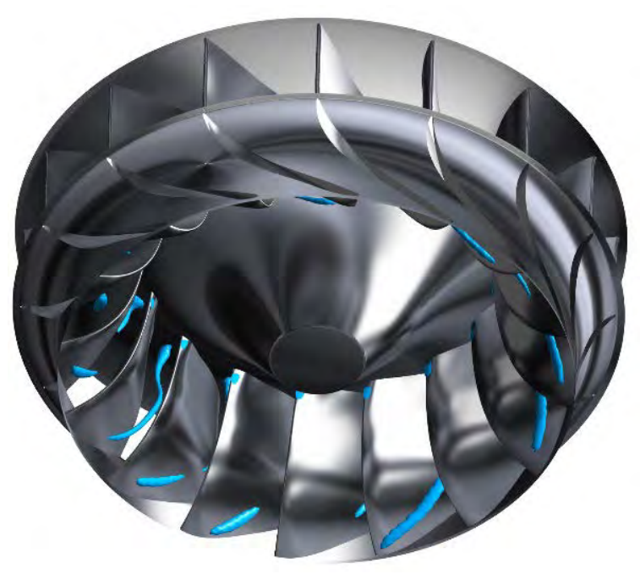


Comparison between predicted and observed resonance conditions



→ Maximum differences between prediction and experiments: $\Delta Q_{ED} = 0.05$

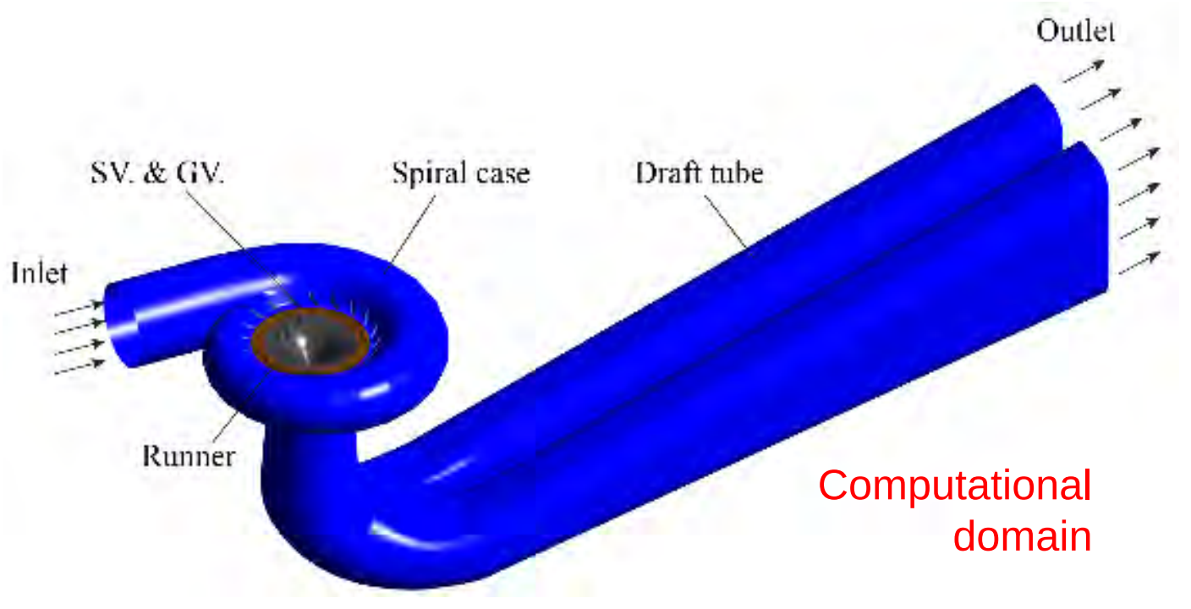
DEEP PART LOAD



Problem: Formation of cavitation vortices in the inter-blade channels (inter-blade vortices) with unknown draft tube flow interaction and erosive potential.

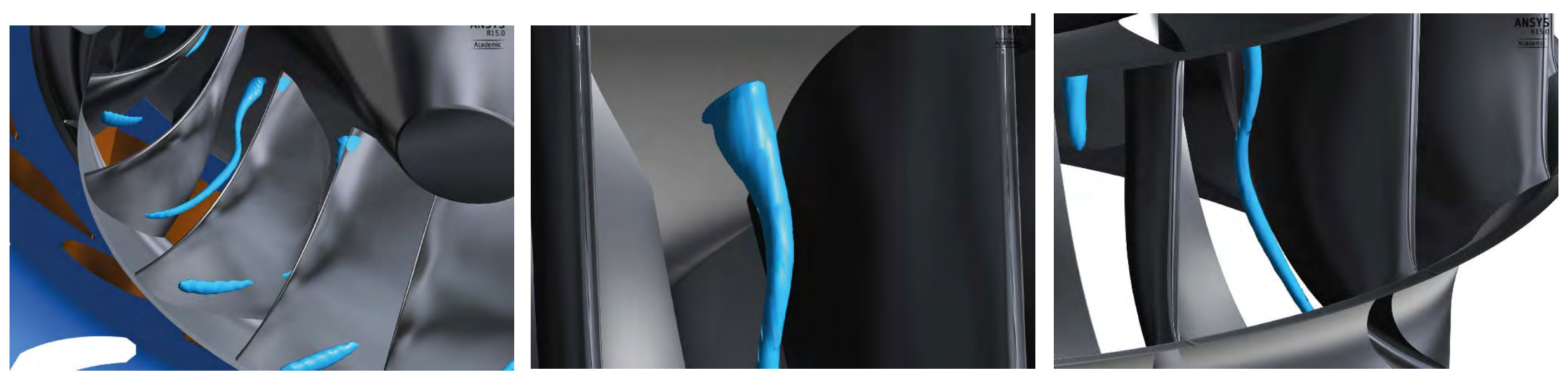
Investigative approach: Understanding of the mechanisms responsible for the formation of cavitation inter-blade vortices by numerical simulation and high-speed visualizations.

Unsteady RANS simulation and high-speed visualizations



- ✓ Homogeneous fluid (water and vapour) with SST-SAS turbulence model.
- ✓ Cavitation model based on Rayleigh-Plesset equation.
- ✓ Mesh: 16 million nodes.

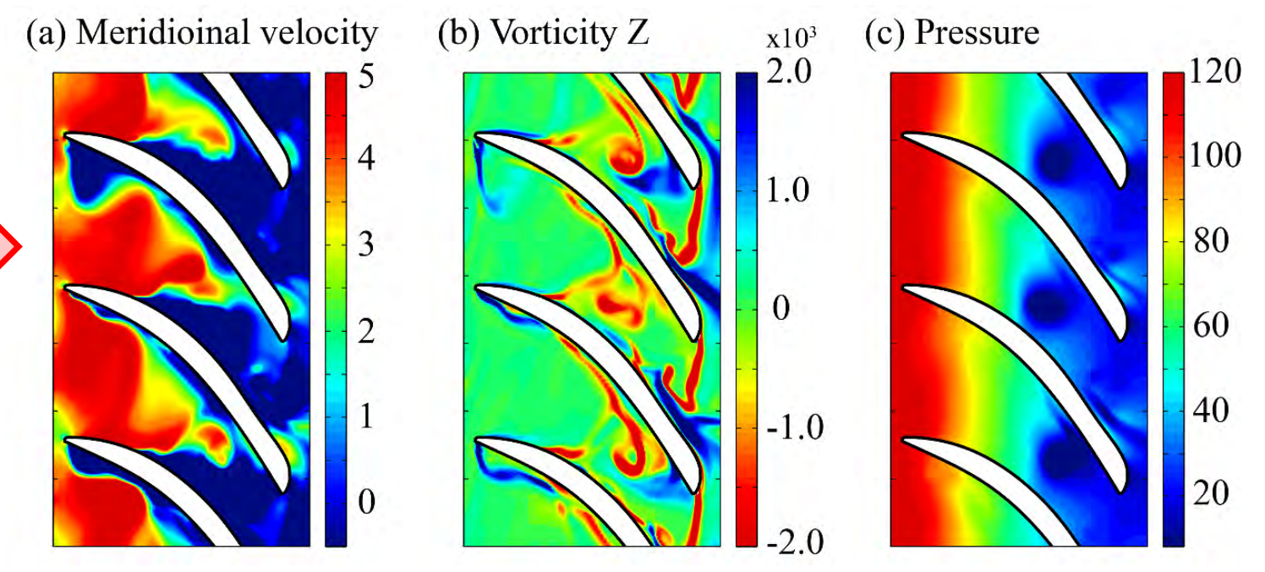
Simulated inter-blade cavitation vortex



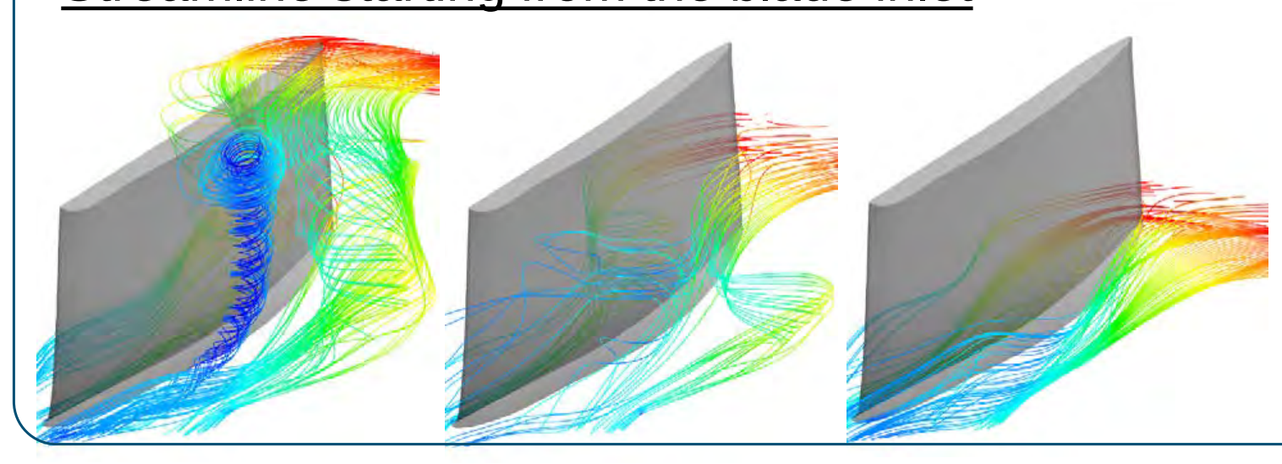
Investigation of the flow field inside the channel

- ✓ Collision of the incoming flow and separated flow region generates the strong vorticity resulting in the low pressure zone

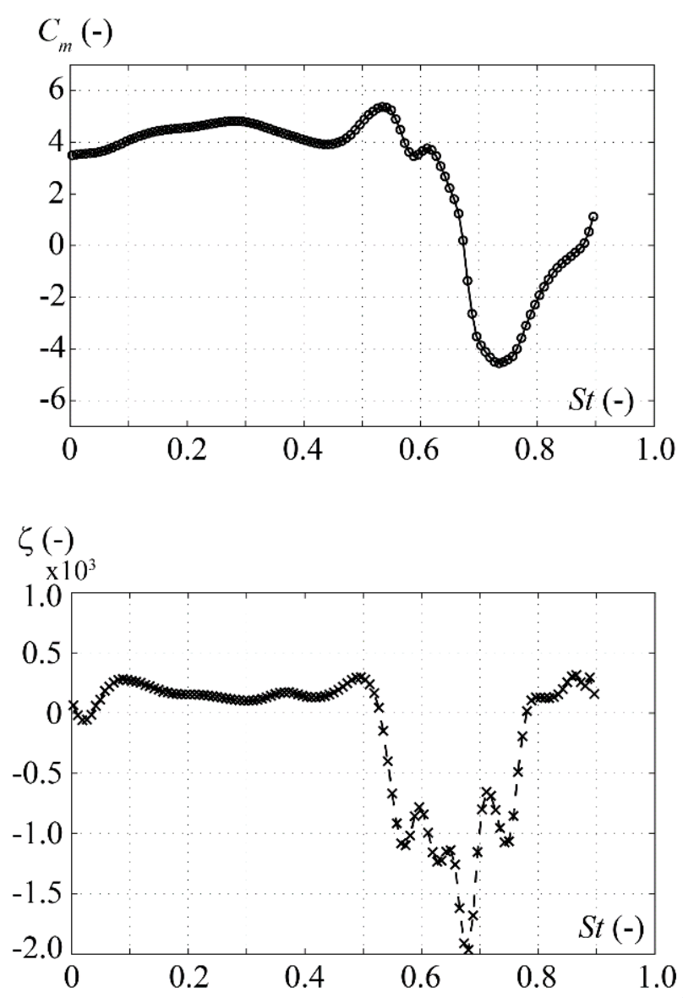
Contour at constant normalized span s* = 0.99



Streamline starting from the blade inlet



Velocity and vorticity profile at constant span s* = 0.99



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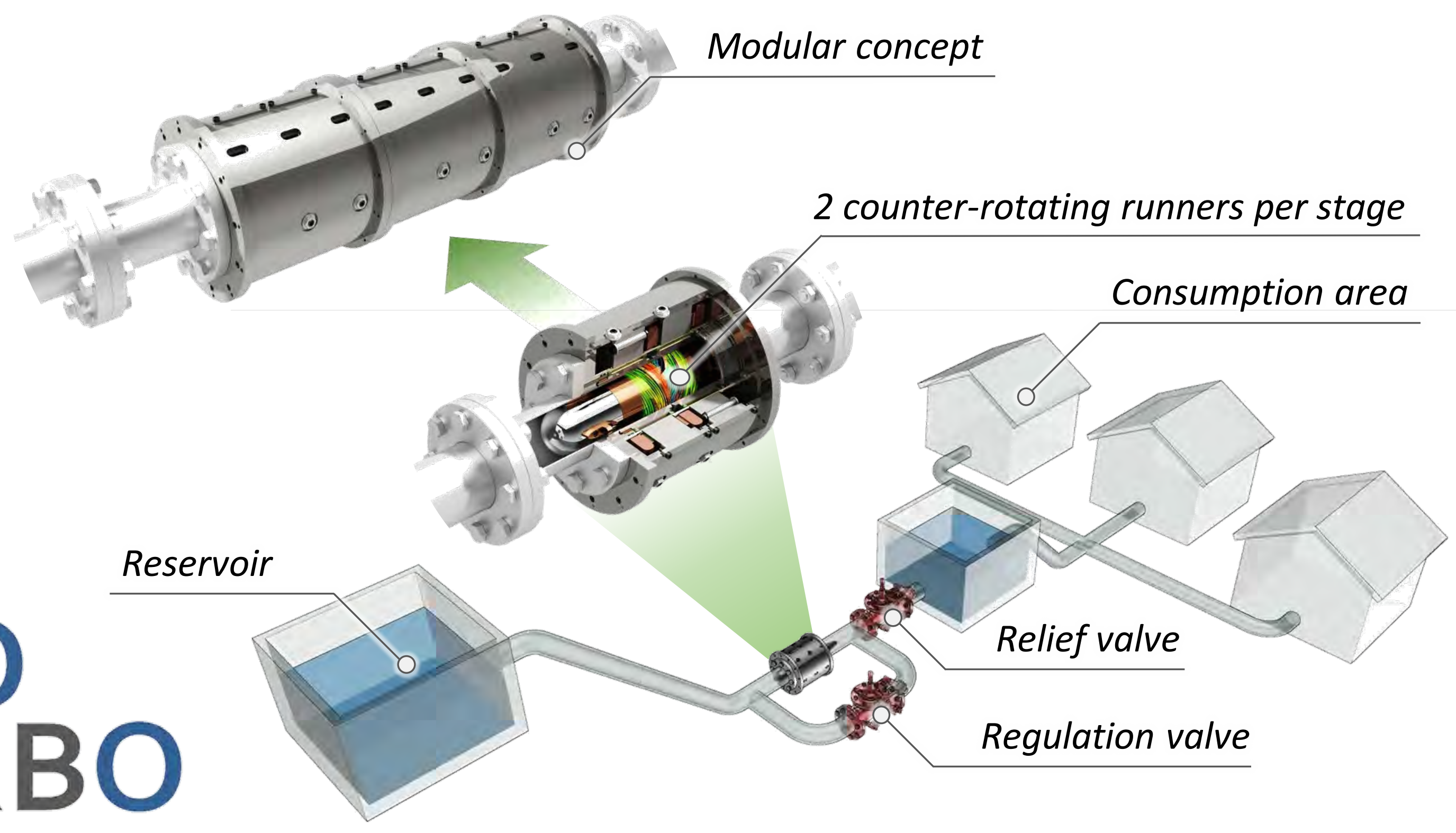
Energy Recovery Station controller tuning based on water utility network simulation

Loïc Andolfatto, Vlad Hasmatuchi, Cécile Münch-Alligné, François Avellan

Context

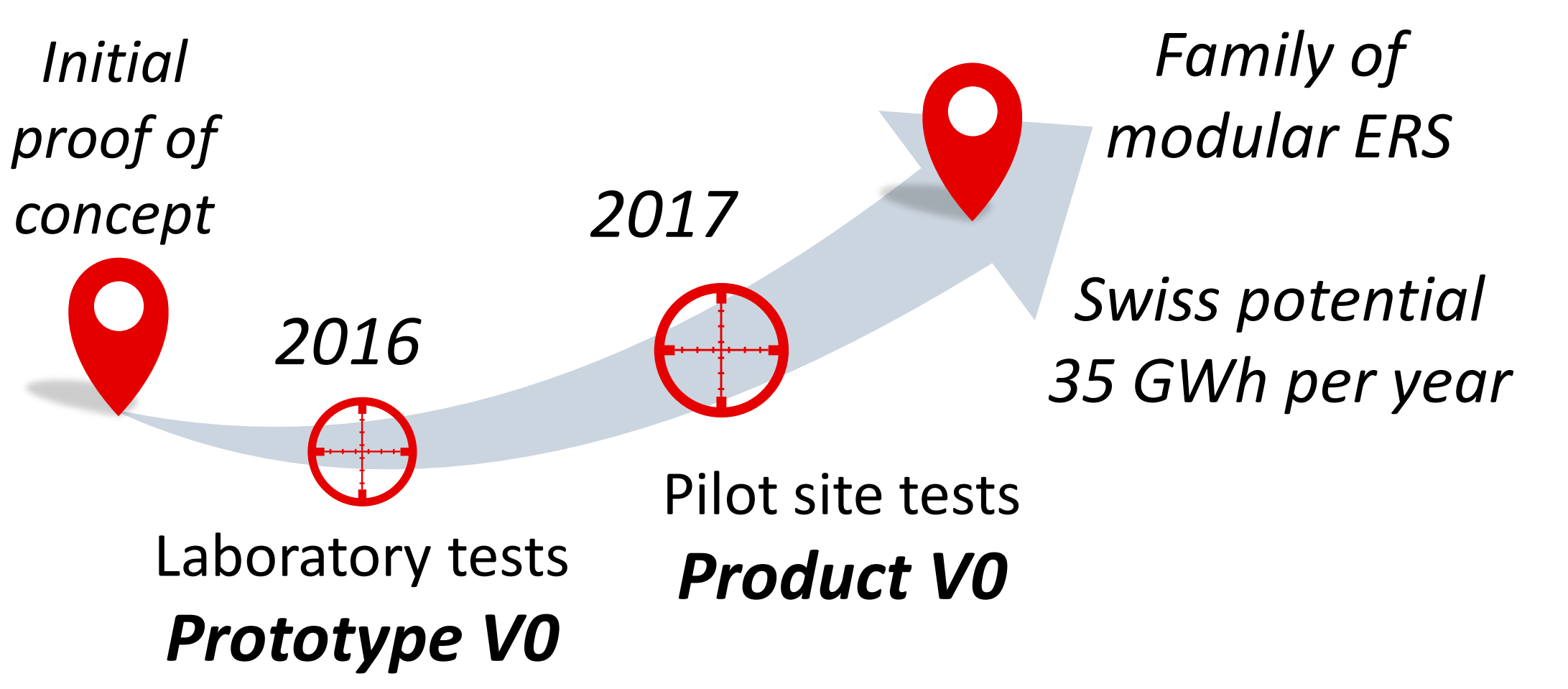
- Recovering hydraulic energy lost in **drinking water networks**
- Modular in-line "plug and play" turbine from **5 to 25 kW**
- No environmental impact
- Low investment costs

DUO TURBO



Project

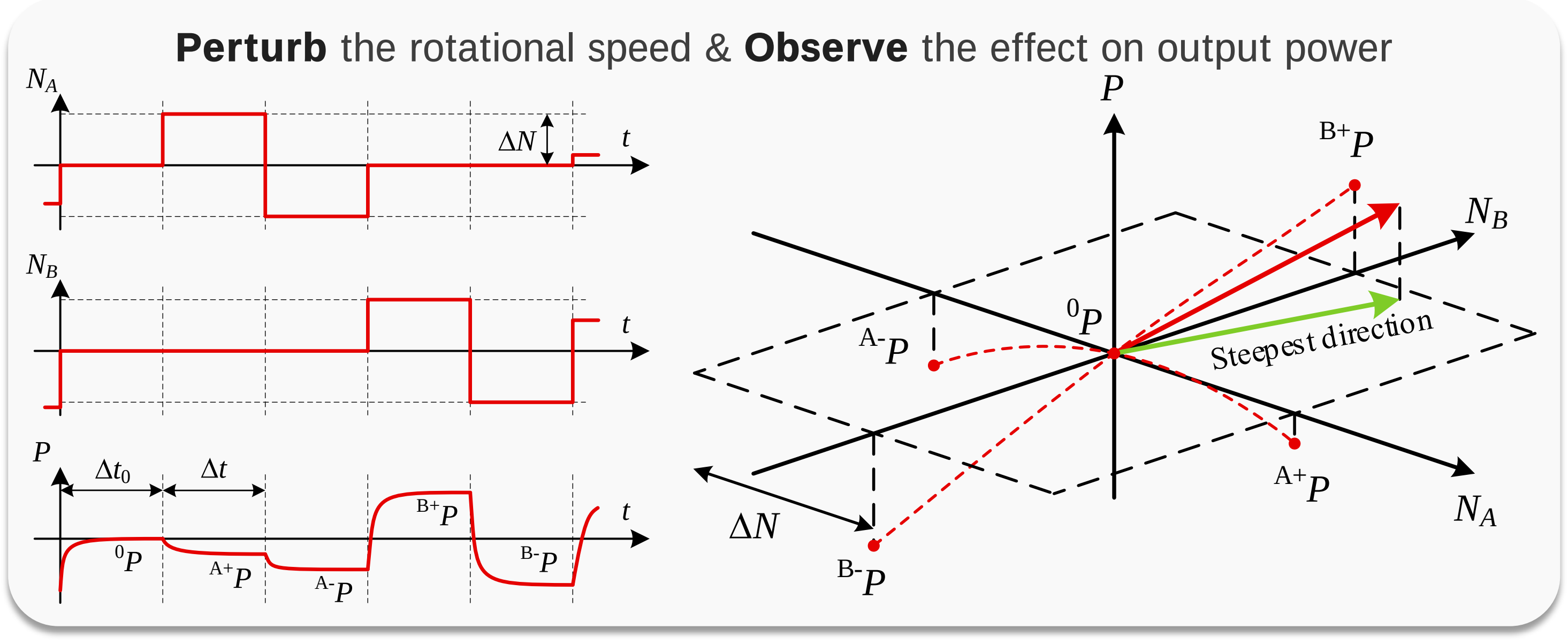
DUOTURBO: Providing Industrial and Competitive Family of Low-capex Integrated Energy Recovery Stations (*CTI project n°17197.1 PFEN-IW)*



Micro-turbine control strategy

- Consumer-driven discharge and operating conditions of the system
- Rotational speed of each runner controlled independently accordingly
- Maximum Power Point Tracking (MPPT) controller avoid expensive sensors

Objective: find the best parameters for the MPPT controller

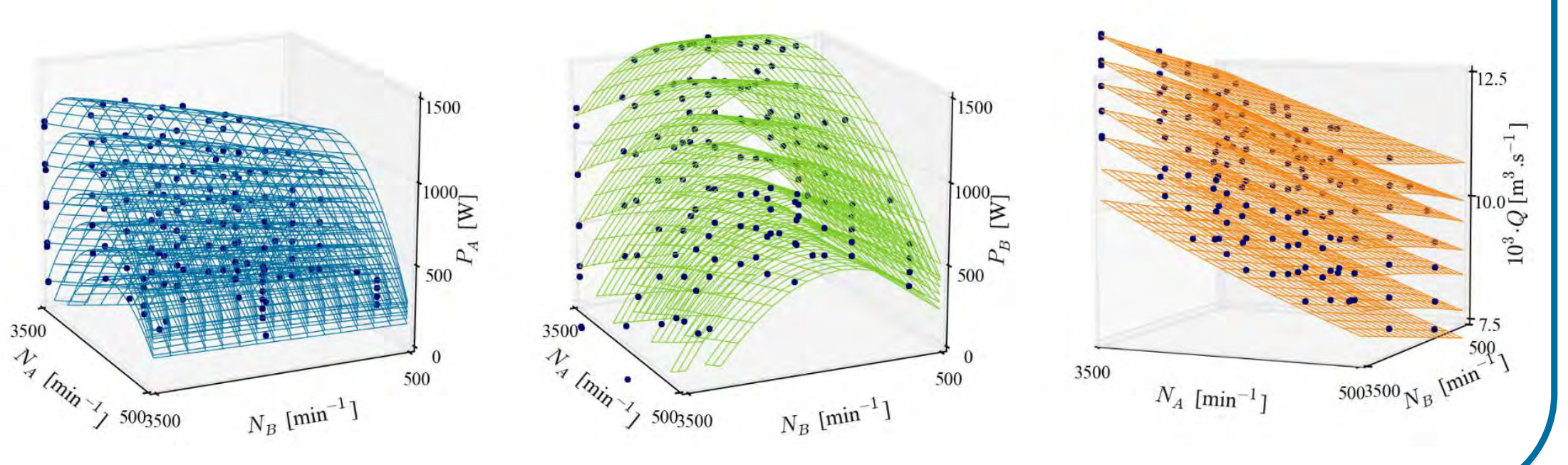

Perturb the rotational speed & **Observe** the effect on output power

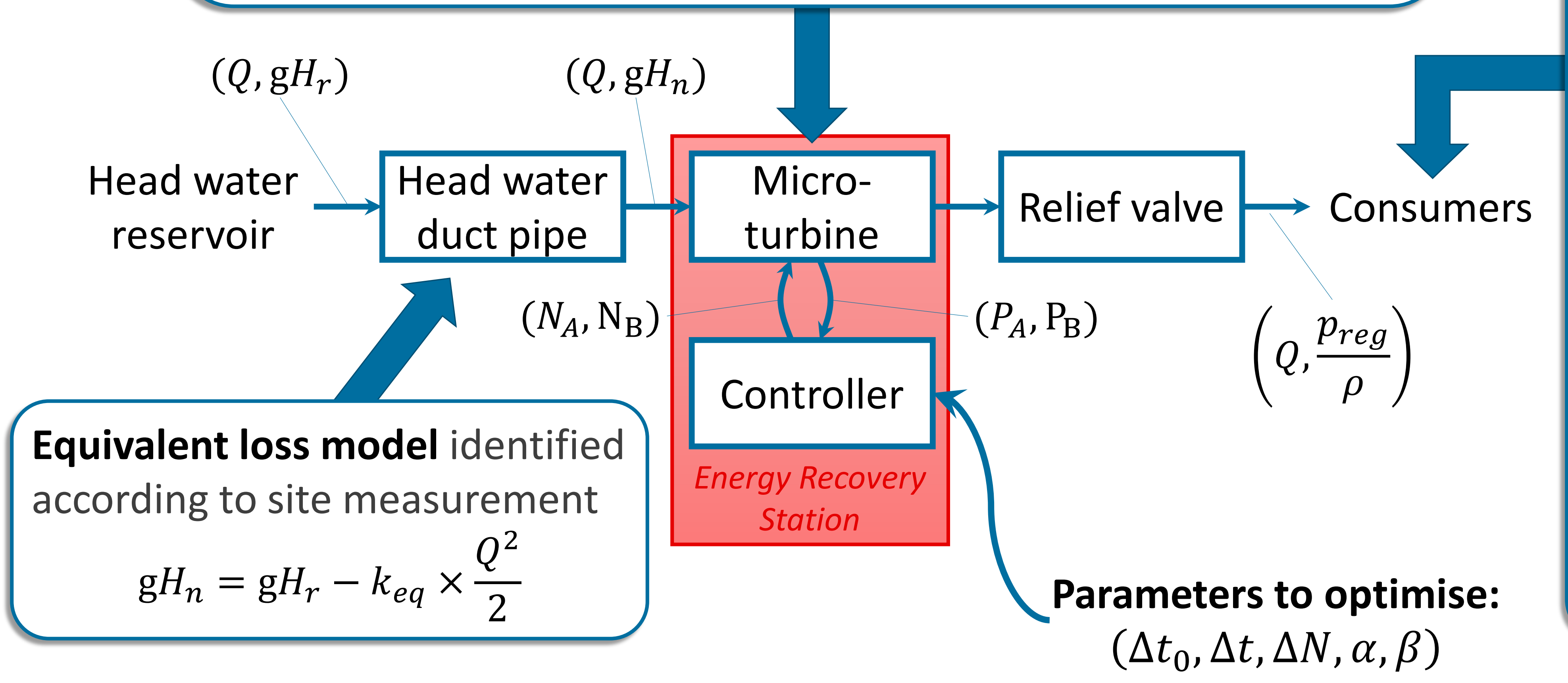
$$\boldsymbol{N}_{(i)} = \boldsymbol{N}_{(i-1)} + \alpha \cdot (\nabla \boldsymbol{P}_{(i-1)} + \beta \cdot \boldsymbol{d}_{(i-1)})$$

Proposed methodology: Optimisation based on the modelling and simulation of the entire system operation on a water utility network

Analytical models of the **micro-turbine** identified according to experimental tests:

- $P_A = f(N_A, N_B, E)$
- $P_B = f(N_A, N_B, E)$
- $Q = f(N_A, N_B, E)$





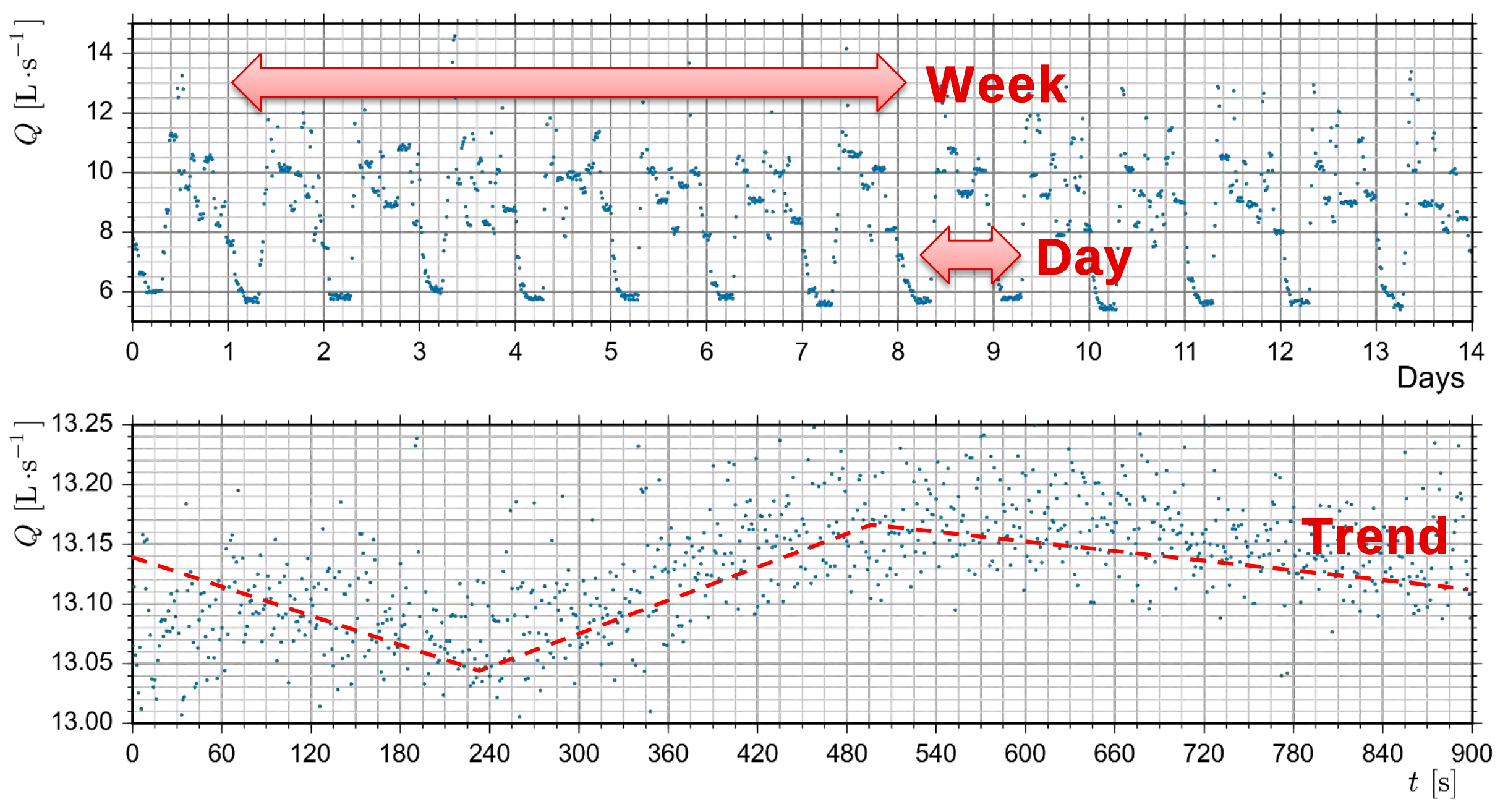
Equivalent loss model identified according to site measurement

$$gH_n = gH_r - k_{eq} \times \frac{Q^2}{2}$$

Parameters to optimise:

$(\Delta t_0, \Delta t, \Delta N, \alpha, \beta)$

Stochastic model of the **consumer driven discharge** identified according to multi time scale site measurement:



Typical measurements of 15-minute-averaged discharge over 14 days and fluctuation within 15 minutes

$$Q(t) = \underset{\text{Annual mean}}{\overline{Q}} + \underset{\text{Seasonal}}{Q_s(t)} + \underset{\text{Daily}}{Q_d(t)} + \underset{\text{Hourly}}{Q_h(t)} + \underbrace{w_s(t) \cdot w_d(t) \cdot w_h(t)}_{\text{Time-dependent weighting of the fluctuations}} \cdot \left[\underset{\text{Stationary time series}}{Q_{pl}(t)} + \underset{\text{Fluctuation}}{Q_f(t)}\right]$$

Results & Conclusions

Parameters	Symbols	Optimum values
Steady state sub-period	Δt_0	8.9 s
Perturbation sub-period	Δt	7.8 s
Perturbation magnitude	ΔN	104.6 min^{-1}
Tracking factor	α	259.6 W^{-1}.min^{-2}
Regularisation coefficient	β	0.15

- The Maximum Power Point Tracking controller parameters are tuned to **maximise the energy recovered** on a given site according to simulations of consumer discharge trajectories
- It operates **without additional sensors**, thus avoiding extra costs
- Only 2% efficiency loss compared to the maximum energy recoverable with a theoretically perfect controller fed with discharge and pressure sensors signals
- For a 10 kW installation operating 8700 h per year with a feed-in tariff of 0.311 CHF/kWh, the loss of revenue is about 350 CHF per year, assessing the **relevance of the approach**

See details: Andolfatto et al., "Simulation of energy recovery on water utility networks by a micro-turbine with counter-rotating runners." in *Proceedings of the 28th IAHR symposium on Hydraulic Machinery and Systems, Grenoble, France, July 4-8 2016*

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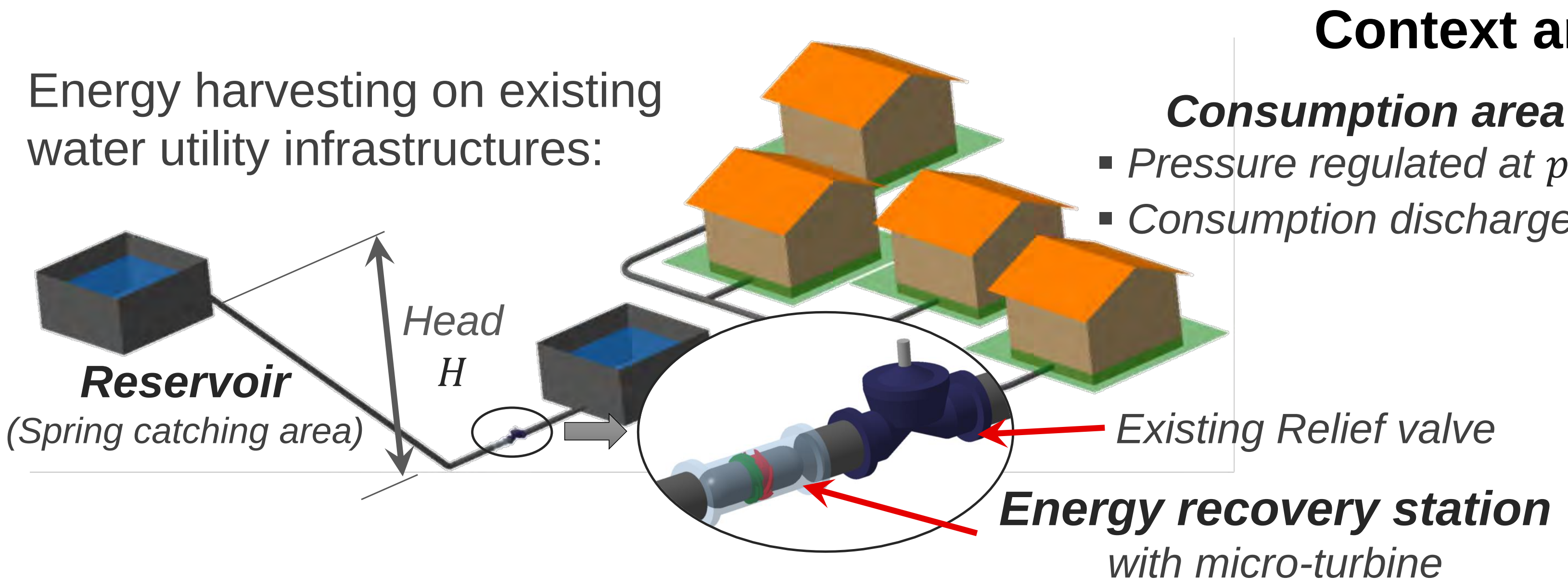
Experimental and numerical simulation investigations of the flow in a micro-turbine with counter-rotating runners

E. Vagnoni, S. Richard, L. Andolfatto, C. Münch, F. Avellan

Context and objectives

Energy harvesting on existing water utility infrastructures:



Consumption area
- *Pressure regulated at p_{reg}*
- *Consumption discharge Q*

Energy recovery station
with micro-turbine

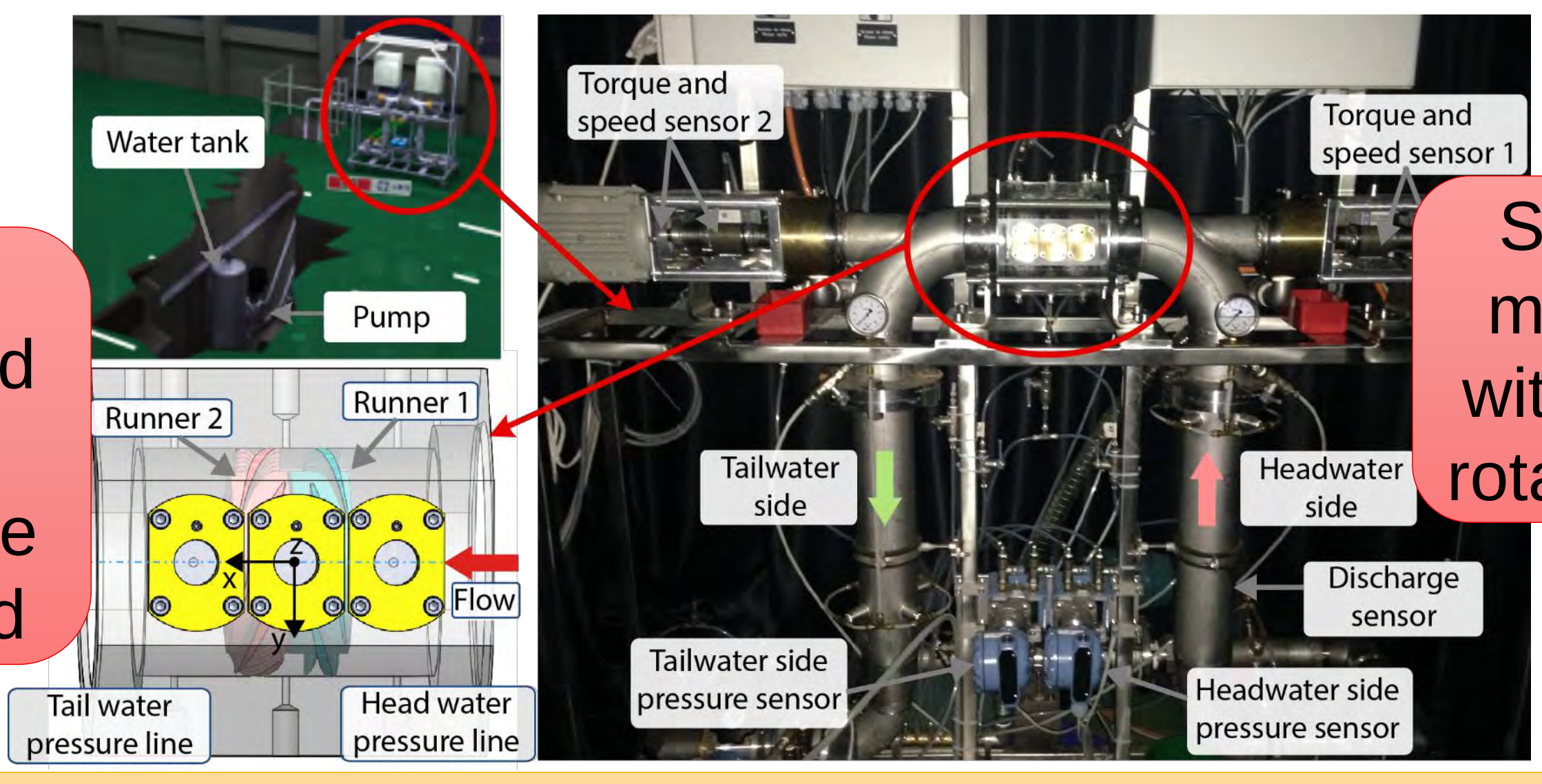
Available hydraulic power:

$$P_h \approx \rho Q\left(gH - k_{eq}\frac{Q^2}{2} - \frac{p_{reg}}{\rho}\right)$$

Key facts

- *Modular concept from 5 to 25 kW*
- *Low environmental impact*
- *Lean in-line installation*
- *Limited capital expenditure*

Experimental set-up for 2D Laser Doppler Velocimetry (LDV)



3 axial sections and 8 radial positions are investigated

Single stage micro-turbine with 2 counter-rotating runners

Velocity field investigation of the **meridional** and **tangential** components.

Reflection of the laser beams on the hub wall

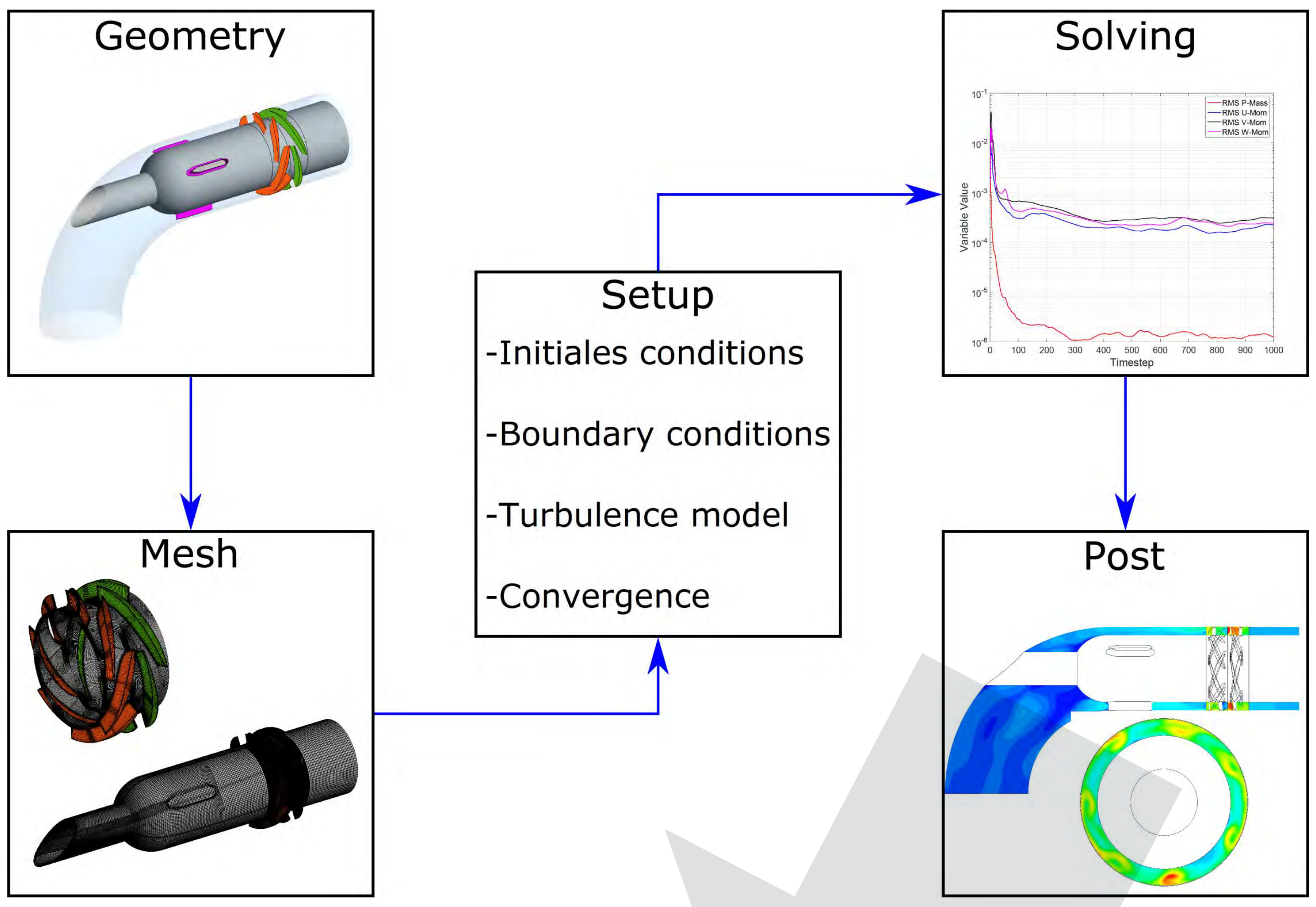
Obstruction of the LDV measurements close to the hub

Solution of the mass balance equation to fulfill the velocity profile

$$\tilde{Q} = \int_A \vec{C}\cdot\vec{n}\,dA = \int_{R_h}^{R_e} 2\pi C_m(r)\,r\,dr$$

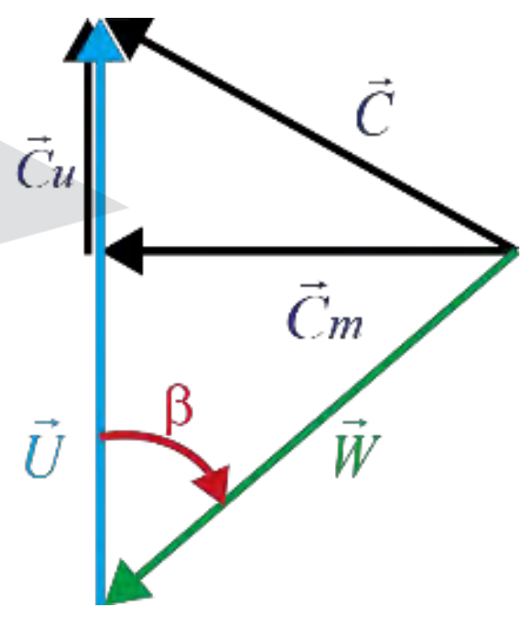
Numerical Simulation

Losses, efficiency and flow characteristics are predicted through steady numerical simulations of the flow performed using ANSYS CFX.



Setup
-Initiales conditions
-Boundary conditions
-Turbulence model
-Convergence

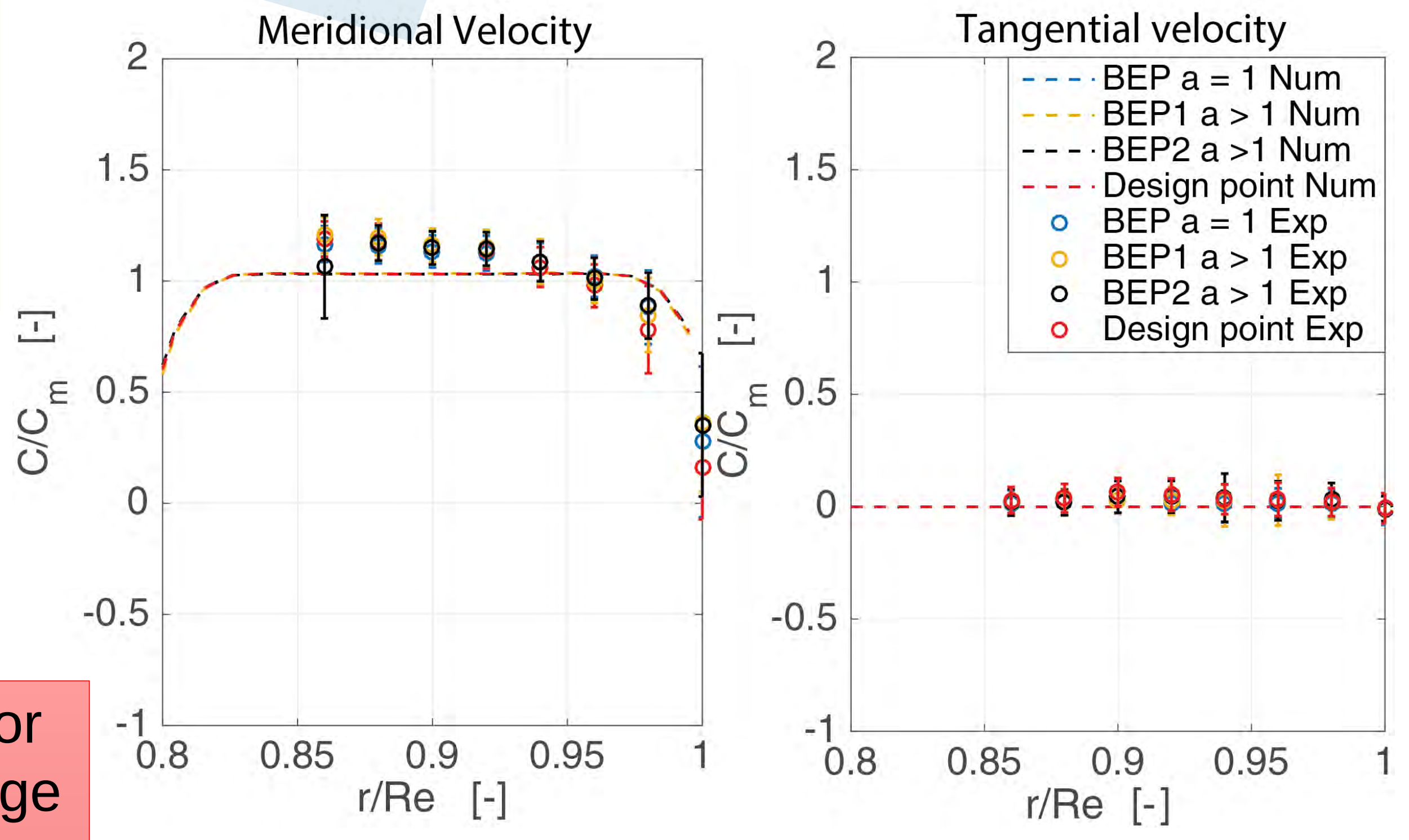
Results



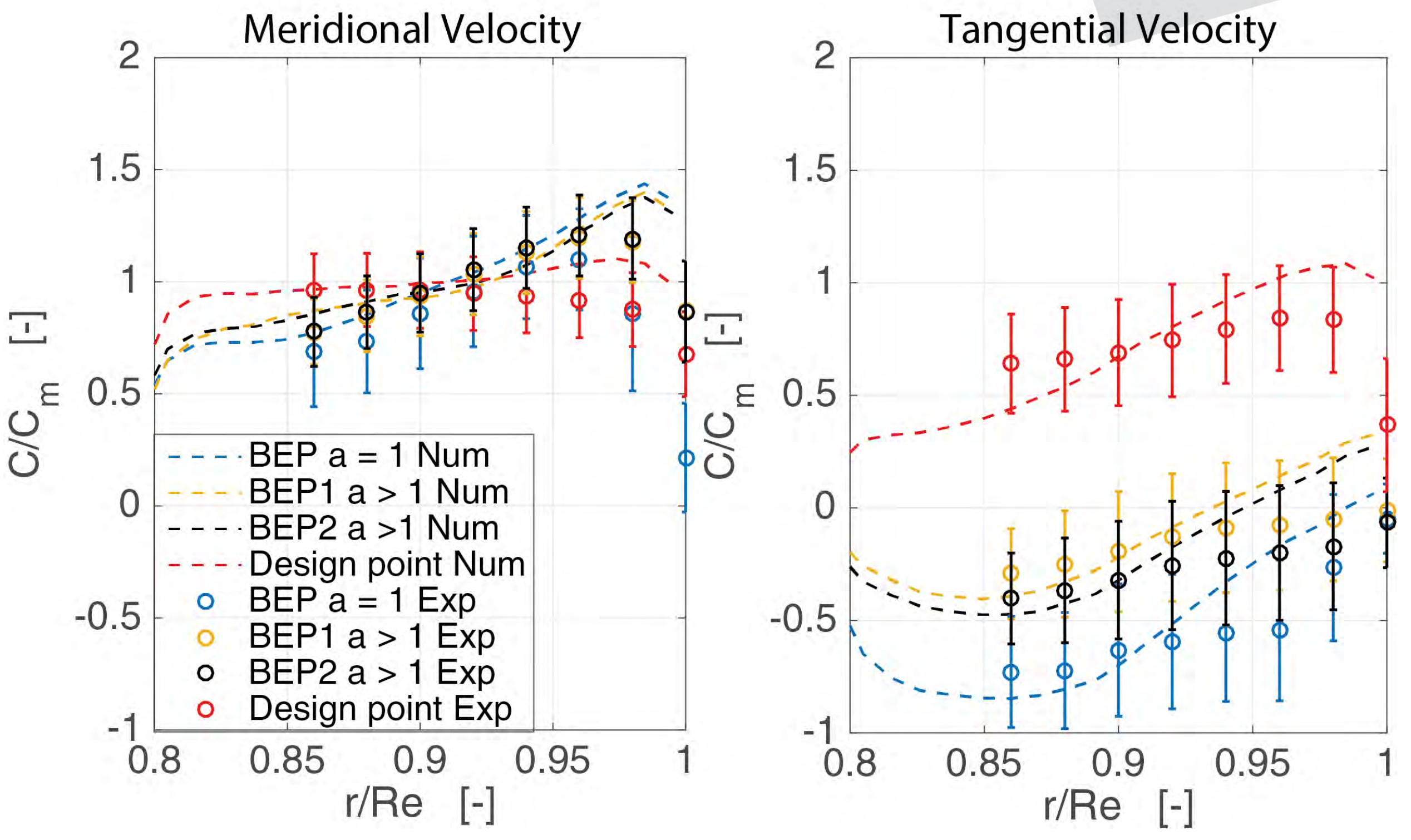
Speed coefficient:

$$a = \frac{\omega_2}{\omega_1}$$

Inlet section



Outlet section

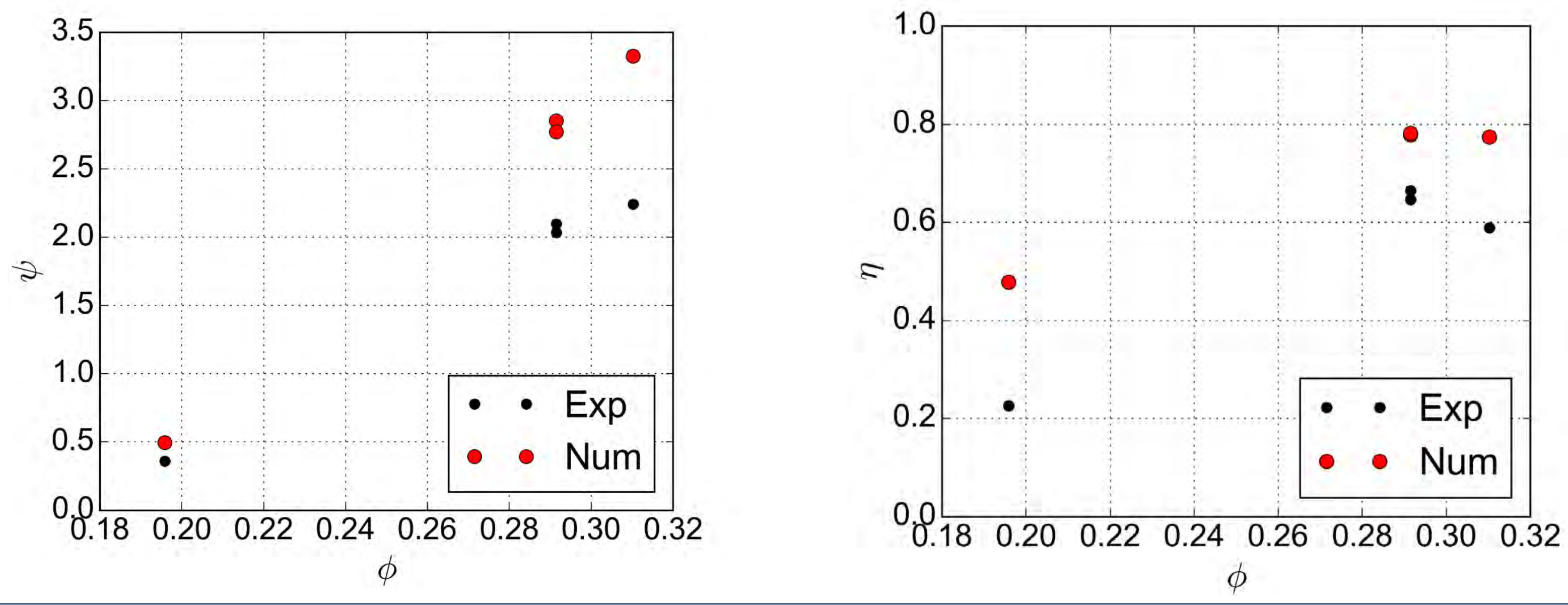


Maximum error on the discharge computation by mass balance equation: 3% of the measured discharge

Performance

$$\psi = \frac{2E}{(\omega_1 R_e)^2}$$

$$\phi = \frac{Q}{\pi\omega_1 R_e(R_e^2 - R_i^2)}$$



Discrepancies correspond to the mechanical losses of the experimental test rig

Conclusions

- ✓ A **good agreement** between numerical end experimental investigation is observed.
- ✓ The **fulfillment** of the experimental velocity profile and the computation of the **power** transmitted by the runners by solving the **total specific rothalpy balance equation** allow the computation of the **efficiency** which is confirmed by the numerical simulation.
- ✓ The **discrepancies** between experiments and numerical simulations correspond to **mechanical losses** due to the energy dissipation in the bearings in the experimental facility.

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Stability Analysis and Optimal Control of a Francis Turbine Vortex Rope

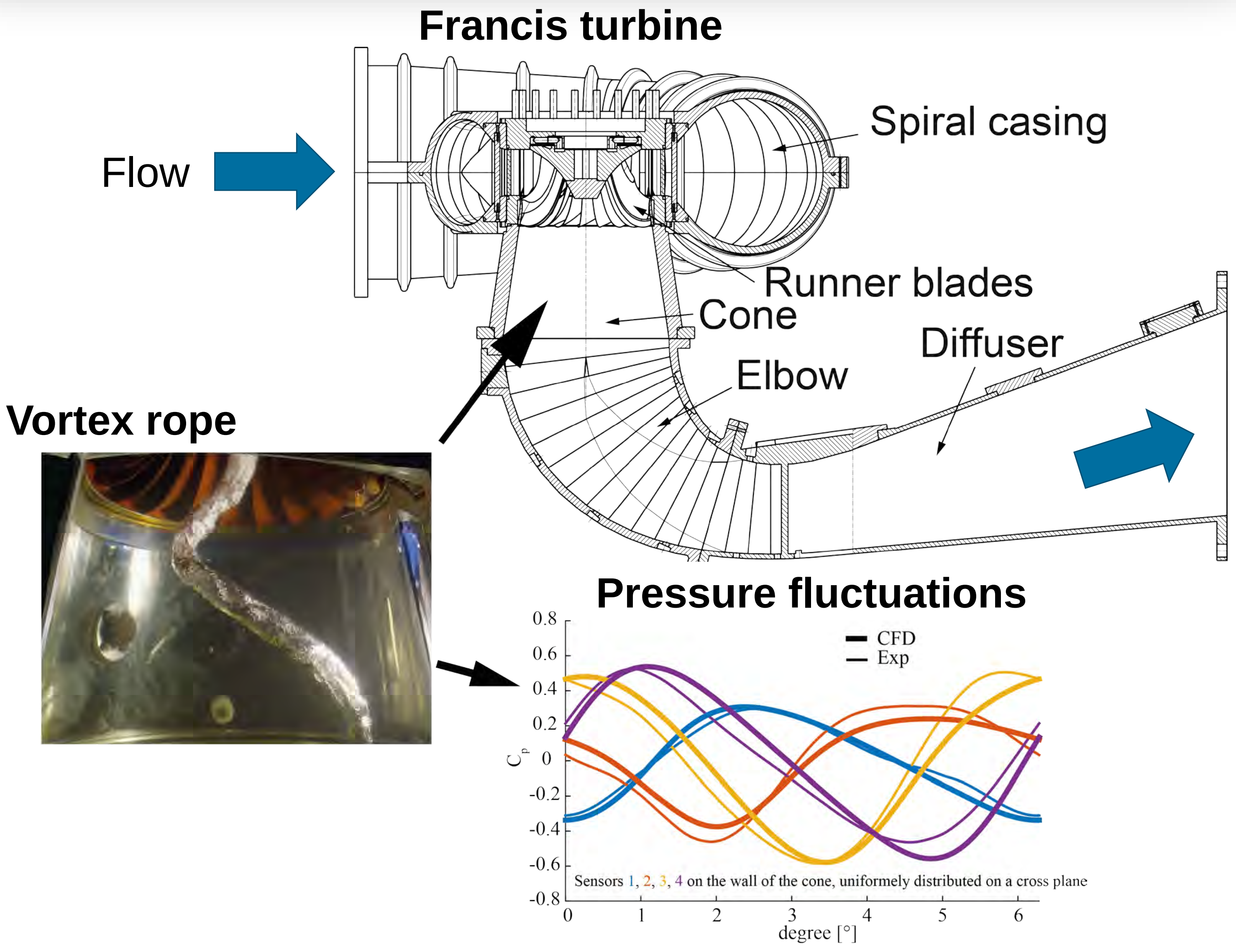
Pasche S., Gallaire F., Avellan F.

Problematic

This project consists of applying the latest flow control theories to an important issue arising in hydraulic turbines: the development of a cavitation vortex rope at part load conditions in Francis turbines.

With the future massive introduction of renewable energy in the distribution systems, the operation of Francis turbines at off-design conditions, corresponding to the part load regime, is thought to be one of the main solutions to mitigate large power fluctuations of the grid.

An intense cavitation rope is however known to appear in these conditions, which produces large pressure fluctuations at a well-defined frequency, with the associated hazards induced by the risks of operating instability and fatigue and resonance of the mechanical structures.



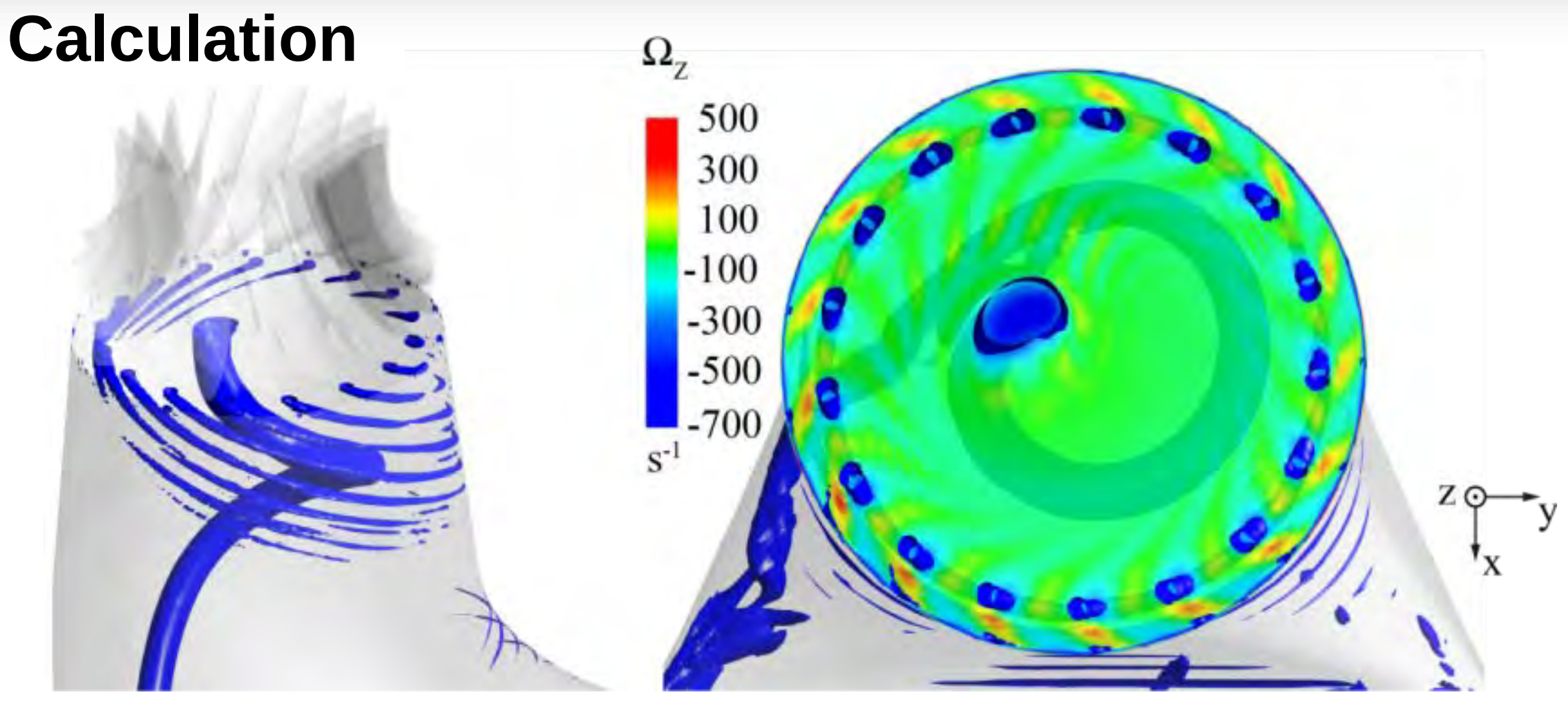
Objectives

- Interpretation of the vortex rope as a global unstable mode
- Sensitivity to base flow modifications (locate region which are sensitive to control device)
- Design a control device to reduce the amplitude and frequency of the vortex rope

Methods

Global stability analysis is performed on the axisymmetric time averaged flow field (mean flow) of the 3-D numerical flow simulation, using ANSYS CFX, of a Francis turbine operating at part load conditions.

CFD Calculation



Vortex rope and Interblade vortices of the CFD calculation

The Navier-Stokes equations in cylindrical coordinates, including turbulence, are reduced to an eigenvalue problem to study the temporal evolution of small perturbations from the mean flow.

For this purpose the equations are linearized, expended in Fourier series and solved by finite element method, using FreeFEM++.

Results

Equations

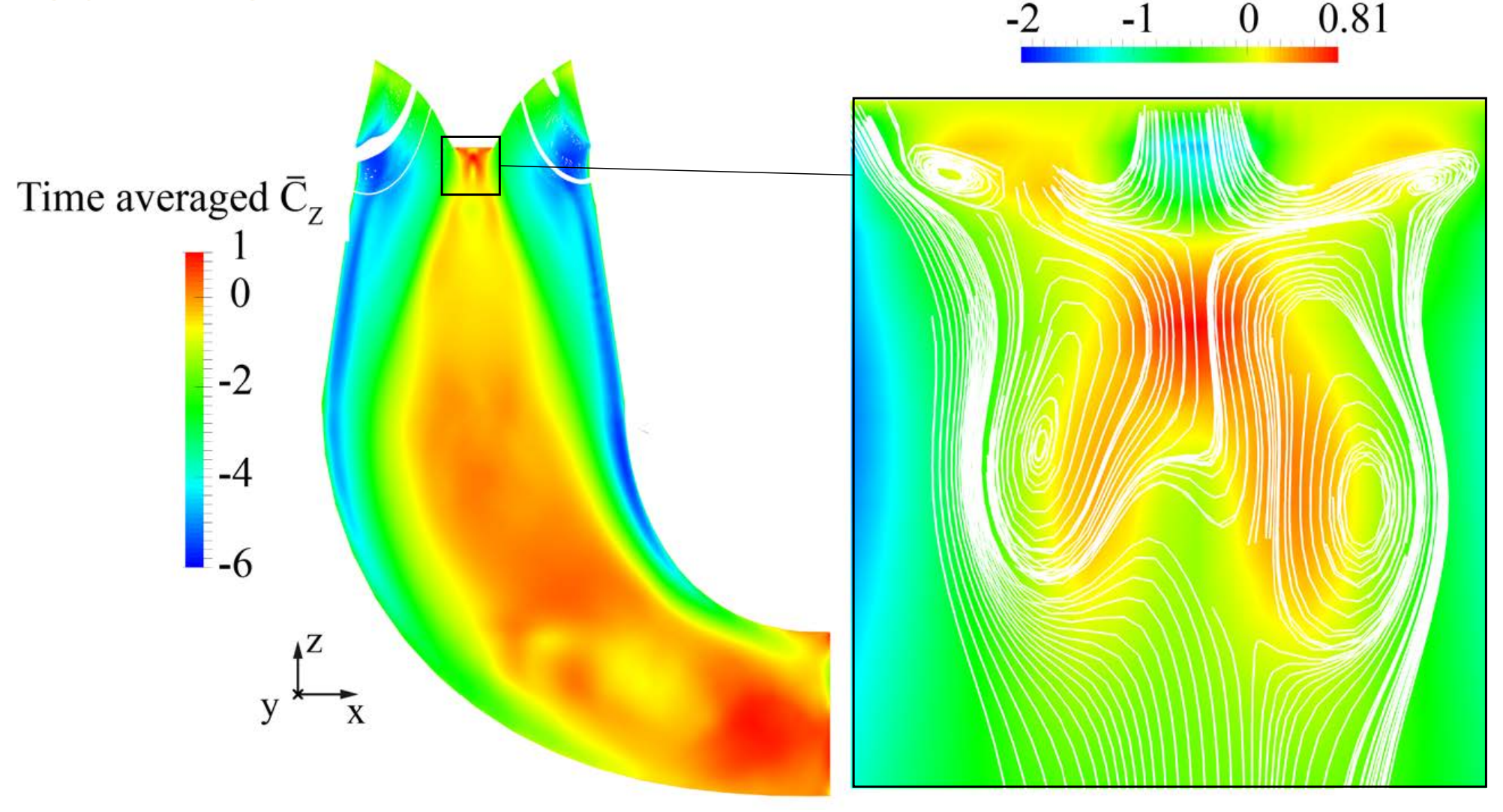
$\bar{q}$: mean flow $\quad q'$: perturbation $\quad \hat{q}$: eigen modes $\quad q = (C, \mathrm{p})$

$$q'(R,\theta,Z,t) = \hat{q}(R,Z)\exp(i(m\theta - \omega t))$$

$$\boxed{\begin{gathered}\nabla \cdot \hat{C} = 0 \\ -i\omega\hat{C} + \nabla\hat{C}\cdot\bar{C} + \nabla\bar{C}\cdot\hat{C} = -\nabla\hat{p} + \frac{1}{\mathrm{Re}}\nabla^2\hat{\mathrm{C}} + \boxed{\nabla\cdot\left(\frac{1}{\mathrm{Re}_t}(\bar{C})\left[\nabla + \nabla^T\right]\hat{C}\right)}\end{gathered}}$$

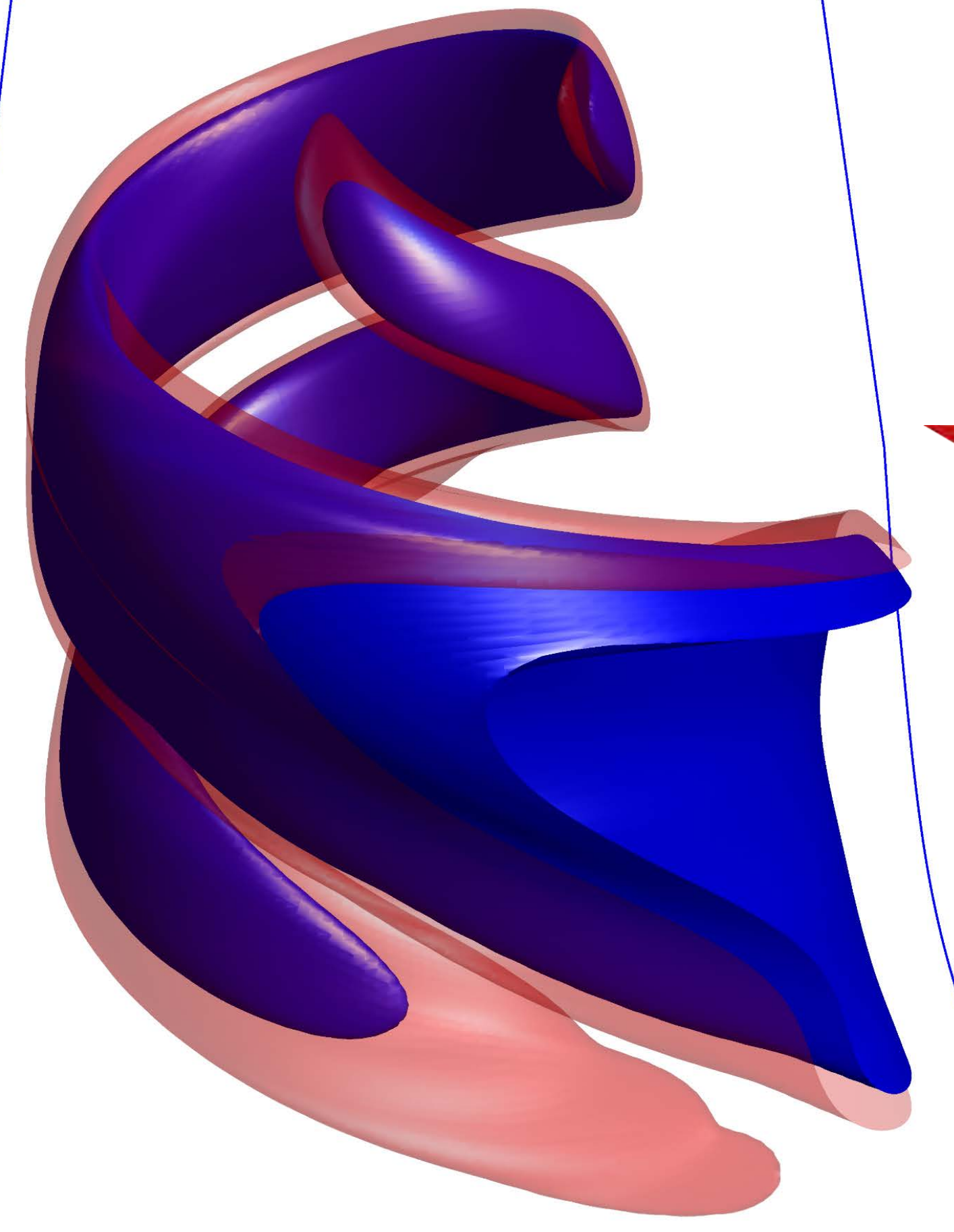
Turbulence term

Mean flow $\bar{C}$

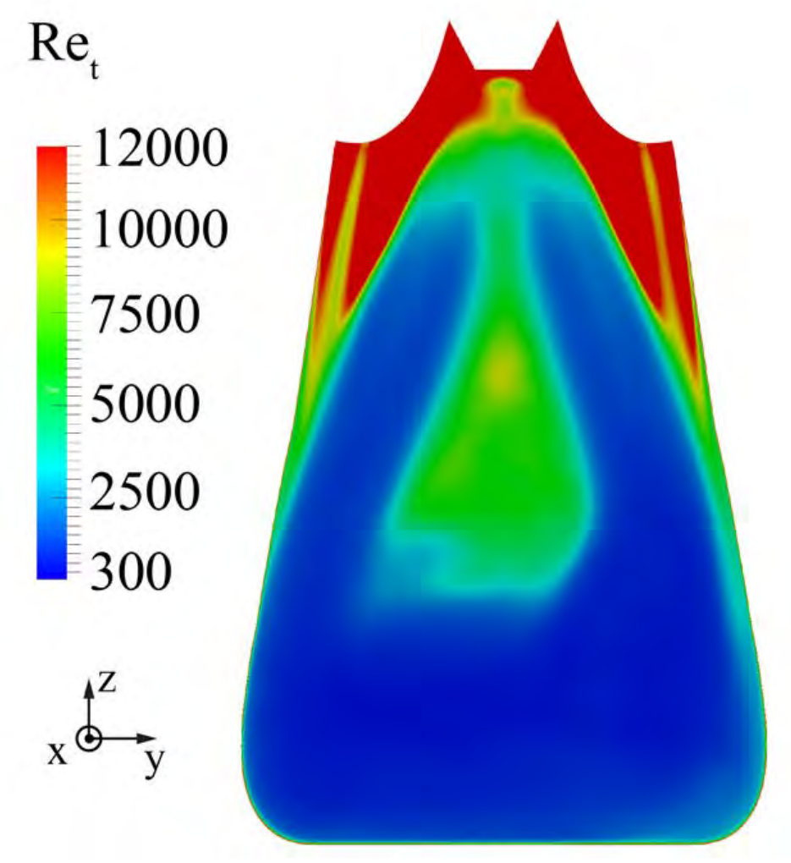


Time averaged flow field of the axial velocity of the CFD calculation and buble region

Vortex Rope, an Unstable Eigenmode

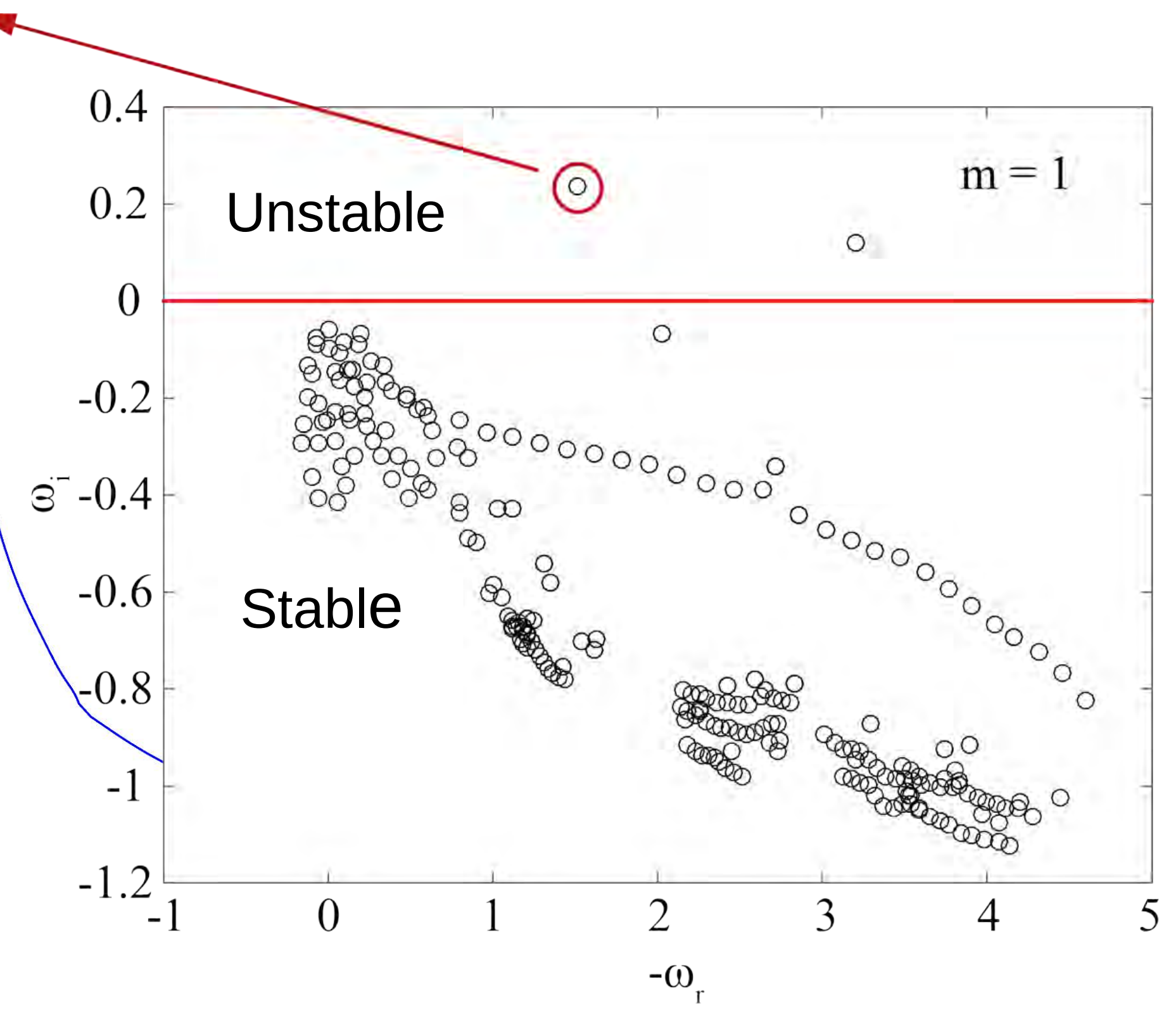


Turbulent Reynolds number Re_t



Time averaged eddy viscosity from the CFD Calculation used in the Turbulence term of the eigenvalue problem

Eigenvalues Spectrum



Accurate frequency prediction: ~20% error

Conclusion

The Francis turbine vortex rope was investigated using global stability analysis in axisymmetric coordinate systems. It was pointed out that the vortex rope is an unstable global mode where turbulent eddy viscosity is active. This eigenmode has the same axial wave number and its frequency has 20% discrepancy with the CFD frequency which is relevant for the applied framework. The remaining work concerns the sensitivity analysis and the control design.

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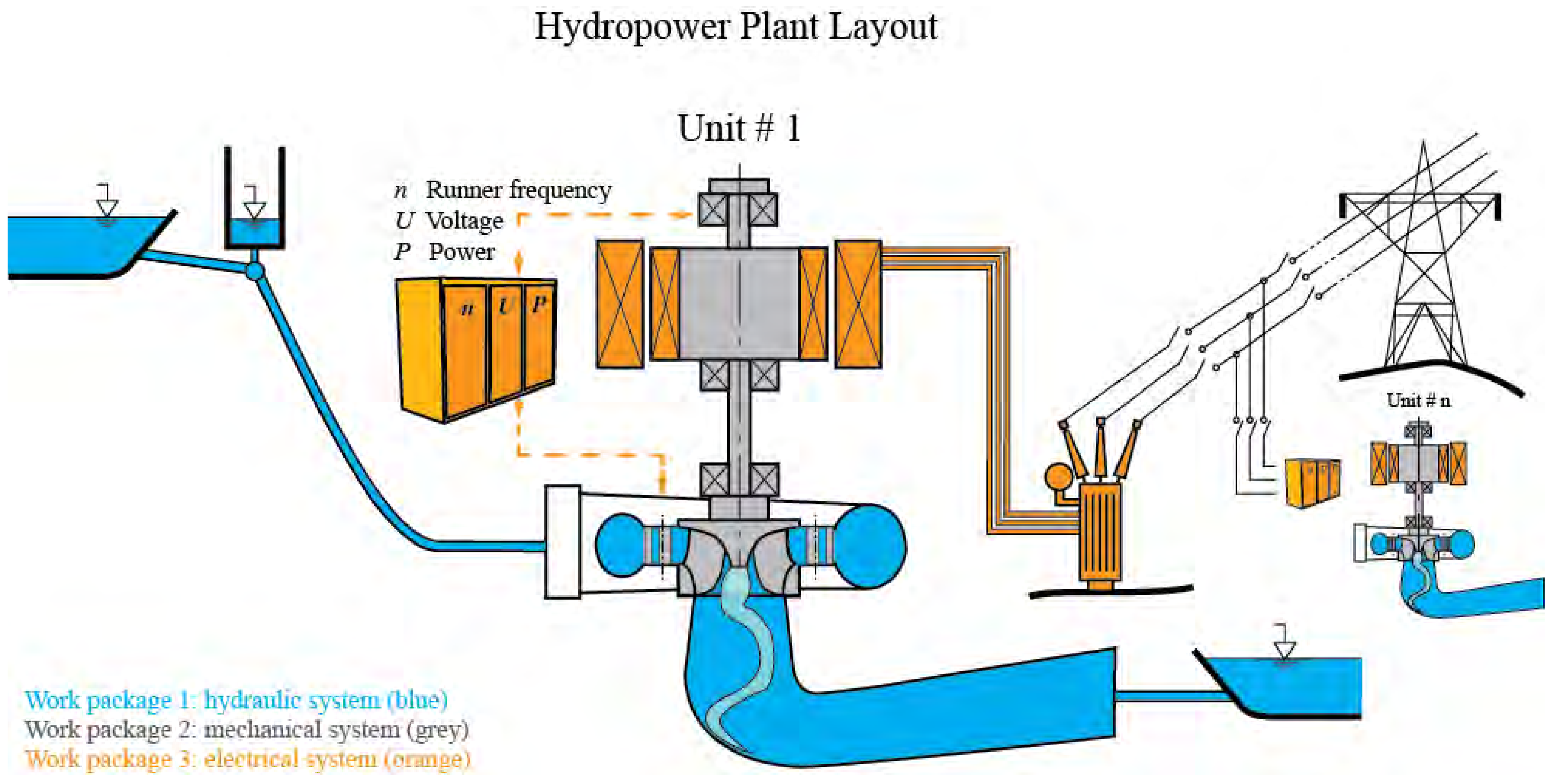
RANS computations for identification of 1-D cavitation model parameters
Application to full load cavitation vortex rope

J. Decaix[1], S. Alligné[2], A. Müller[3], C. Nicolet[2], F. Avellan[3], C. Münch[1]

1. HES-SO Valais//Wallis, Route du Rawyl 47 Sion ; 2. Power Vision Engineering Sàrl, Chemin des Champs Courbes 1, 1024 Ecublens ; 3. EPFL Laboratory for Hydraulic Machines, Avenue de Cour 33 bis, 1007 Lausanne

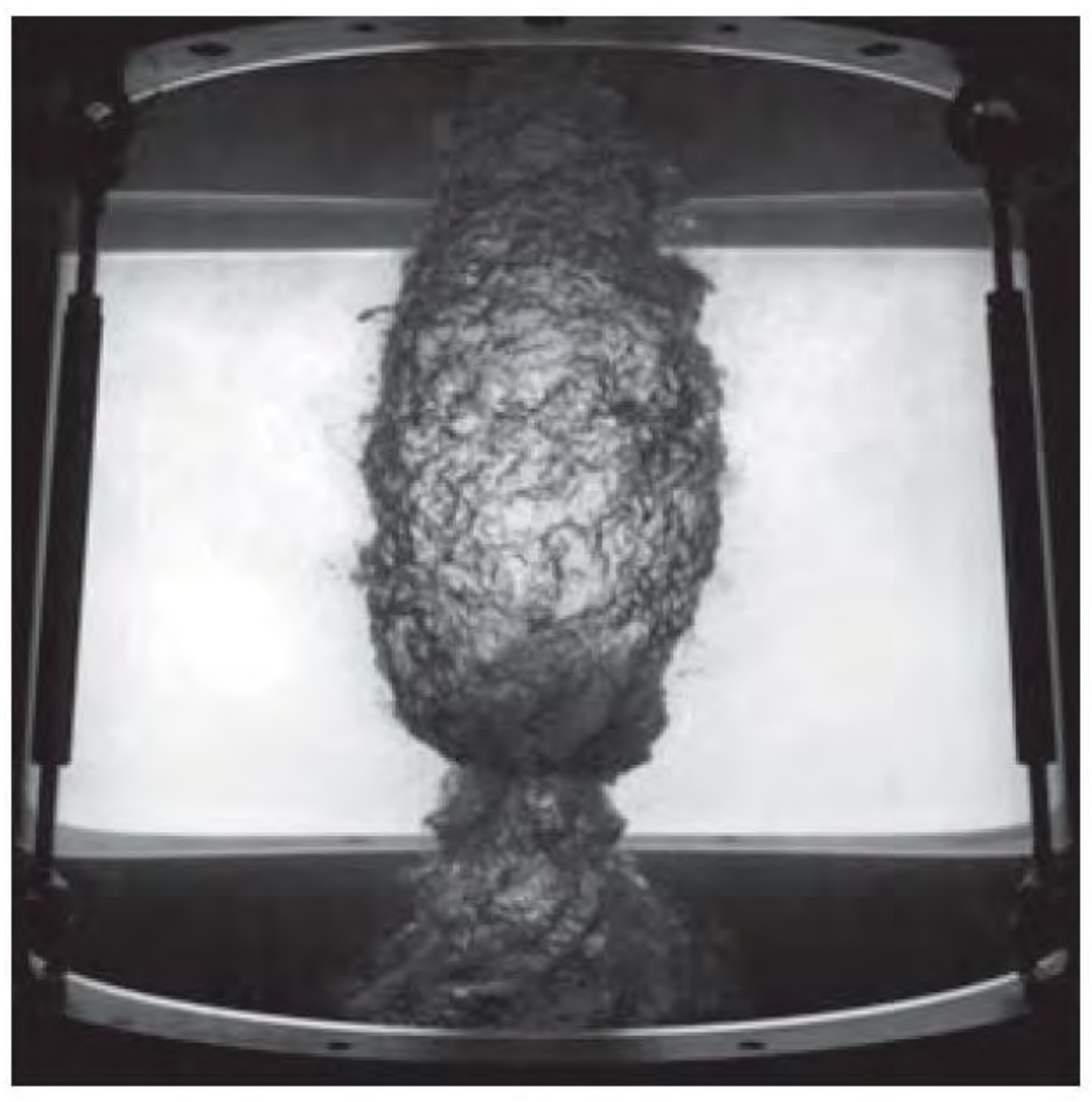
Context

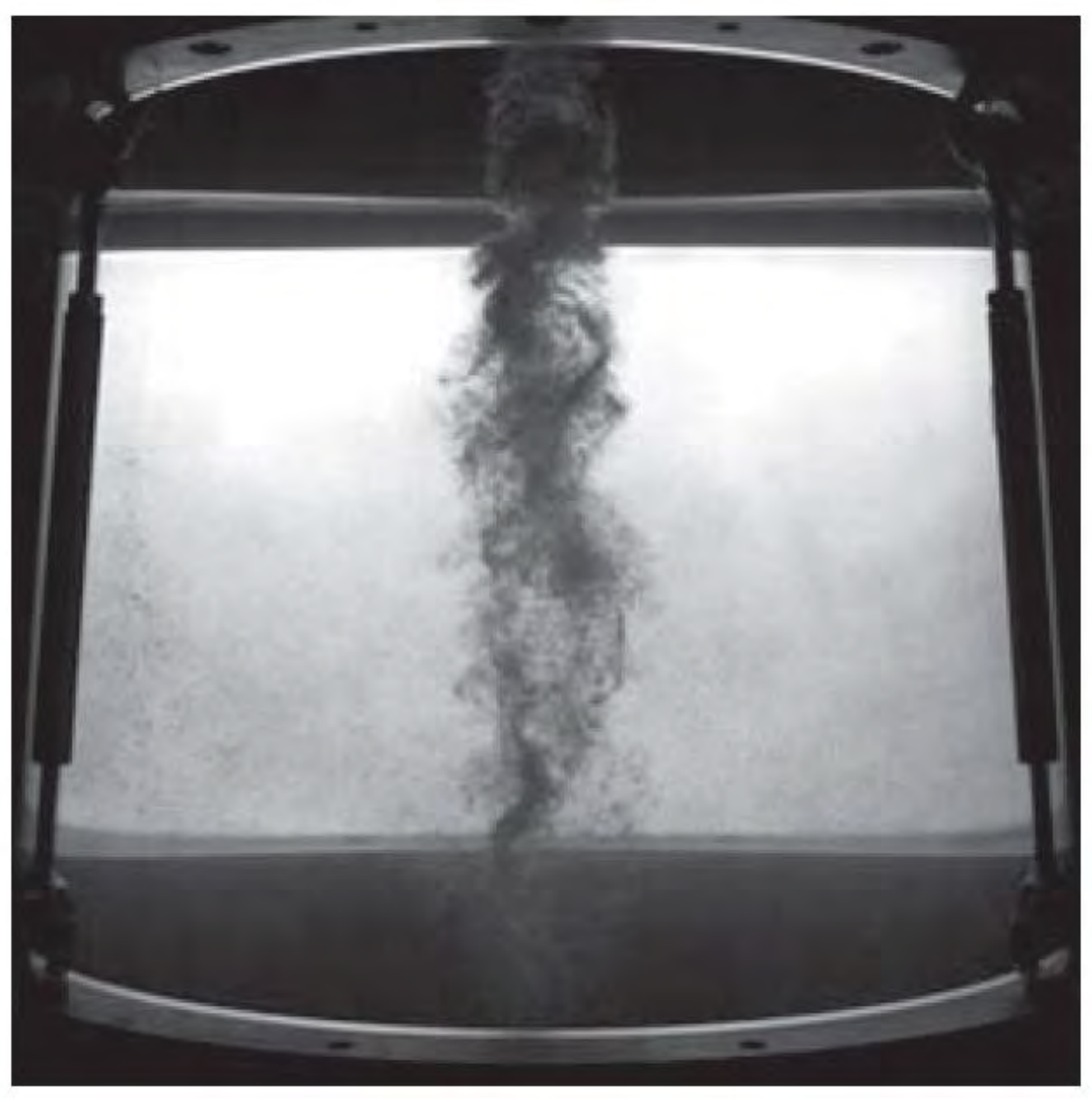
- The development of new renewable energy is related with problems of electrical grid stabilization. Hydraulic power plants are key energy resources to compensate the stochastic nature of the variable energy sources.
- Hydraulic, mechanical and electrical dynamics of hydraulic machines such as Francis turbines and reversible pump-turbine are studied under extended range of operating conditions: from deep part load to overload.
- 1-D models are useful tool to investigate the behavior of an entire hydropower plant including fluid, mechanical and electrical interactions. Such models required the calibration of several parameters. Calibration can be achieved by performing detailed 3-D CFD computations.

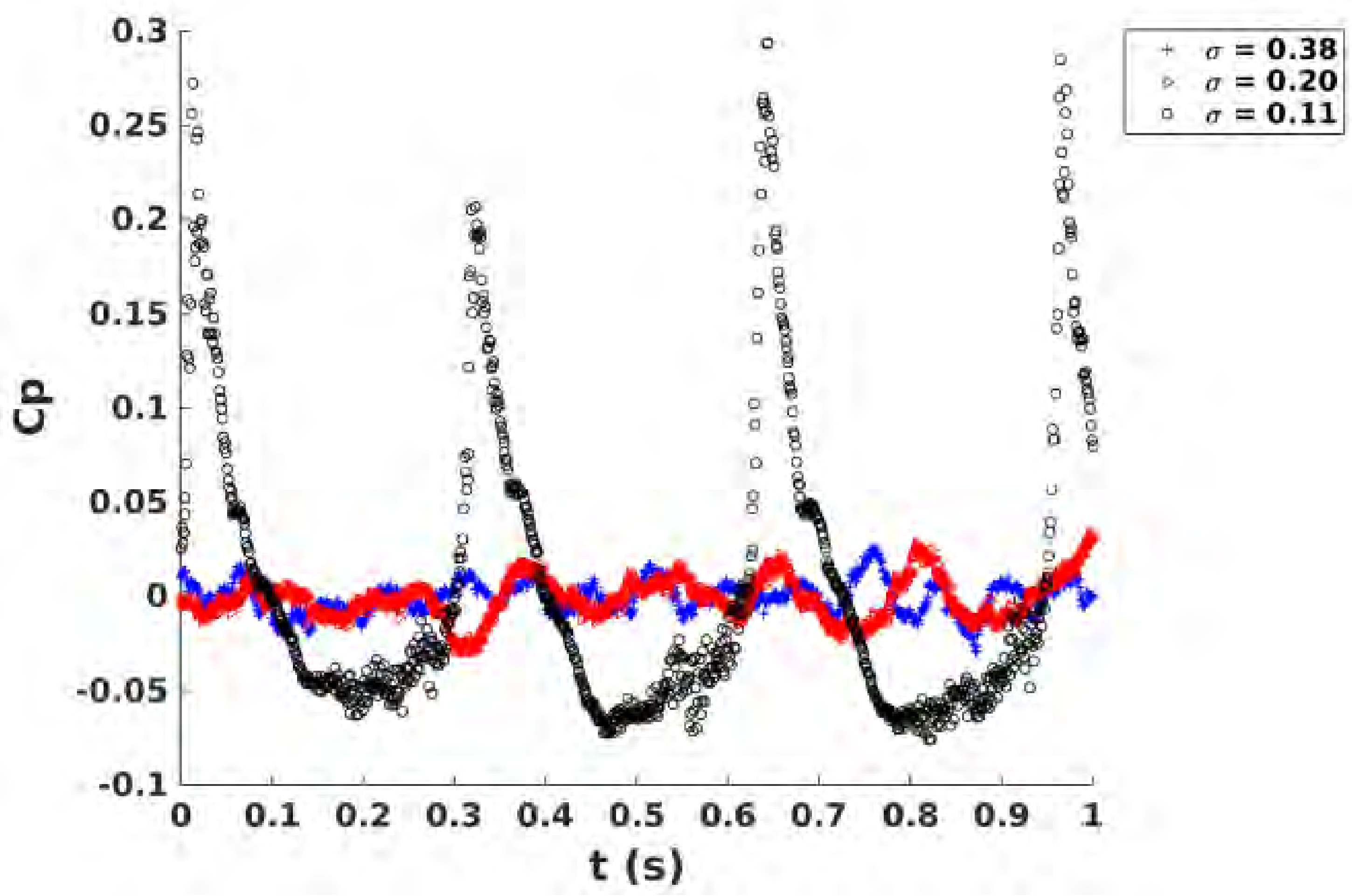


Francis turbine at full load

Running at a flow discharge larger than the flow discharge at the best efficient leads to the development of a vortex rope. At the core of the vortex rope, cavitation occurs leading in some cases to the instability of the vortex rope with strong pressure and load fluctuations.

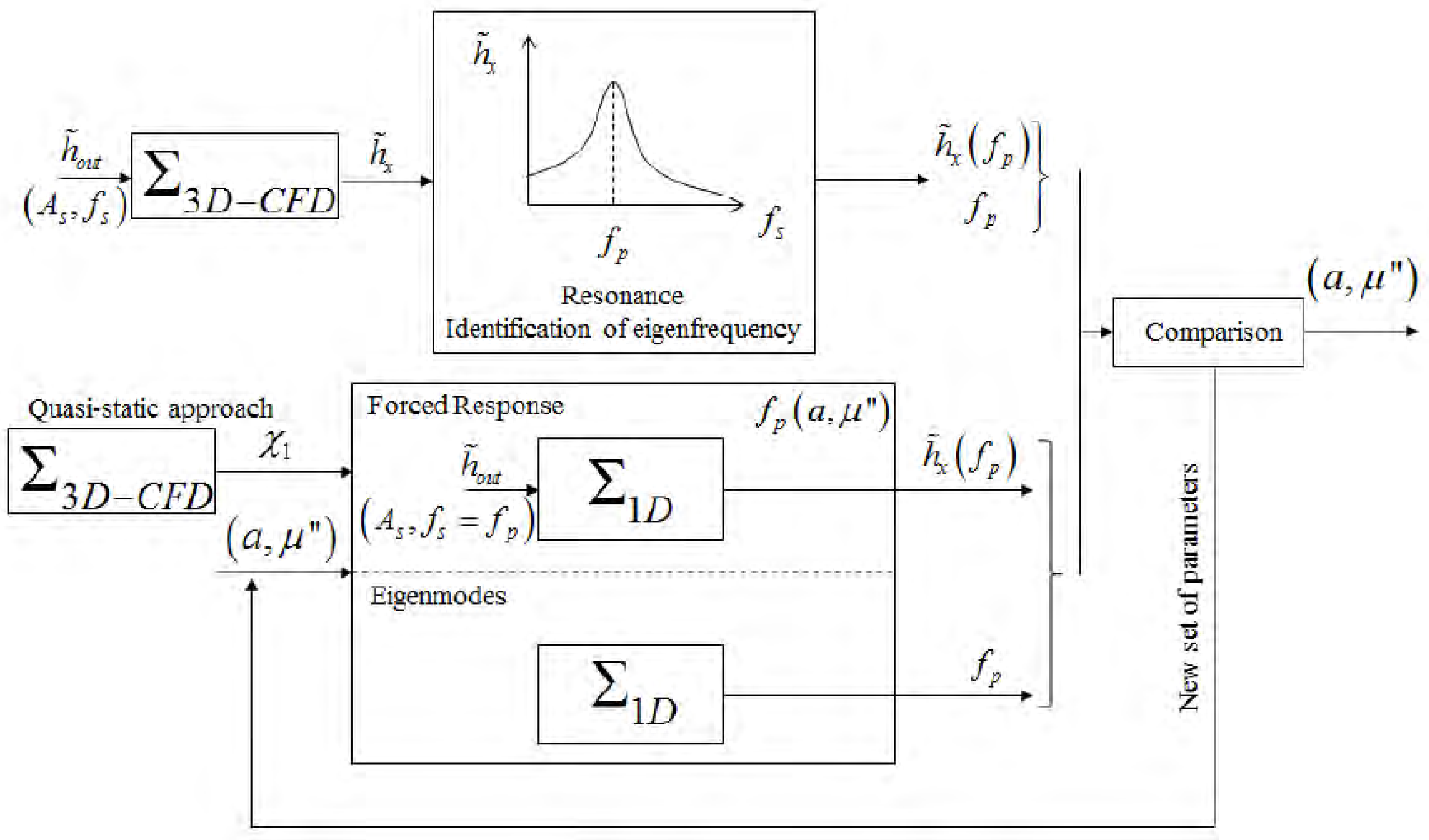




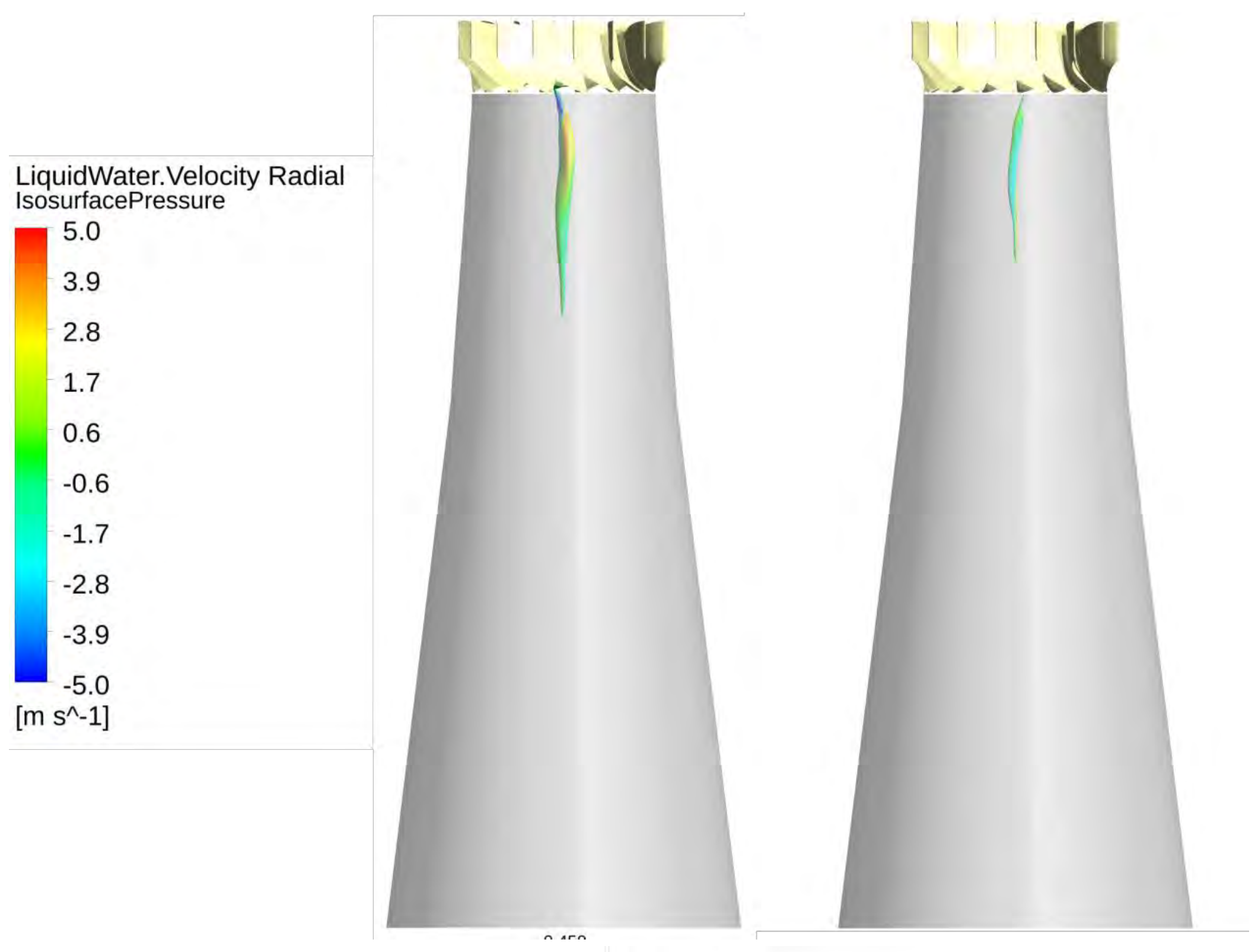


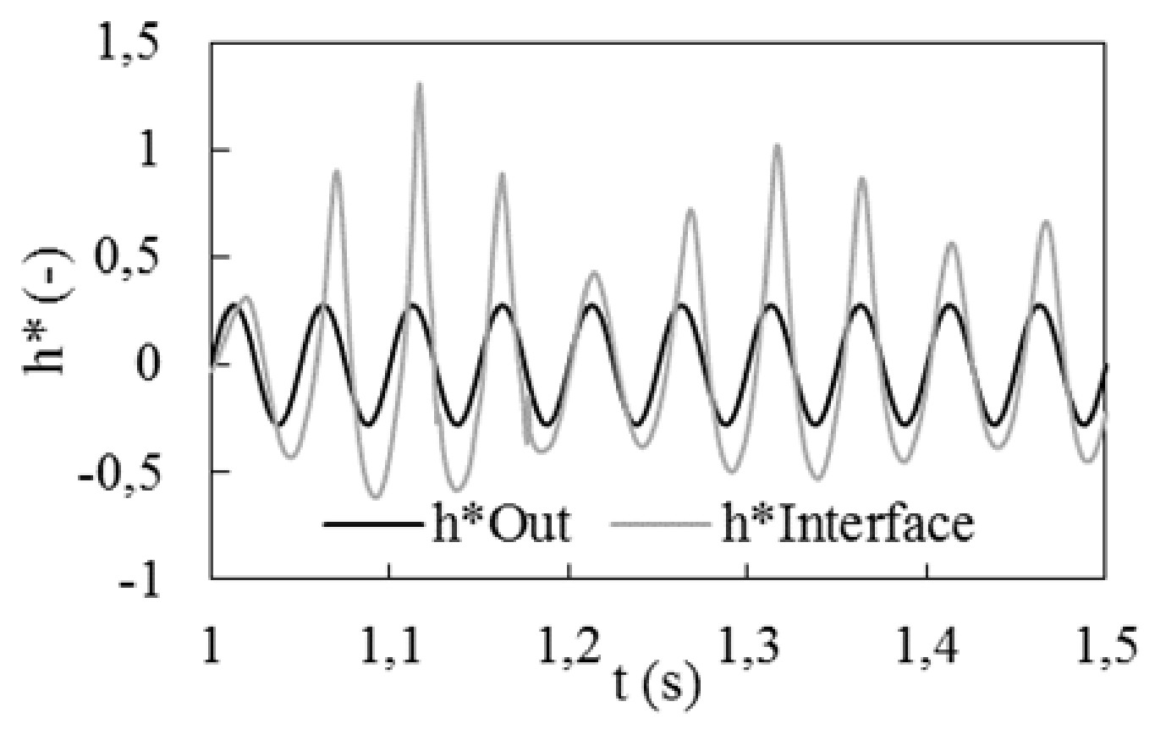
Numerical Simulations

- A simplified computational domain with only the runner and the cone of the draft tube.
- A sinusoidal pressure signal is set with at the outlet boundary.
- 3-D CFD Cavitation computations have been performed for several frequencies of the outlet pressure conditions.
- 3-D CFD results are used as objective functions for the 1-D model (SIMSEN).

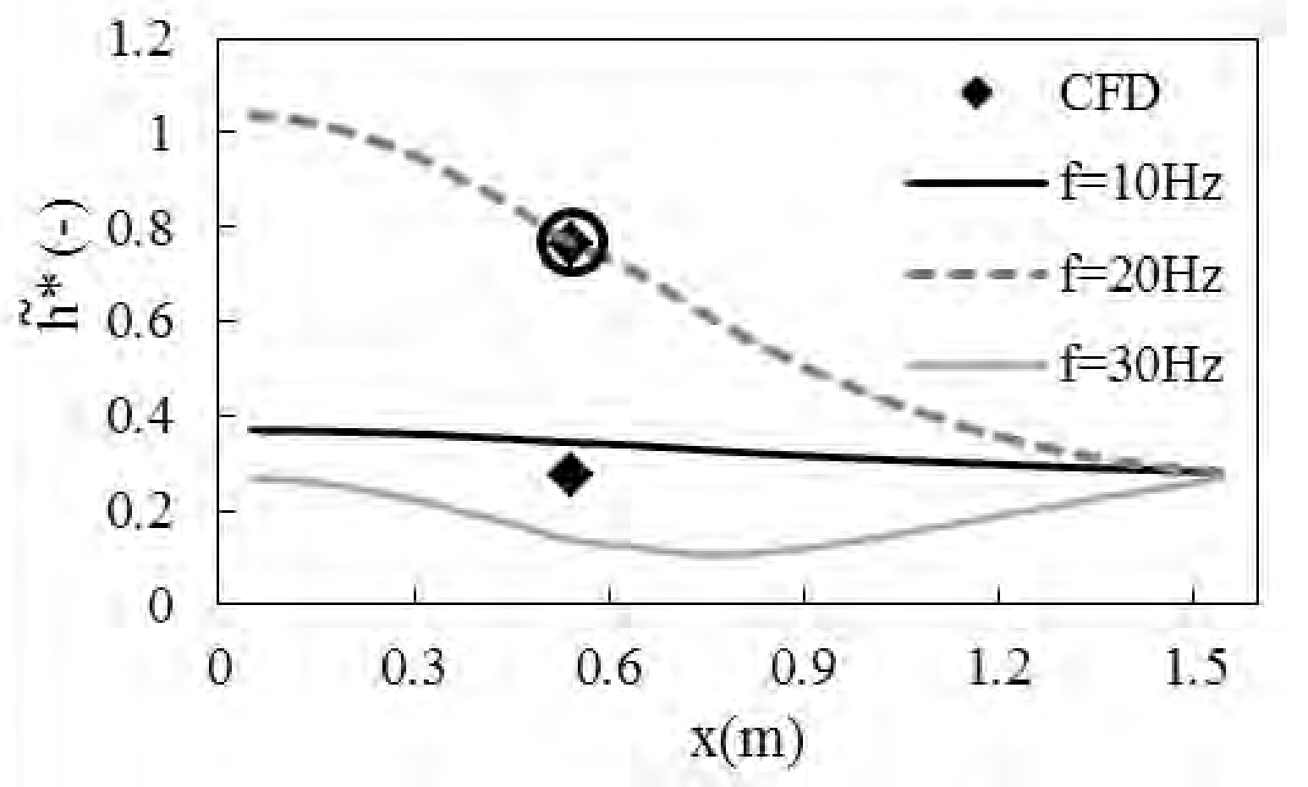


Results





Pressure fluctuations in resonance conditions obtained by CFD



Forced response of the system for different excitation frequency obtained with the 1-D model.

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Dynamic method for model testing hydraulic performance measurements

V. Hasmatuchi, A. Bosioc, S. Luisier, C. Münch-Alligné

Motivation

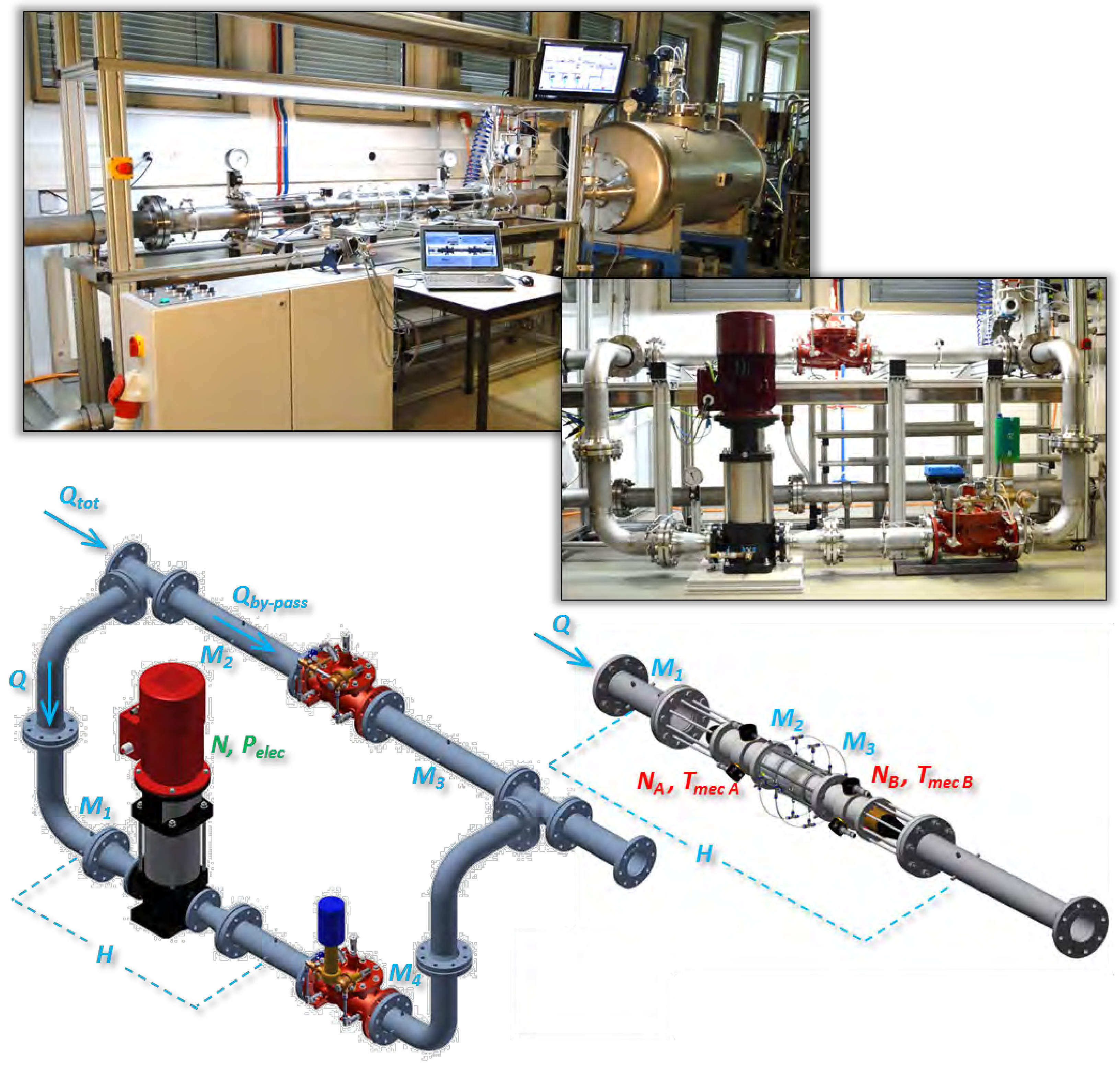
- ✓ Standard efficiency measurements on model testing: point-by-point method
  - Proved, but laborious and time expensive
  - Small hydro development: the investment is much more limited compared to large hydro
- ✓ Alternative faster solution: dynamic method
  - The "Sliding gate" dynamic method (Almquist et al. 1997) is successfully used for index testing of Francis and Kaplan units
  - Steady-state conditions must be ensured during measurements

Objective: implementation and validation of the dynamic method on model testing

Experimental setup

Case studies

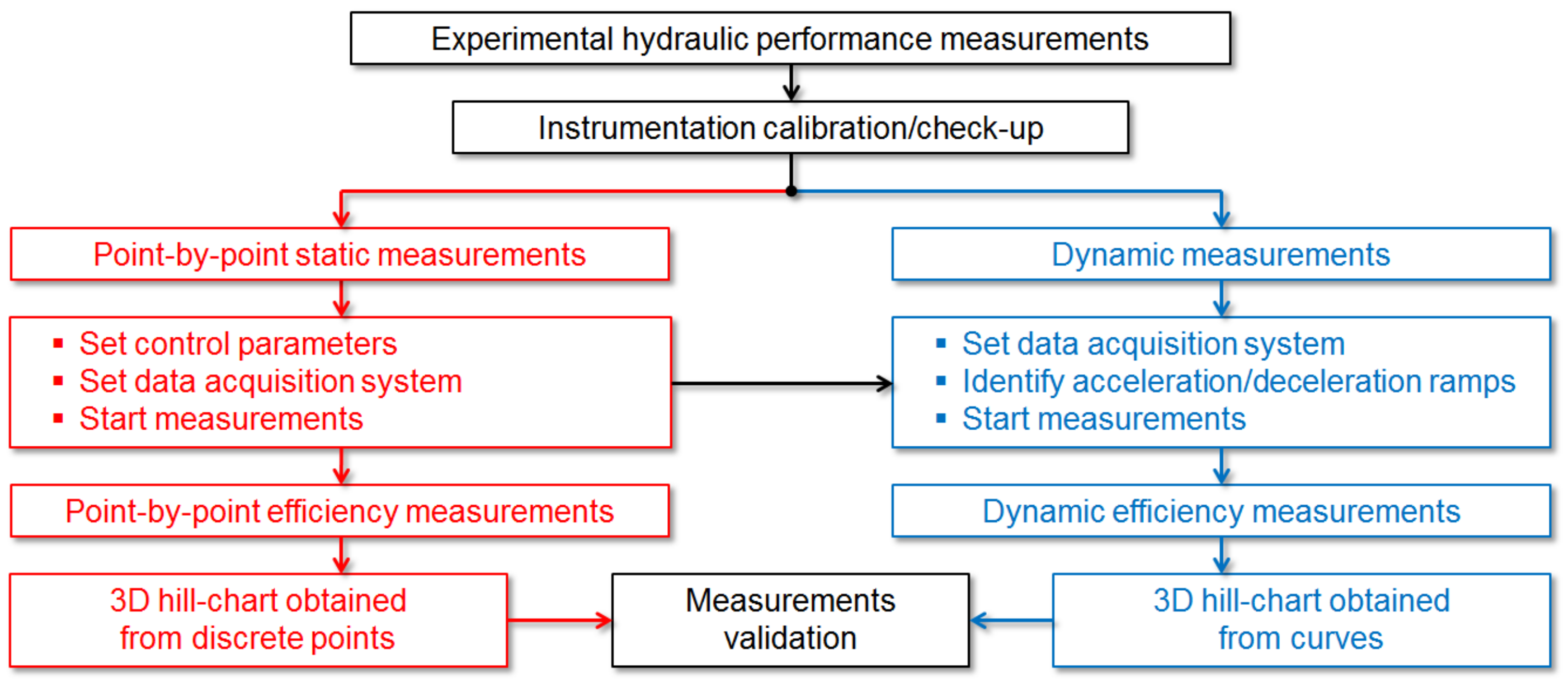
- ✓ 2.65 kW axial double-regulated counter-rotating turbine with variable speed
- ✓ 11 kW multi-stage pump-as-turbine (PAT) with variable speed.



Instrumentation

- ✓ Experimental facility:
  - HES-SO VS hydraulic test rig
  - instrumented in accordance with the IEC 60193 recommendations
- ✓ Dynamic method instrumentation:
  - based on the same sensors used for static measurements
  - a second digitizer is employed to acquire synchronised signals of all employed sensors

Methodology



Experimental hydraulic performance measurements

Instrumentation calibration/check-up

Point-by-point static measurements

- Set control parameters
- Set data acquisition system
- Start measurements

Point-by-point efficiency measurements

3D hill-chart obtained from discrete points

Dynamic measurements

- Set data acquisition system
- Identify acceleration/deceleration ramps
- Start measurements

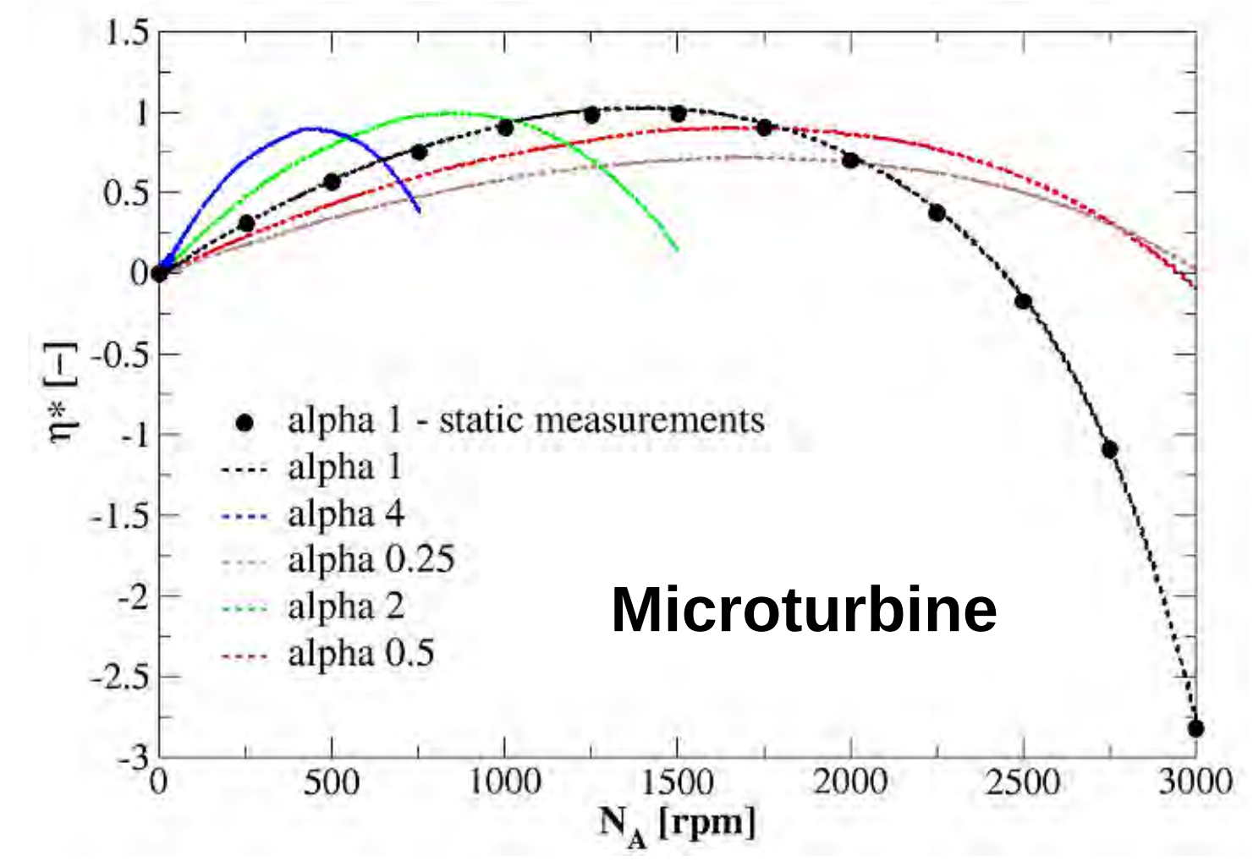
Dynamic efficiency measurements

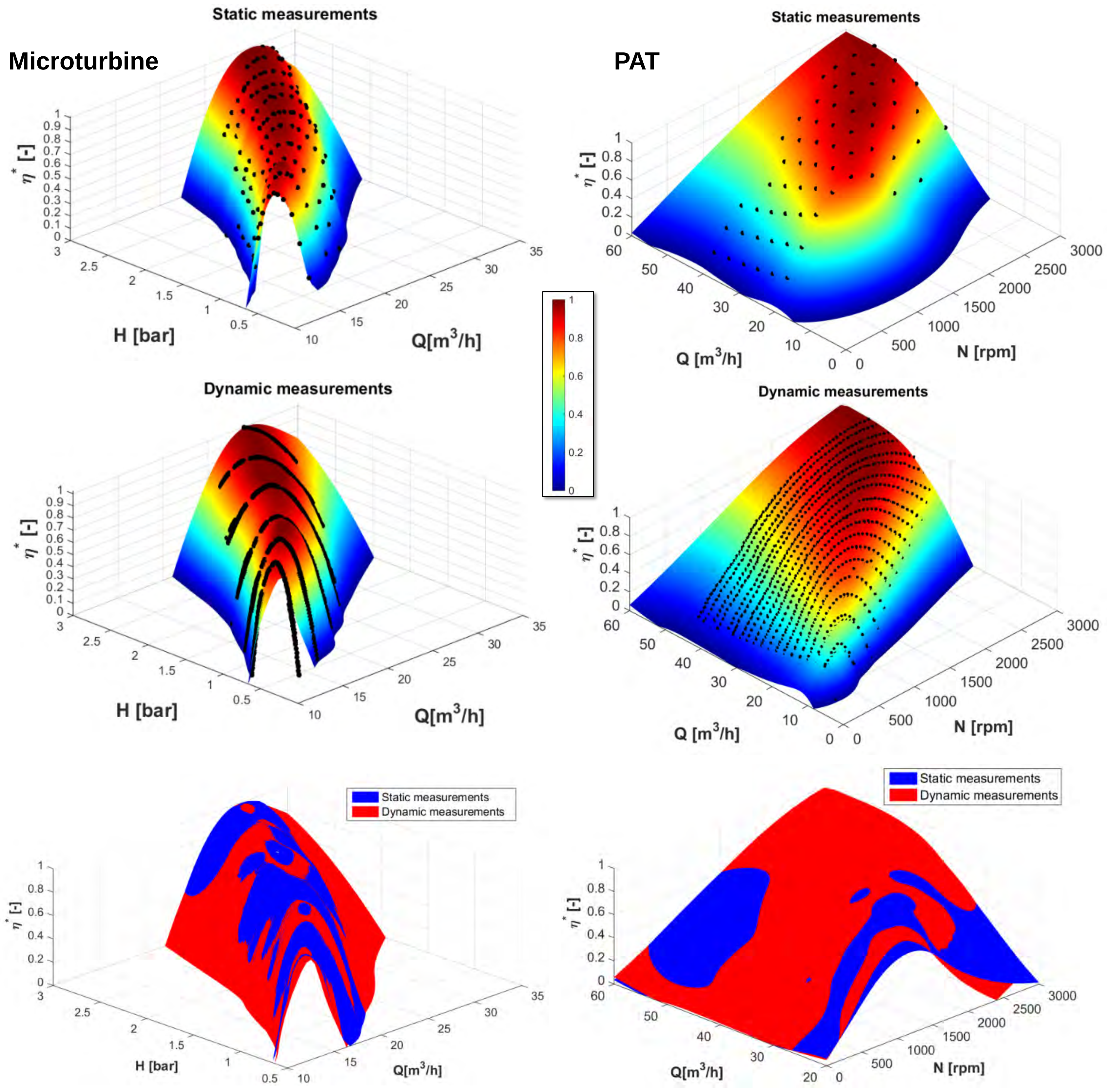
3D hill-chart obtained from curves

Measurements validation

Results

- ✓ Resulting efficiency measurements at fixed inflow conditions
- ✓ Resulting full 3D efficiency hill-charts
- ✓ Static vs dynamic methods: satisfactory qualitative and quantitative match between the two methods





Conclusions & perspectives

- ✓ The so-called "sliding gate" dynamic method has been adapted, implemented and successfully tested on two model testing cases;
- ✓ Optimal acceleration/deceleration ramp speed of the runner(s) has been previously identified;
- ✓ The new implemented dynamic method can reduce (by a factor of up to ten) the time necessary to measure the efficiency characteristics on turbomachinery model testing.
- ✓ Implementation/validation of the dynamic measurements method on more testing models;
- ✓ Application of the dynamic method to detect hydrodynamic instabilities within the operating range of a turbomachine or for fast detection of hydrodynamic instability operating regions.

Acknowledgements

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Partners of Hydro VS and Savièse projects

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Open-air laboratory for a new isokinetic turbine prototype

V. Hasmatuchi, A. Gaspoz, L. Rapillard, N. Brunner, S. Richard, S. Chevailler, C. Münch-Alligné

Objectives of this “pilot & demonstrator” project

- ✓ Design and construction of a first prototype of isokinetic turbine for artificial channels with a power of 1 kW
- ✓ Evaluation of its hydraulic performances in the tailrace canal of the Lavey run-of-river powerplant (Rhône river)
- ✓ Validation of the numerical simulation results
- ✓ Preparation of an industrialization phase to exploit this energetic potential in Switzerland and abroad

Estimation of artificial waterways energetic potential

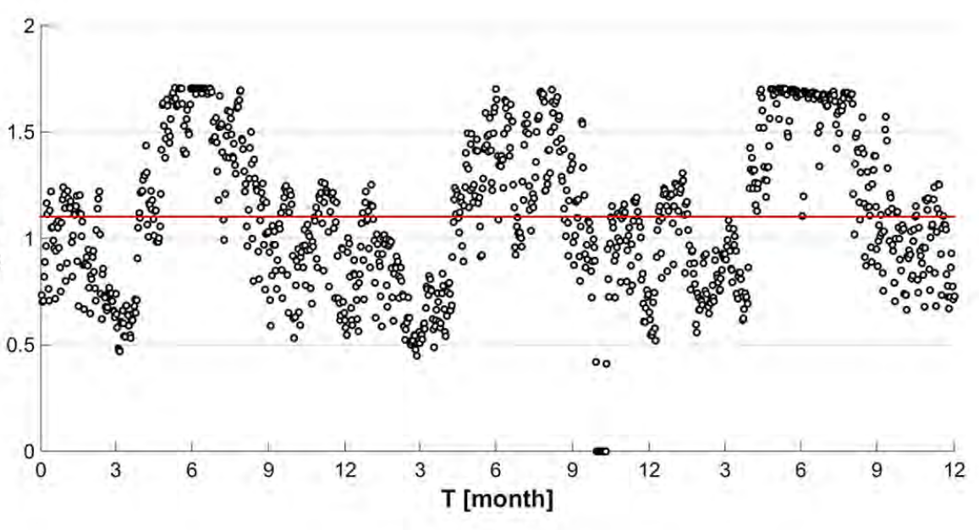
		Hydroelectricity statistics		Isokinetic energy potential of tailrace canals	
	Type of powerplant	**Installed power [MW]**	**Annual production [GWh]**	**Installed power [kW]**	**Annual production [MWh]**
Lavey	**Run-of-river**	90	400	25	140
Suisse	**Run-of-river**	3854	17’022	1’070	5’957
	Storage	8'081	17’297	2’244	6’053
	Pumped-storage	1'383	1’594	0	0
	Total	**13’318**	**35’908**	**3’314**	**12’010**

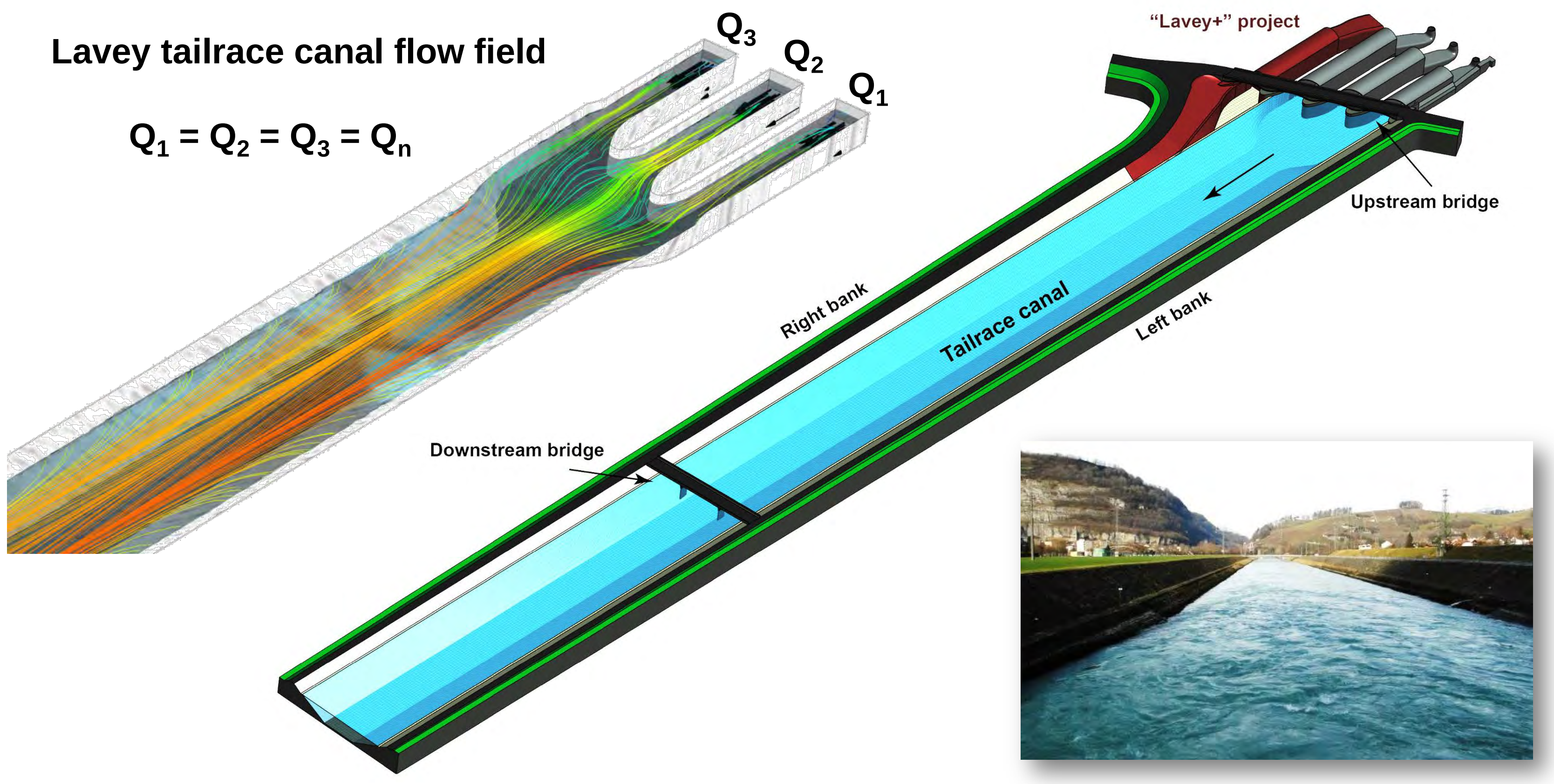
Estimation of Swiss small-hydro potential: 1.3 TWh

1% of small-hydro potential

Pilot site

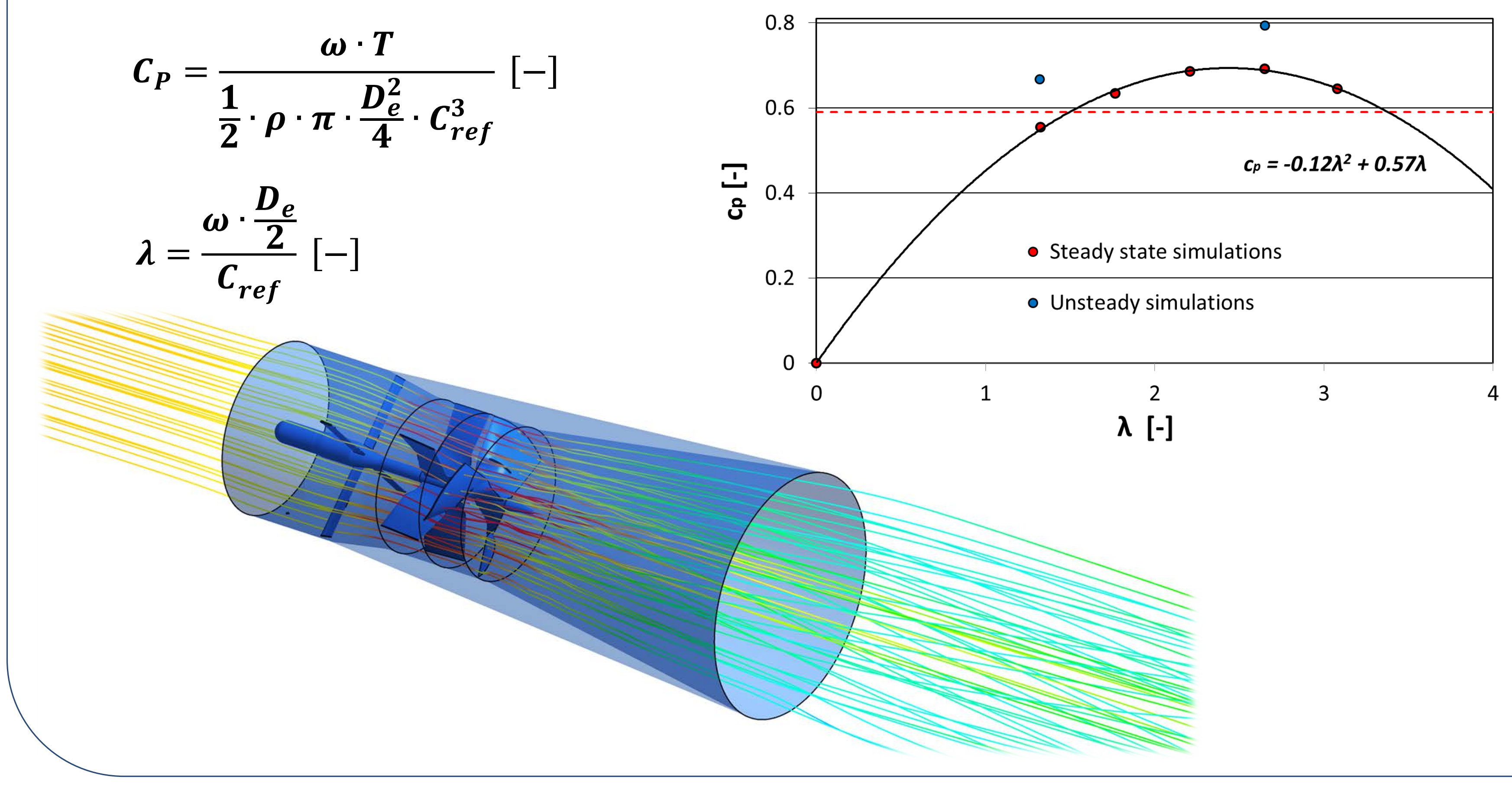
- ✓ Tailrace canal of the Lavey run-of-river power plant (Rhône River)
- ✓ Free-surface flow numerical simulations been performed to investigate its isokinetic potential
- ✓ Numerical simulations validated with in situ velocity measurements
- ✓ Potential of mean flow velocity: 0.5 ÷ 1.7 m/s
- ✓ Nominal mean flow velocity : 1.4 m/s





Hydraulic profile design and optimisation

- ✓ Hydraulic profile of a 1 kW turbine optimized with steady incompressible monophasic turbulent flow numerical simulations
- ✓ 5 stator blades and 3 runner blades
- ✓ Convergent-divergent duct to exceed the Betz limit

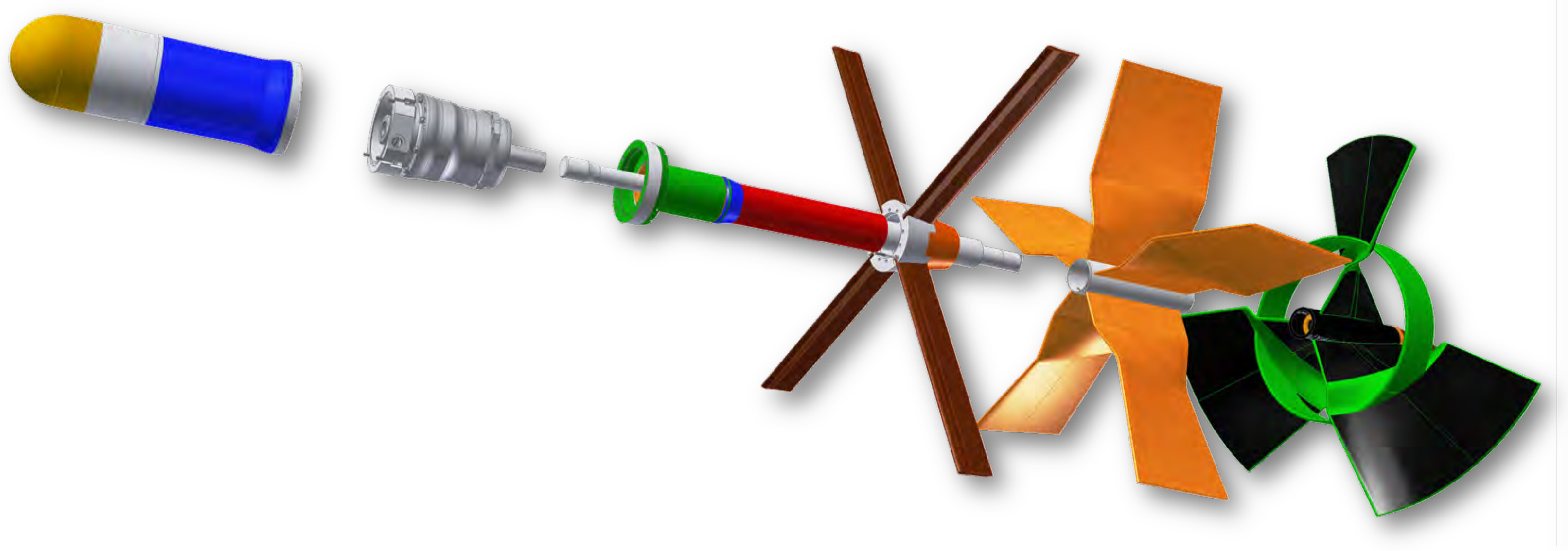


$$C_P = \frac{\omega \cdot T}{\frac{1}{2} \cdot \rho \cdot \pi \cdot \frac{D_e^2}{4} \cdot C_{ref}^3} \; [-]$$

$$\lambda = \frac{\omega \cdot \frac{D_e}{2}}{C_{ref}} \; [-]$$

Electro-mechanical concept

- ✓ Sealed bulb housing including the variable speed generator, the encoder, the speed multiplier and the mechanical coupling
- ✓ 1kW compact permanent magnet synchronous generator
- ✓ Coaxial gear speed multiplier with a factor of 1:16
- ✓ Mechanical shaft sealing: resistant to suspended sediment conditions

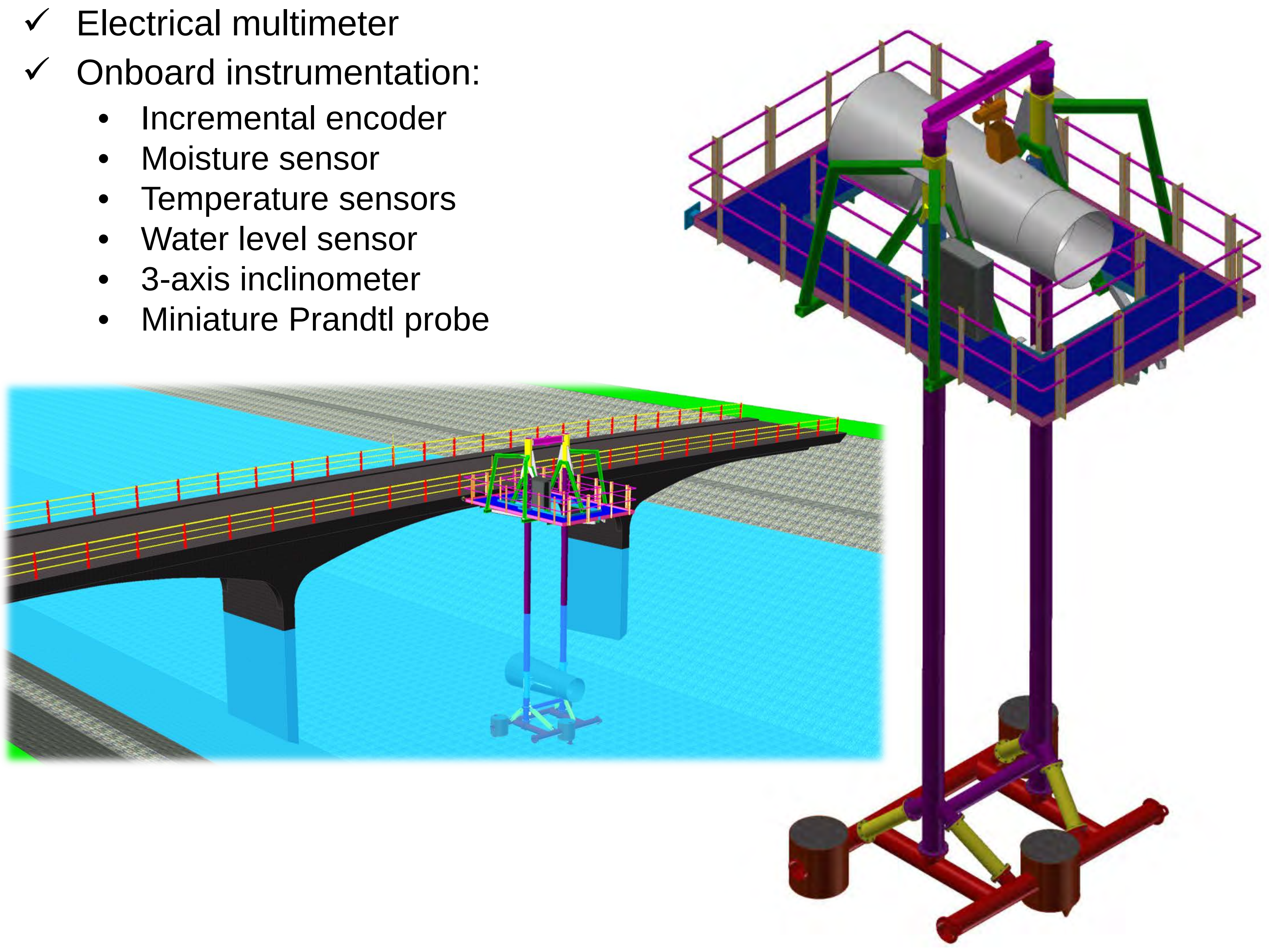


Open-air testing platform

- ✓ Dedicated to hydraulic performance measurements on isokinetic turbine prototype
- ✓ Allows the immersion of the prototype at the desired water depth
- ✓ Give an easy and secured access to the machine for handling, instrumentation and control.

Instrumentation:

- ✓ Acquisition/control system
- ✓ River boat equipped with an ADCP system
- ✓ Electrical multimeter
- ✓ Onboard instrumentation:
  - Incremental encoder
  - Moisture sensor
  - Temperature sensors
  - Water level sensor
  - 3-axis inclinometer
  - Miniature Prandtl probe



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Partners of the Hydro VS – WP4 project

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Experimental investigation of a pump-as-turbine (PAT) to recover the energy lost in drinking water networks

V. Hasmatuchi, S. Luisier, C. Cachelin, C. Münch-Allingé

Objective

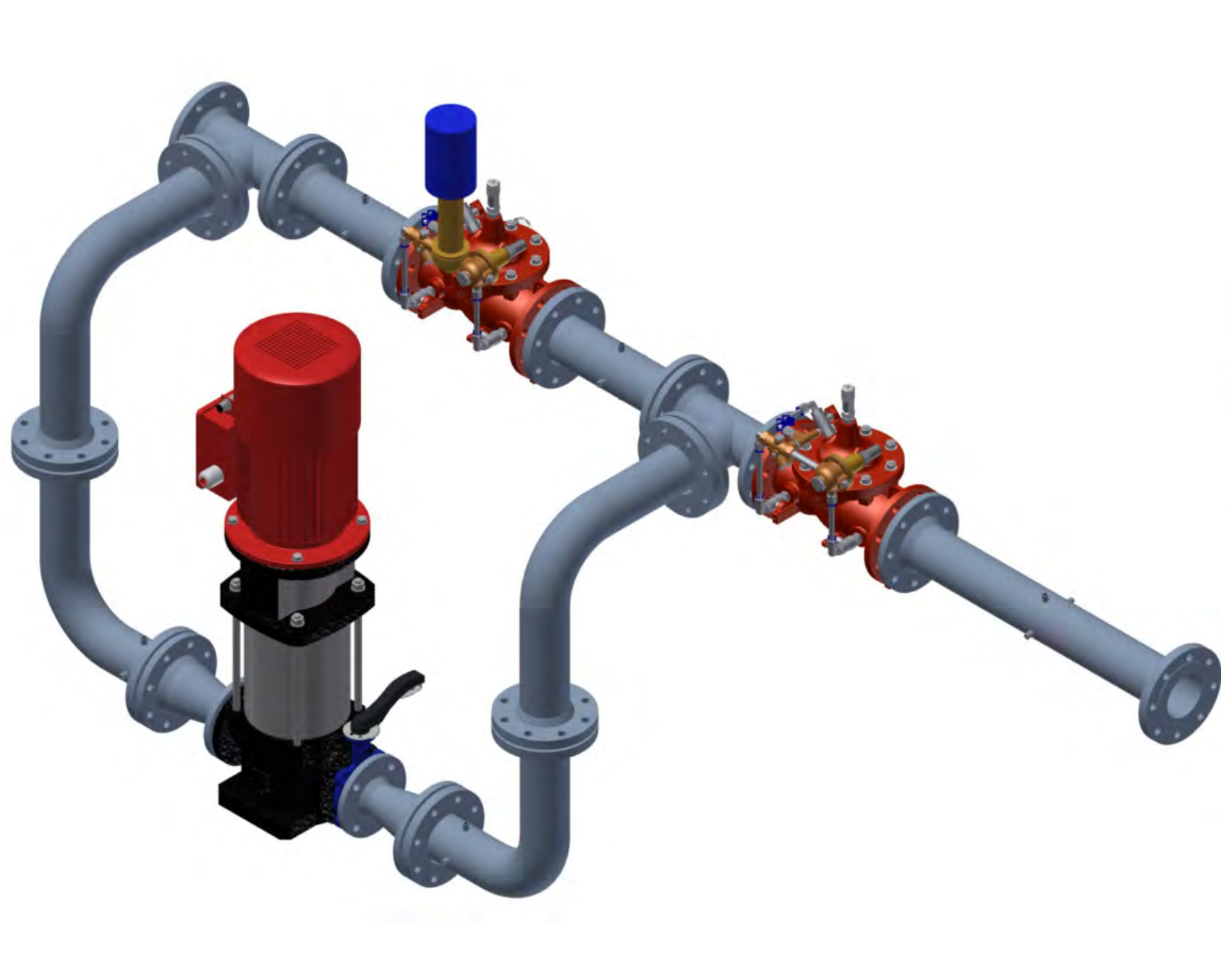
The project focuses on the experimental investigation of a standard multi-stage pump used as turbine to recover the energy lost in a relief valve of a drinking water supply network.

Main project steps:

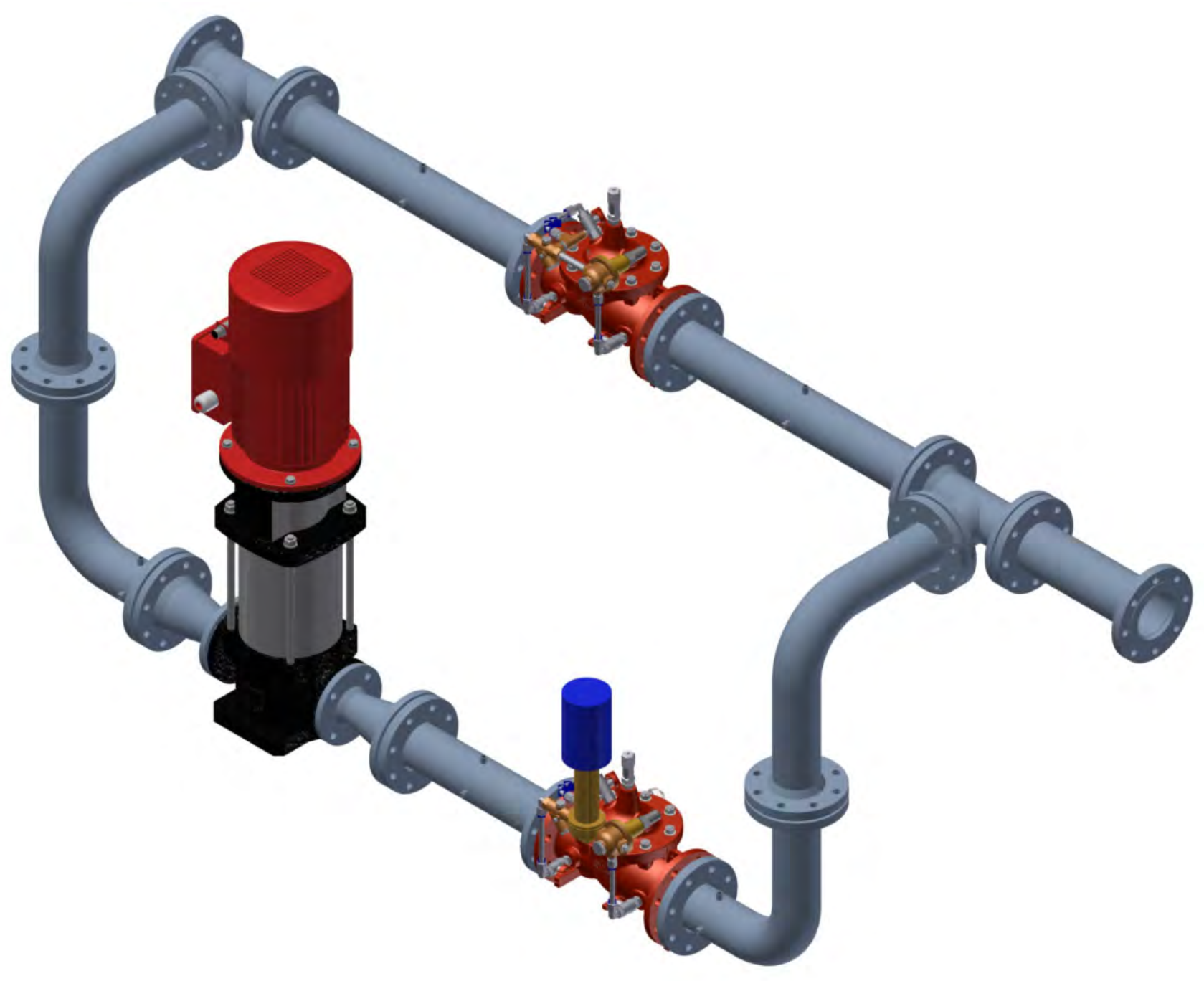
- ✓ Study of installation of a pump-as-turbine along with a regulation valve on the Savièse (Switzerland) pilot site;
- ✓ Design and manufacturing of two possible setting configurations (in series and in parallel), including a relief valve, a pump-as-turbine and a regulation valve;
- ✓ Experimental measurements campaign on the parallel version installed in the HES-SO Valais//Wallis universal hydraulic test rig.

Possible setting solutions

“Serial connection”



“Parallel connection”

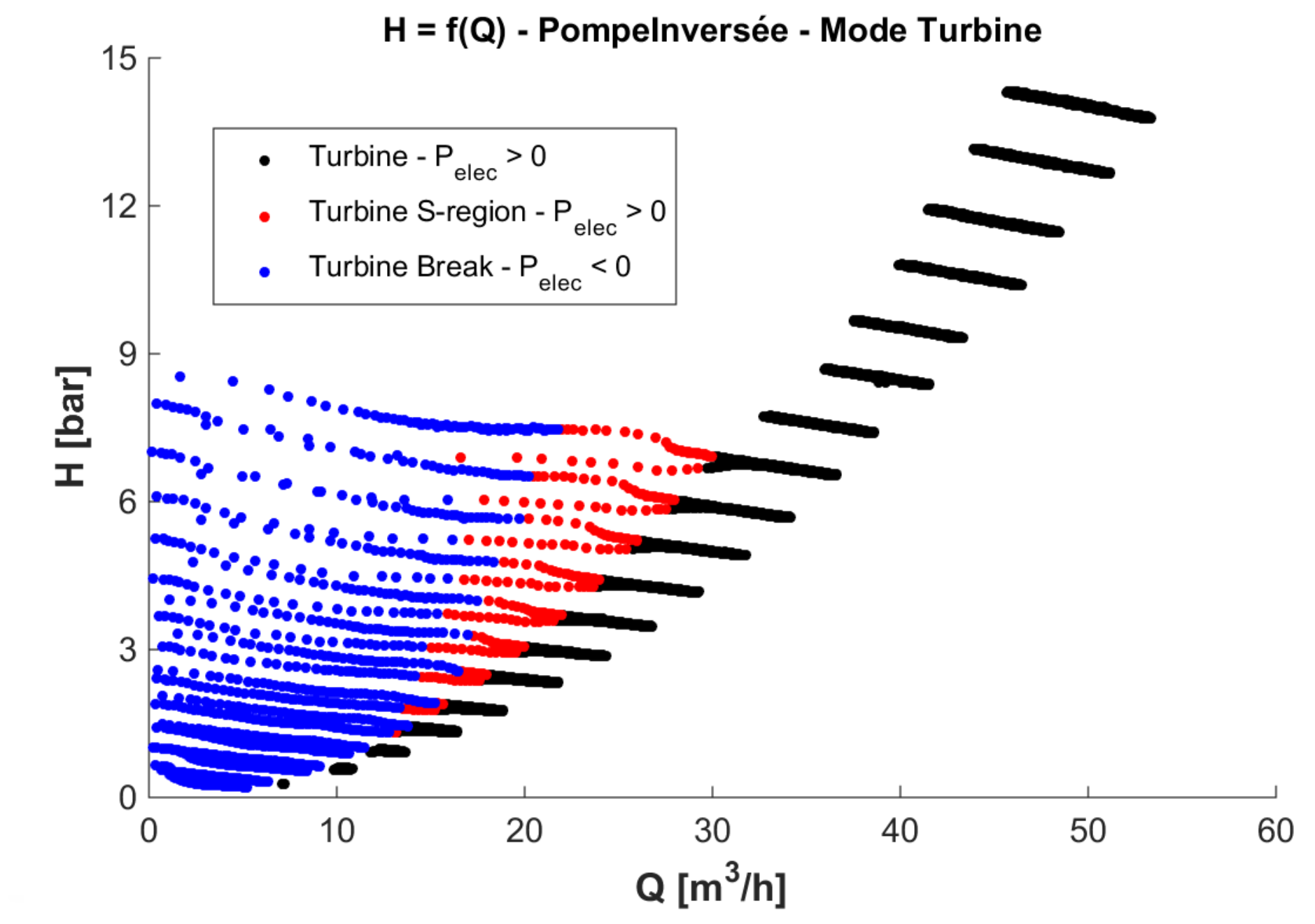


Experimental setup and instrumentation

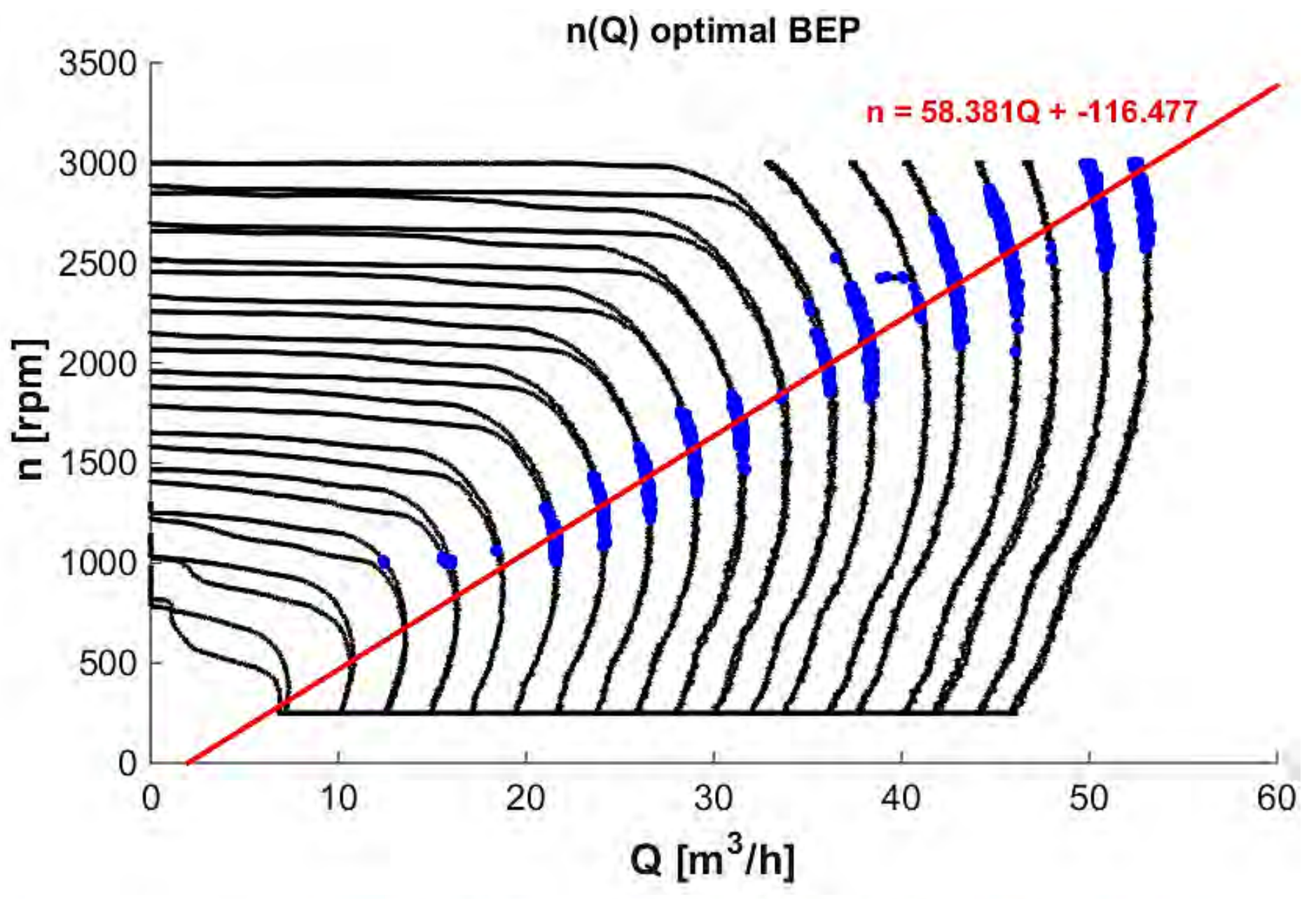
- ✓ Main components of the system:
  - Ebara EVMG32 5-0F5/11 pump as turbine – DN65, 5-stages
  - Leroy-Sommer LSRPM 132 M generator – 15.8 kW, 3000 rpm
  - ClaVal 90-G1E-01/KCOS relief valve - DN100
  - ClaVal PCM 49E-G1E-93/H1/KCOSX pressure reducing valve with actuated pilot – DN100
- ✓ Connection scheme: “parallel” - similar with the one of the pilot site
- ✓ Instrumentation:
  - Performed in accordance with the IEC 60193 standard
  - List of main employed instruments:

Measured quantity	Sensor type	Range	Precision
Discharge, **Q**	Electromagnetic flowmeter	0..±60 [m^3/h]	± 0.5 [%]
Head, **H**	Differential pressure sensor	0..16 [bar]	± 0.1 [%]
Setting level, **H_s**	Differential pressure sensor	0..5 [bar]	± 0.2 [%]
Absolute static pressure, **$M_{1,2,3}$**	Capacitive pressure transducer	0..10/20 [bar]	± 0.05 [%]
Electrical power, **P_{elec}**	Electrical multimeter	0..1000 [V_{trms}] 0..32 [A_{trms}]	± 0.03 [%]
Turbine rotational speed, **n**	UVW incremental encoder	0..6000 [rpm]	4096 [ppr]

Measured characteristic curves (turbine mode)

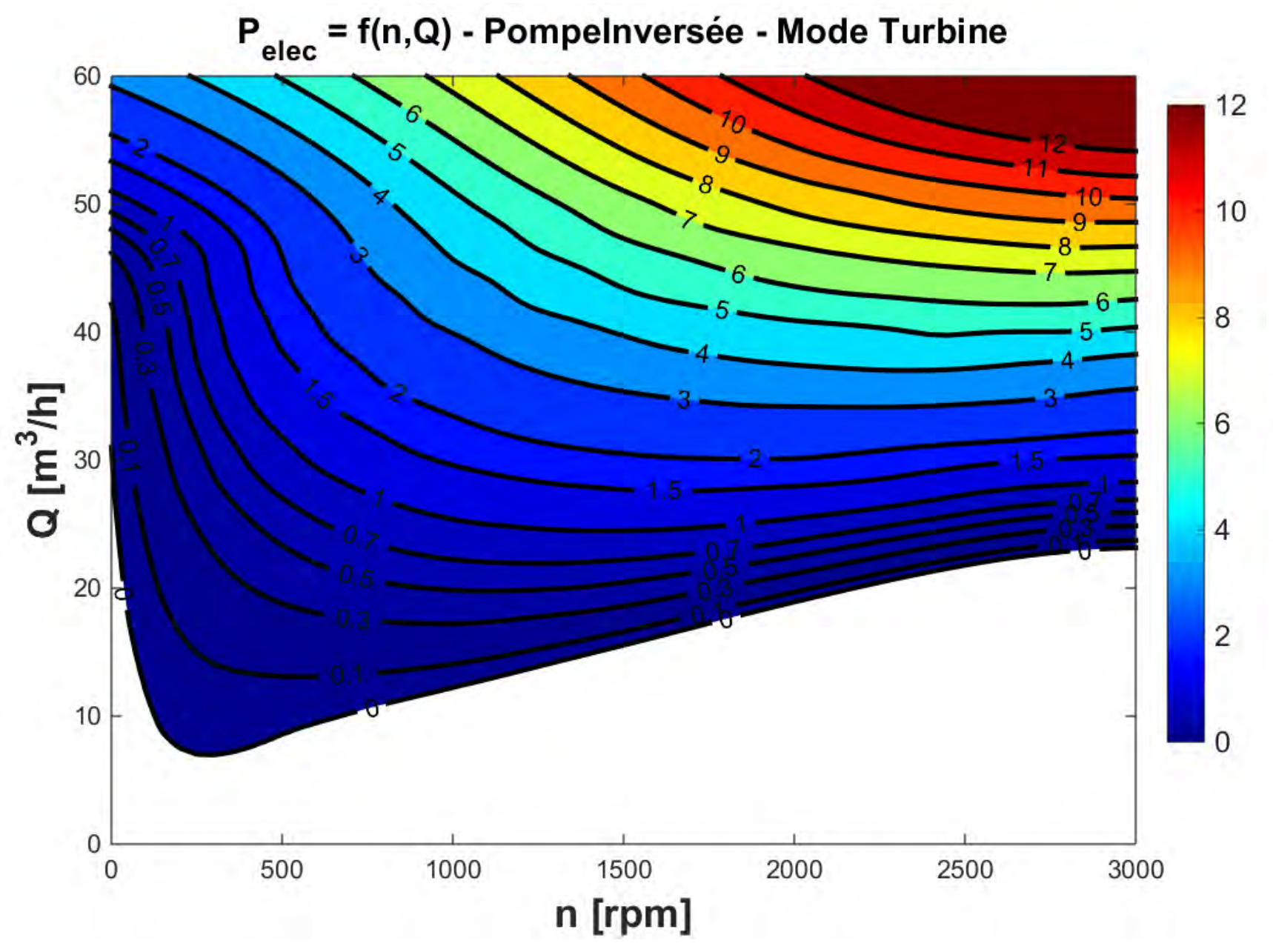


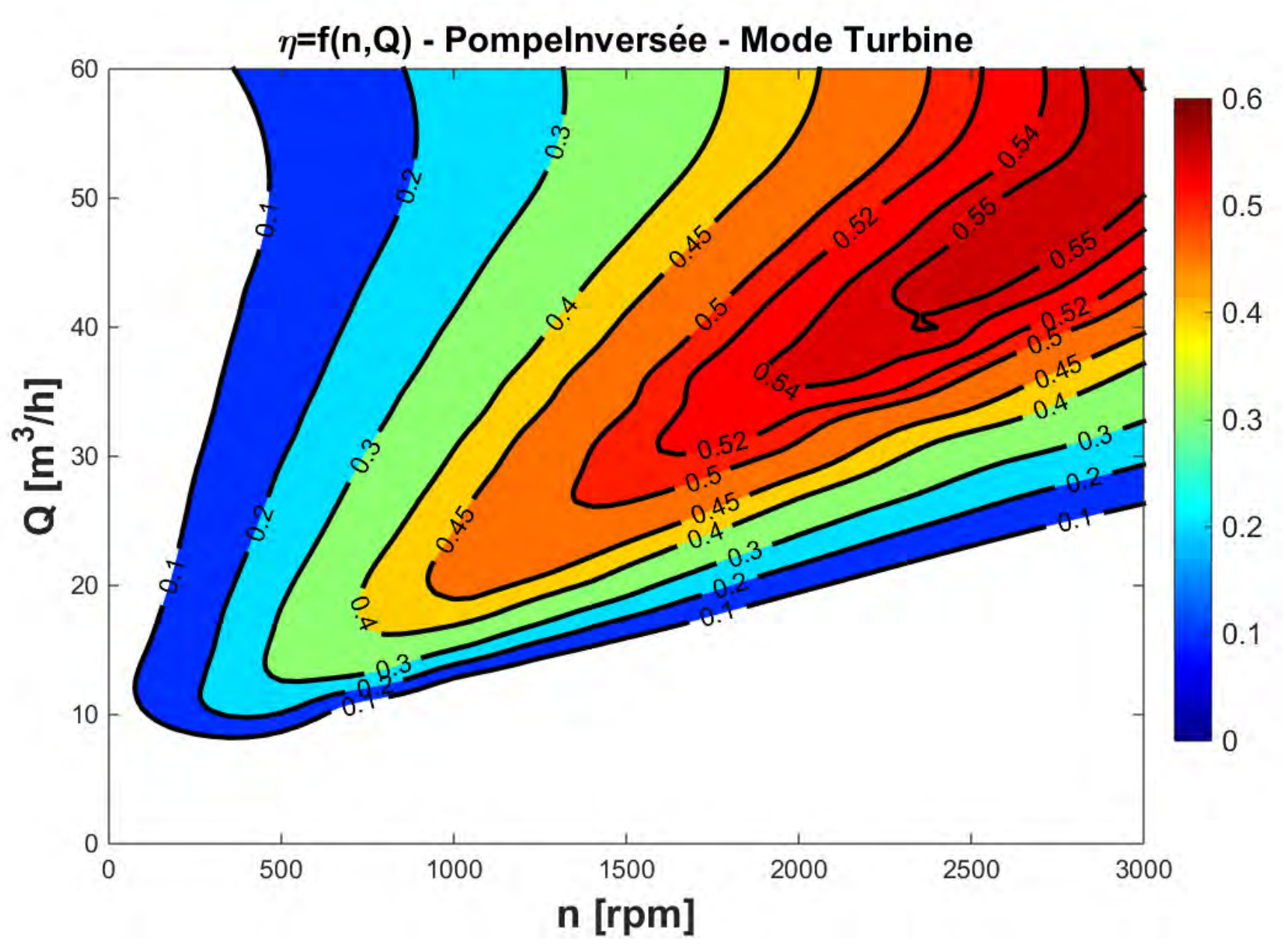
- ✓ Operating range:
  - Q = 10 ÷ 55 m^3/h
  - H = 0 ÷ 146 m
- ✓ Best efficiency point:
  - n_{BEP} = 2’650 rpm
  - Q_{BEP} = 47.5 m^3/h
  - H_{BEP} = 115 m
  - $P_{elec\ BEP}$ = 8’500 W
  - η_{BEP} = 56 %



- ✓ Maximum power point:
  - $n_{Pelec\ max}$ = 3’000 rpm
  - $Q_{Pelec\ max}$ = 52.6 m^3/h
  - $H_{Pelec\ max}$ = 136 m
  - $P_{elec\ max}$ = 11’250 W
  - $\eta_{Pelec\ max}$ = 55.7 %

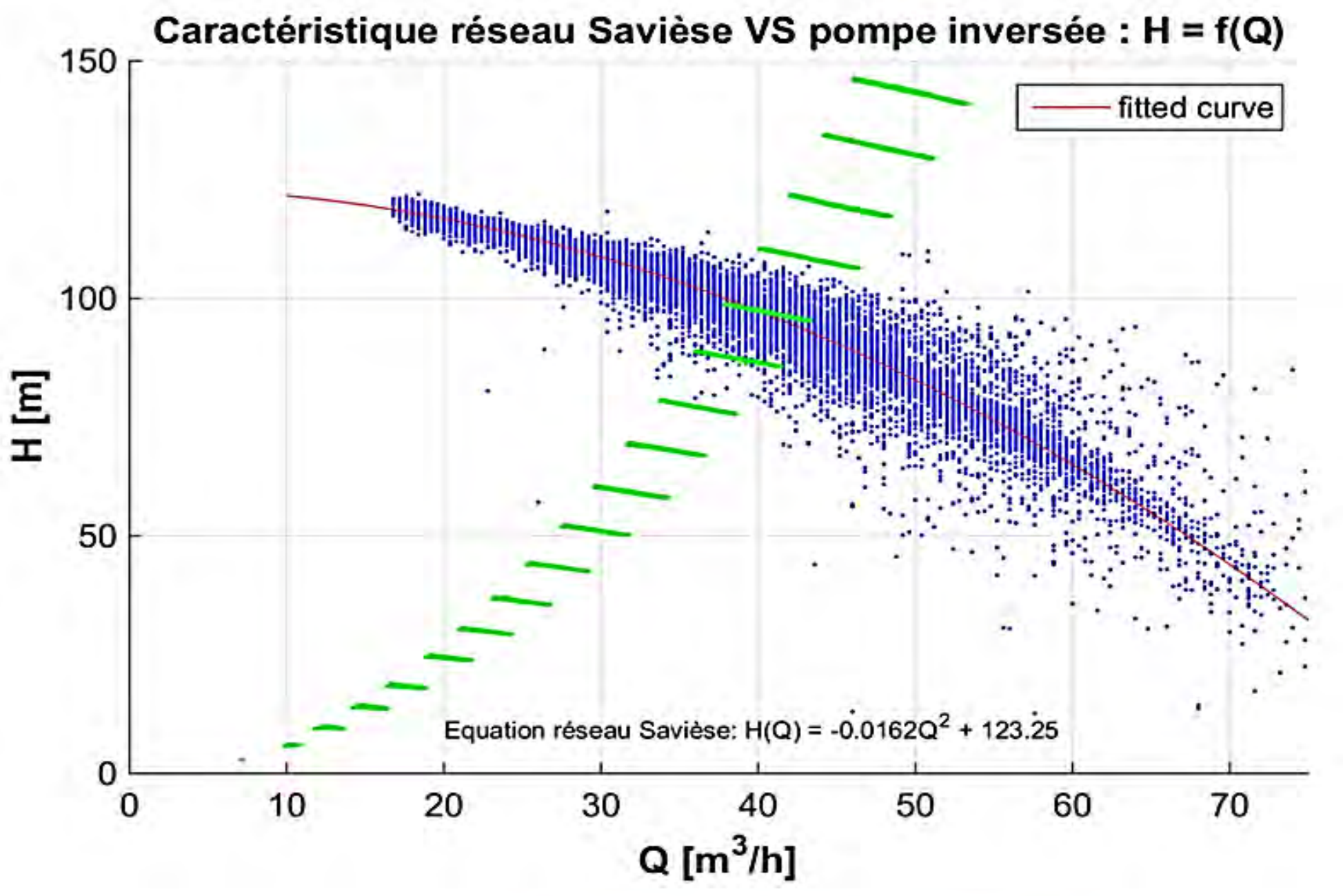
$$\eta = \frac{P_{elec}}{\rho \cdot Q \cdot (gH)} [-]$$

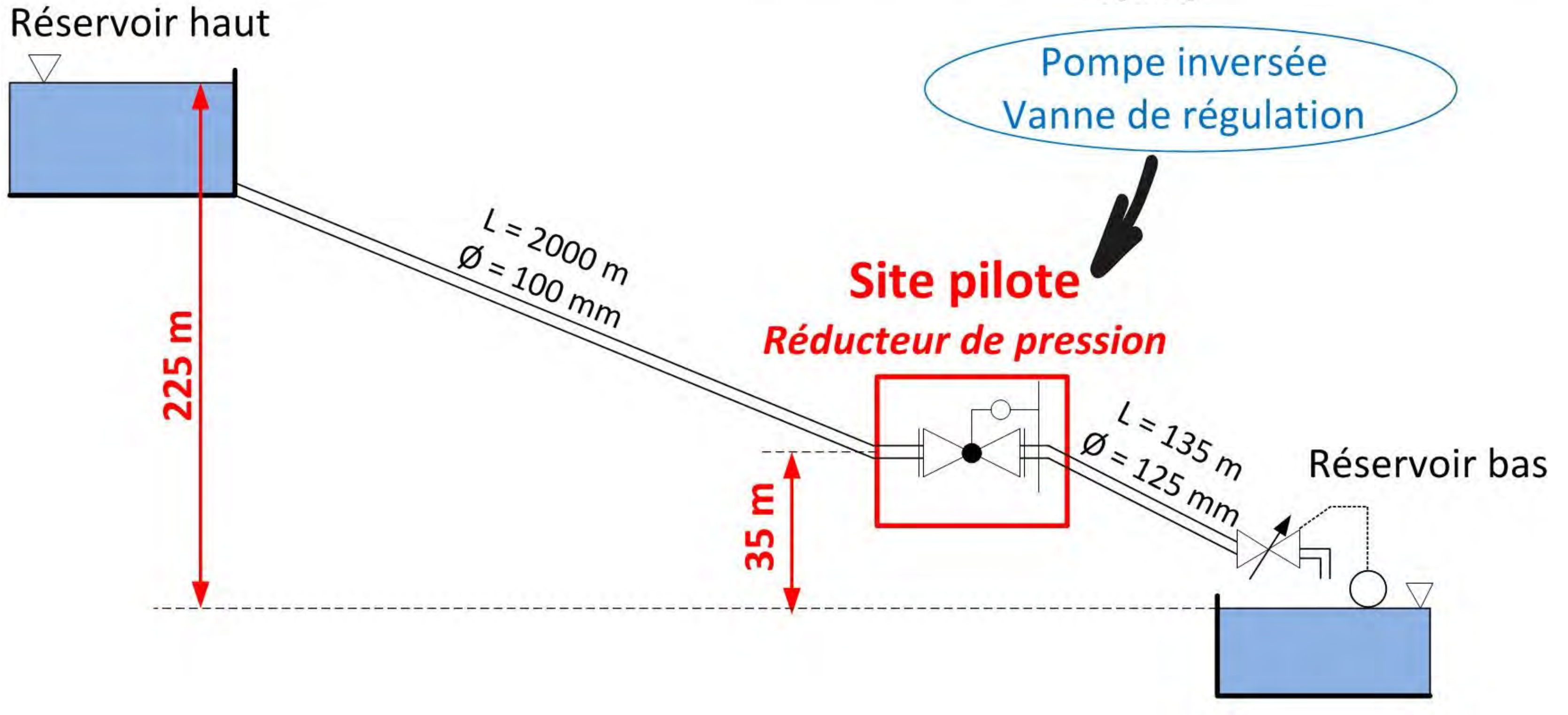




Main characteristics of the Savièse pilot site

- ✓ Gross head: 192 m
- ✓ Net head at maximum discharge: H_{net} = 37 m
- ✓ Maximum discharge: 97.2 m^3/h
- ✓ Half-time available conditions:
  - $Q_{50\%}$ = 35 m^3/h
  - $H_{50\%}$ = 105 m
  - $P_{h\ 50\%}$ = 10 kW





Savièse project partners

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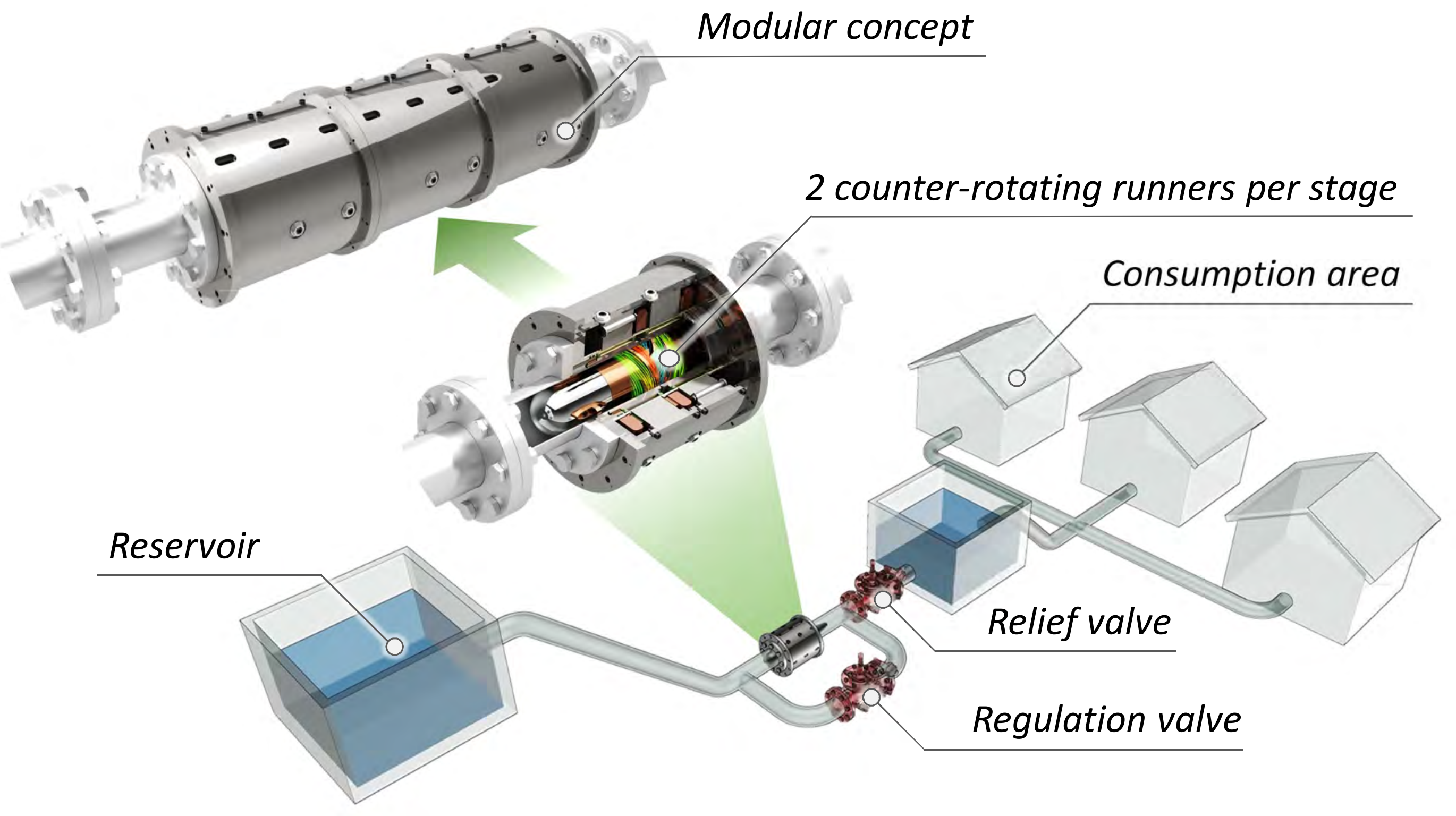
DuoTurbo Prototype V0

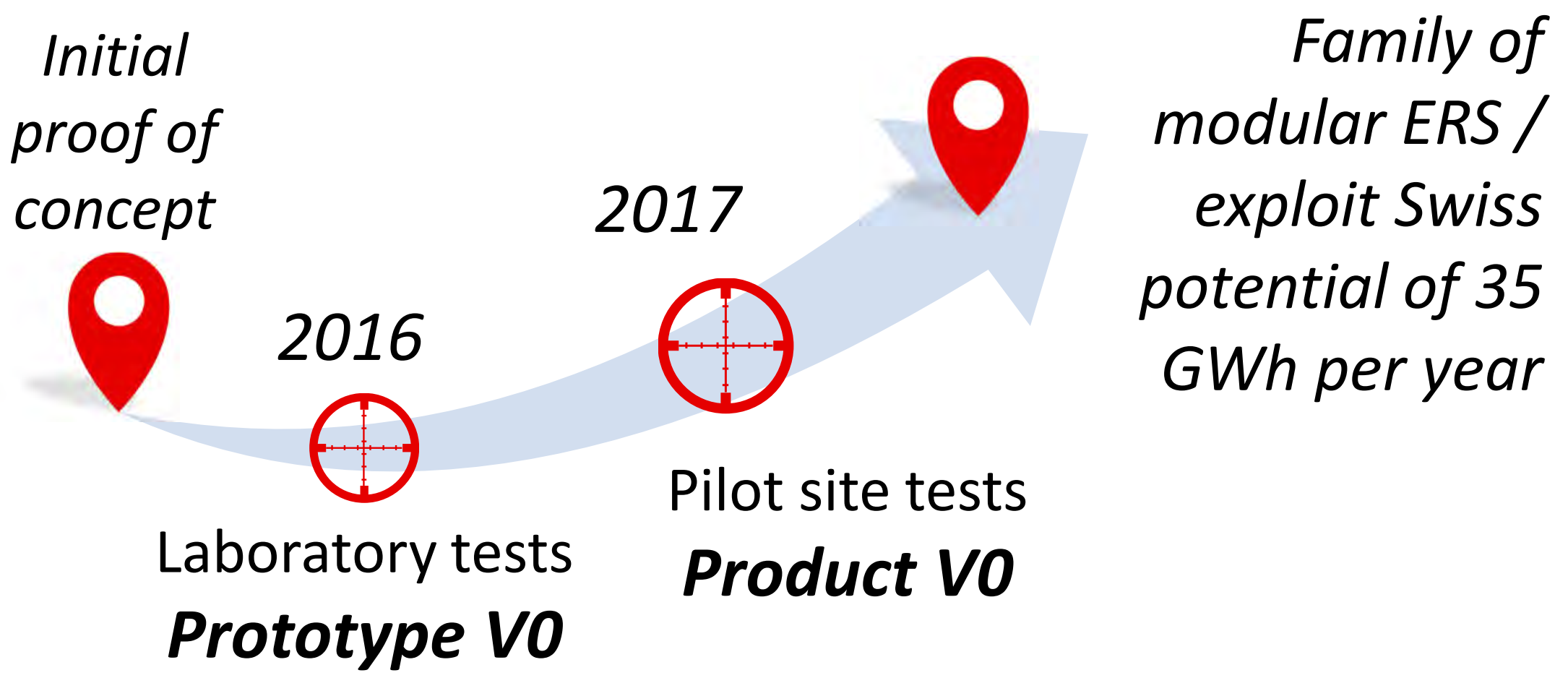
D. Biner, V. Hasmatuchi, L. Andolfatto, F. Avellan, C. Münch-Alligné

Context

- Recovering hydraulic energy lost in **drinking water networks**
- Modular in-line "plug and play" turbine from **5 to 25 kW**
- No environmental impact
- Low investment costs



Project



Initial proof of concept

2016

Laboratory tests
Prototype V0

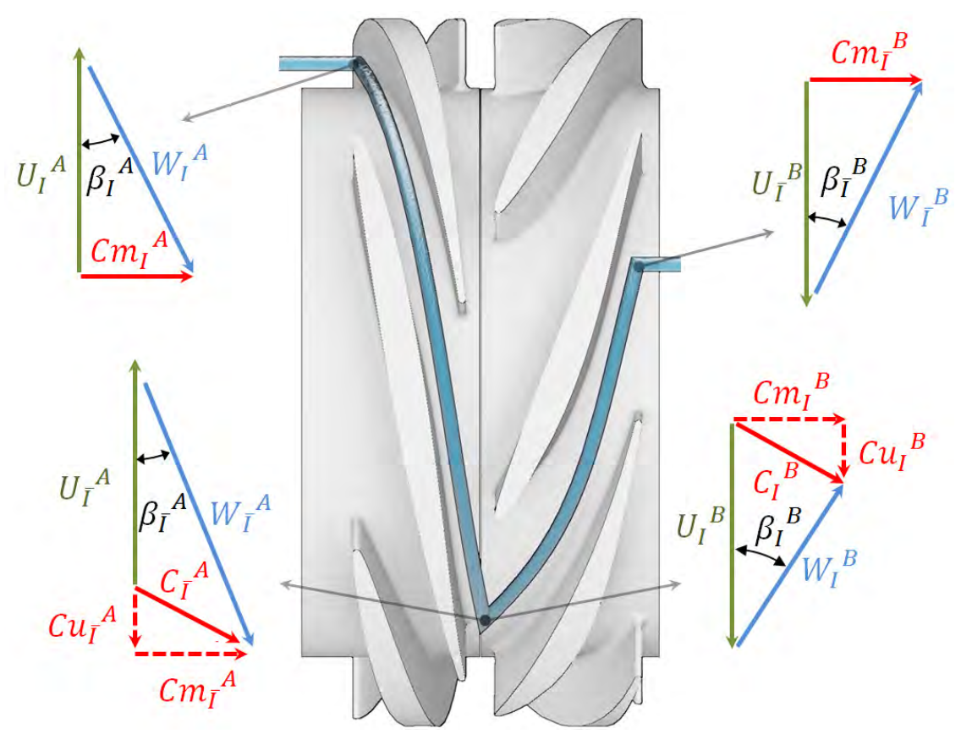
2017

Pilot site tests
Product V0

Family of modular ERS / exploit Swiss potential of 35 GWh per year

Hydraulic concept

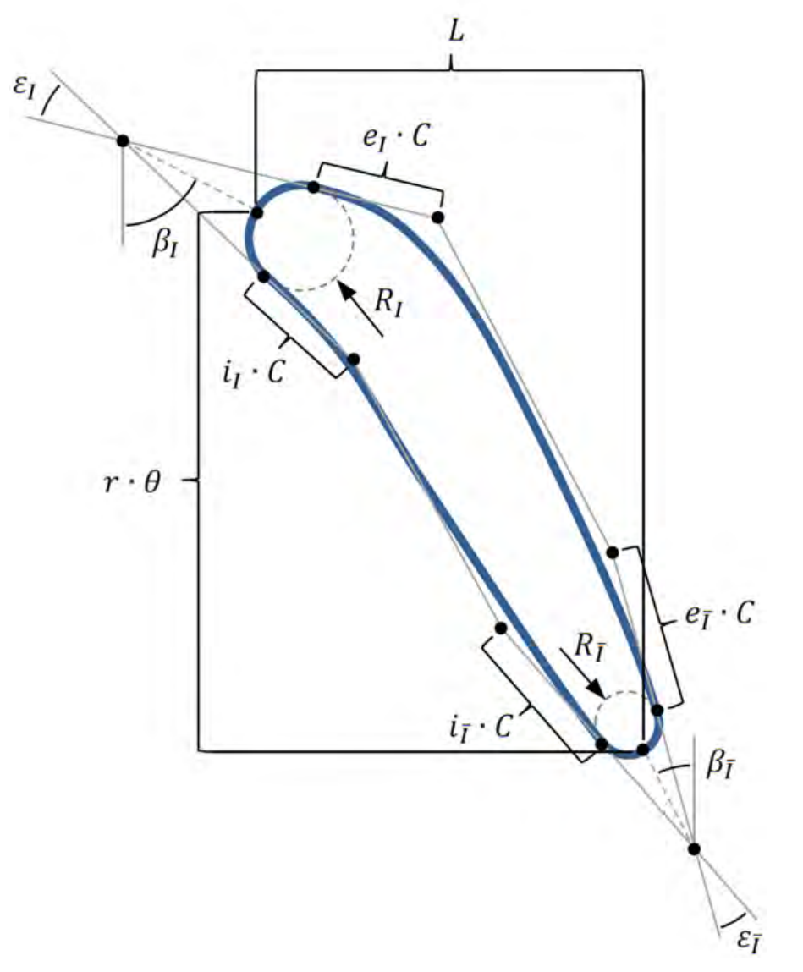
- **Two axial counter-rotating** runners per stage
- **Regulation of the runner speeds** to cope with changing operating conditions
- One **rim generator** per runner

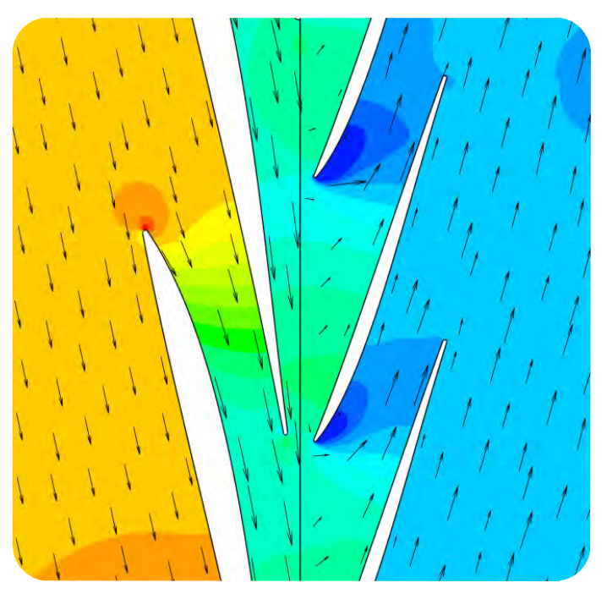


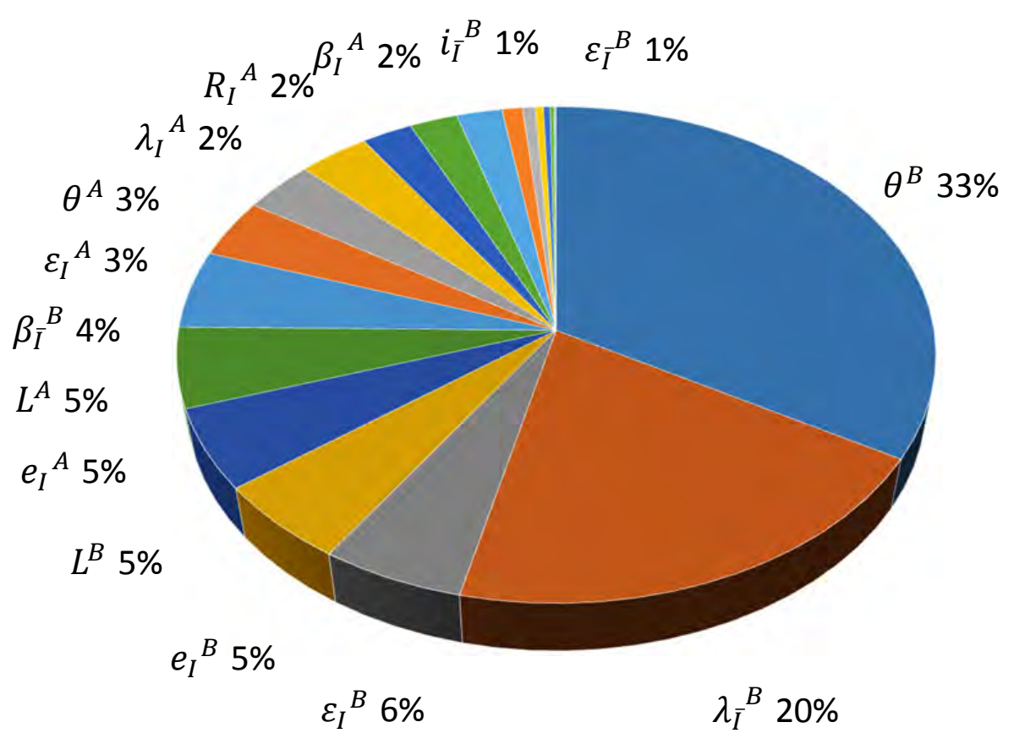
Runner Optimization

Objective: Maximization of the annual energy production

- **Parameterization** of the hydrofoil geometry using 2 circle segments and two 3rd order Bézier curves
- Automation of **quasi 3D flow simulations**, using Matlab, ICEM CFD and ANSYS Fluent
- **Preliminary exploration** of the hydrofoil design by simulating 2'000 sampled runner geometries provided by a Halton sequence
- **Reduction** of the optimization problem dimension by creating an **importance ranking** and using a clustering approach
- Implementation of the **optimization algorithm** (2017)

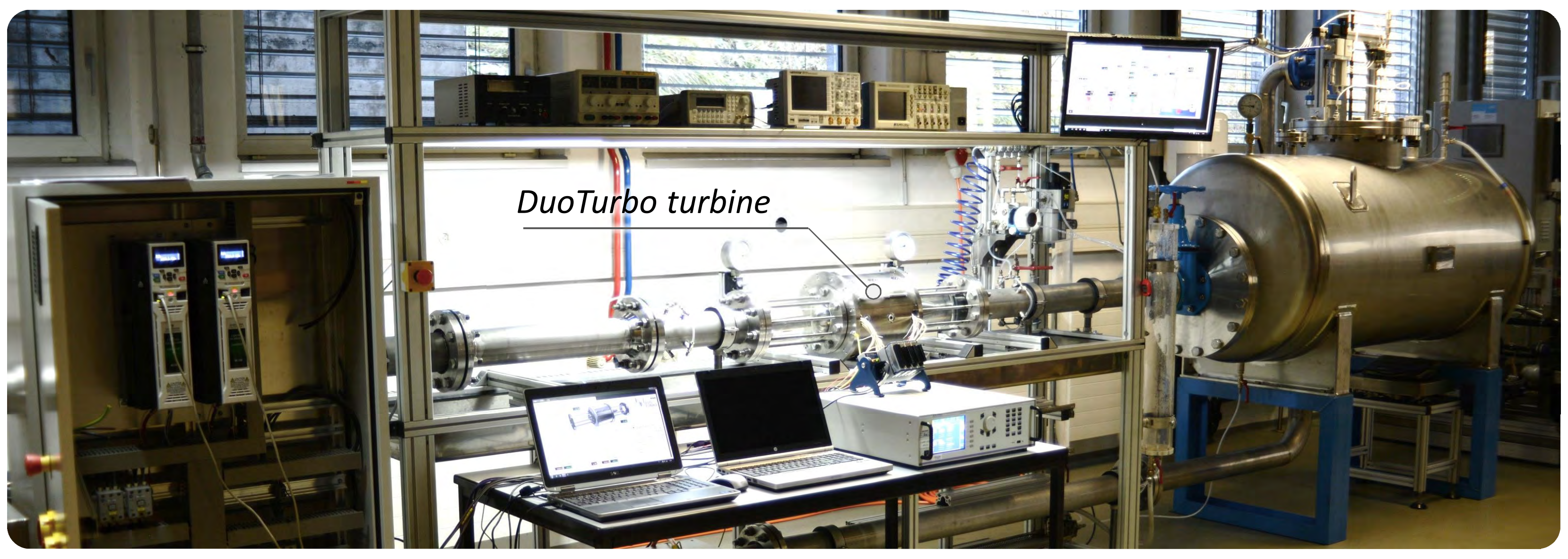


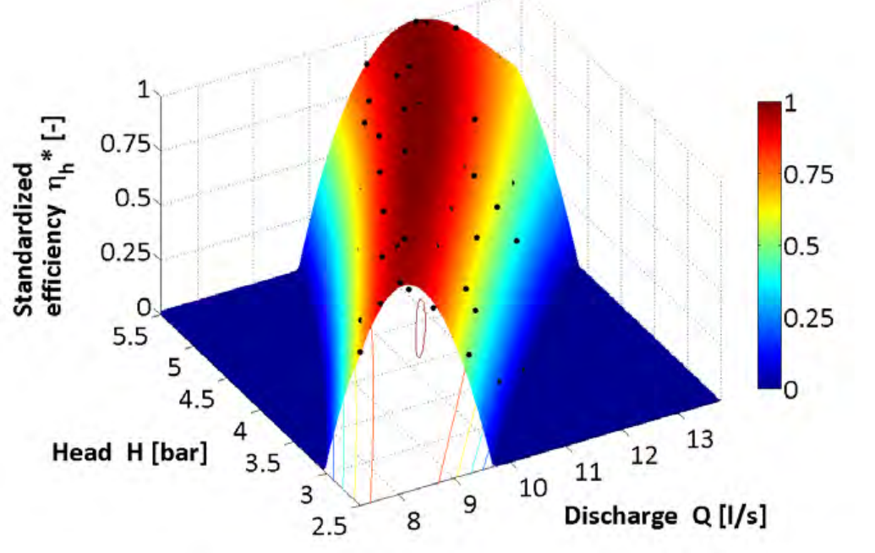


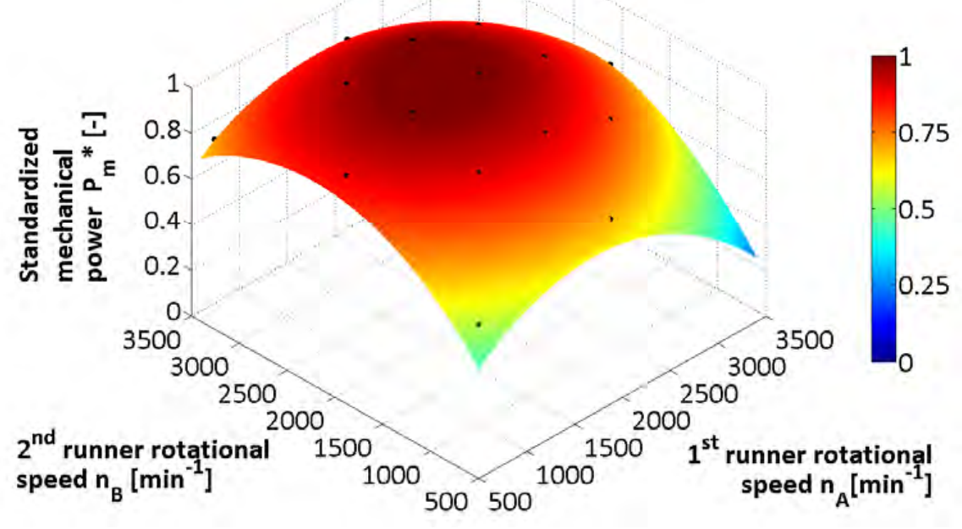


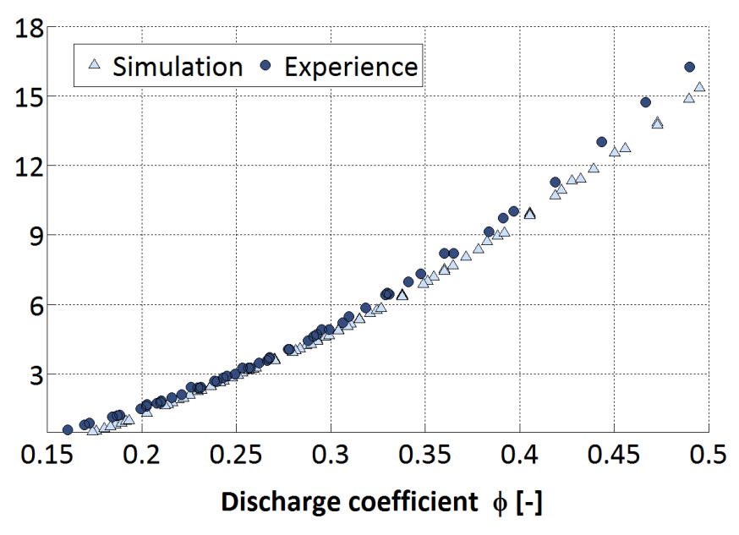
Experimental tests

- **Performance measurements** of the DuoTurbo prototype effected on the **hydraulic test rig** of the HES-SO Valais//Wallis
- **Hydraulic characteristics** obtained by CFD simulations successfully **validated** by the experimental tests

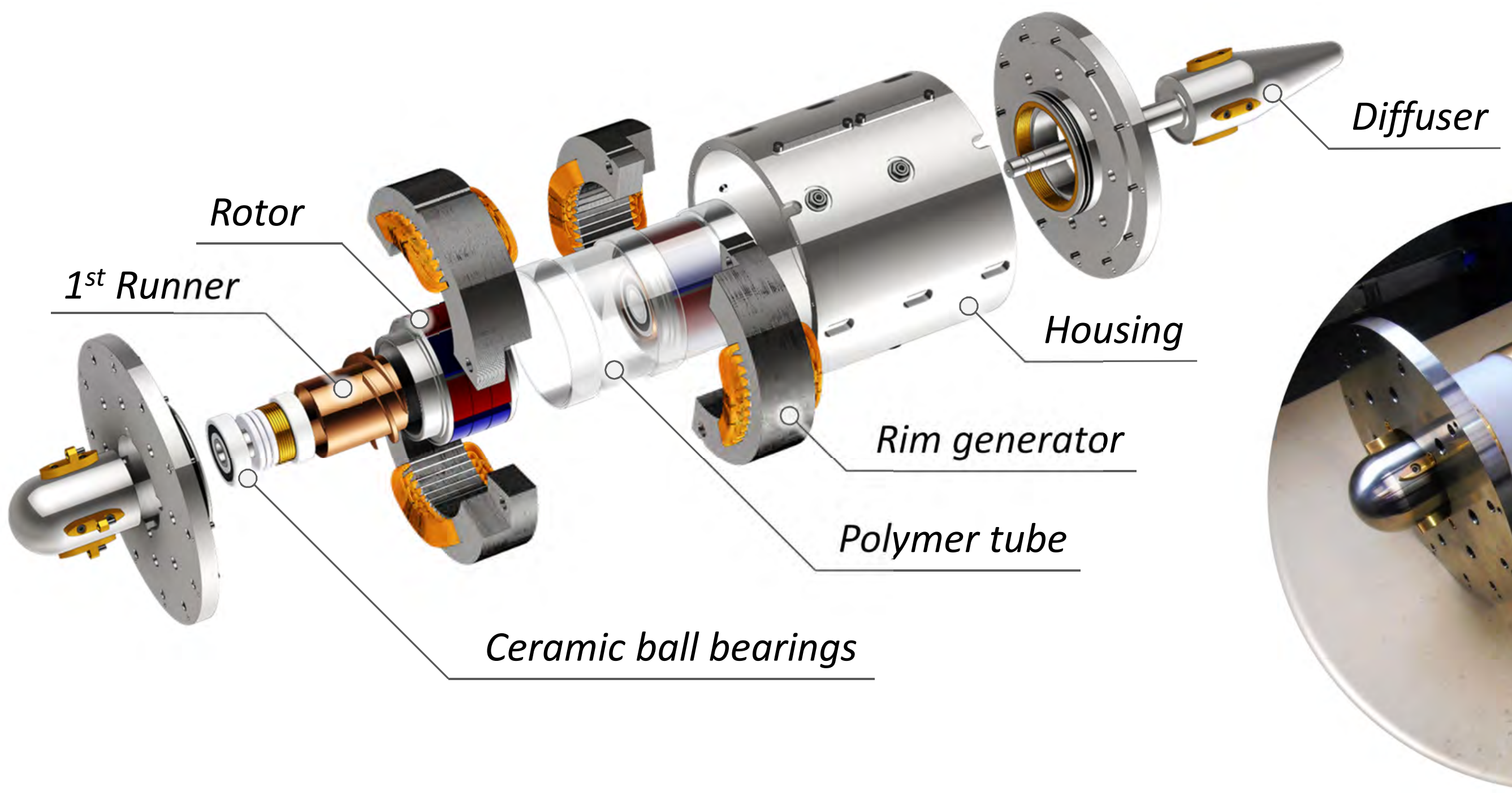






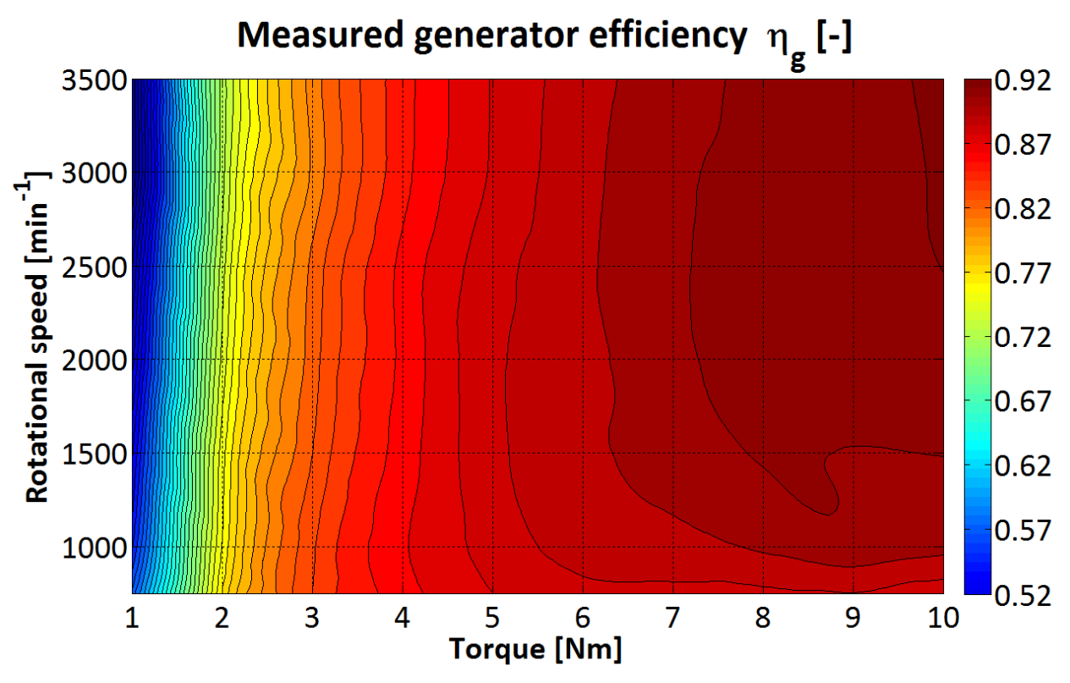


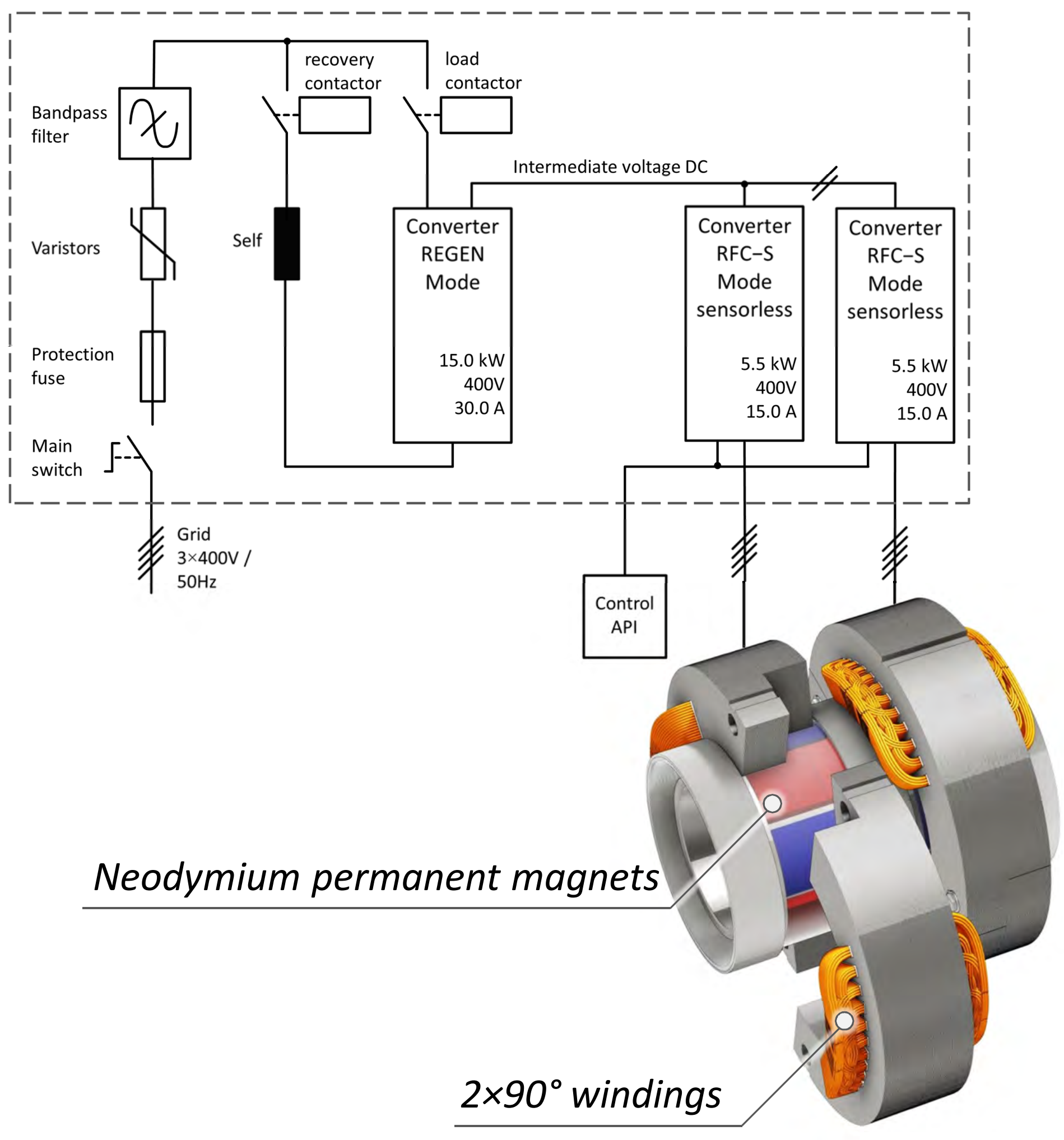
Mechanical concept



Electrical concept

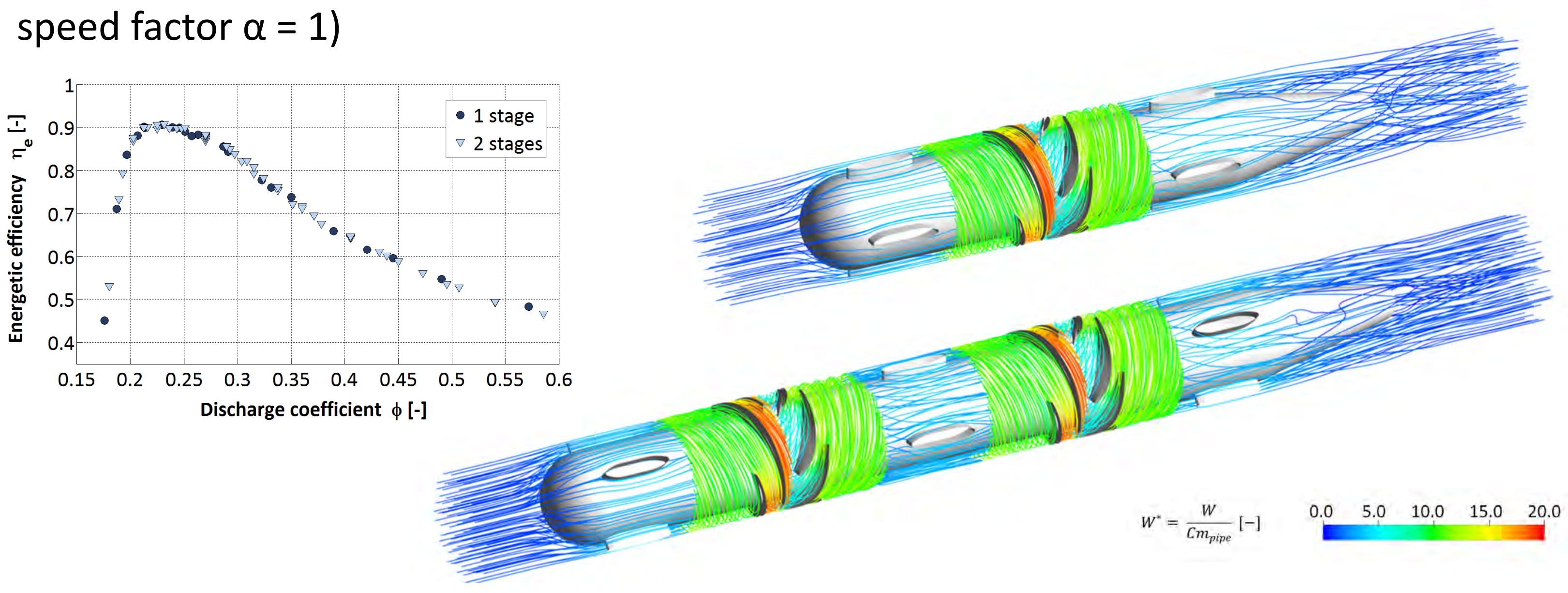
- **In-house** developed 8-pole **synchronous generators** with permanent magnets
- Nominal generator power of **3.37 kW** (3500 min^{-1}, 10 Nm)
- **15 kW** converter on grid side
- **2 × 5.5 kW** converter on generator side





CFD simulations

- **CFD simulations** of the one-stage and **two-stage configuration** have been carried out
- **No significant influence** of the first stage on the second stage has been detected (for a speed factor α = 1)



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- D. Biner, V. Hasmatuchi, D. Violante, S. Richard, S. Chevailler, L. Andolfatto, F. Avellan, C. Münch, **"Engineering and Performance of DuoTurbo: Microturbine with Counter-Rotating Runners"**, *28nd IAHR Symposium - Grenoble*, July 2016.

Development team of Duo Turbo (CTI Nr. 17197.1 PFEN-IW)

HES-SO Valais//Wallis:

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EPFL LMH:

L. Andolfatto, F. Avellan

Industrial partners:

Telsa SA, Jacquier-Luisier SA, Valelectric Farner SA

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Hochschule für Ingenieurwissenschaften
LMH Laboratory for Hydraulic Machines
EPFL Ecole Polytechnique Fédérale de Lausanne
Valelectric Farner SA
Telsa Electrotechnique
Jacquier & Luisier SA Atelier mecanique

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Hes·so Valais Wallis
School of Engineering

Limnimeter for Mountain Streams

Grégory Emery, Eric Bardou**, Christian Cachelin*, Joseph Moerschell*, Eric Travaglini****
** HES-SO Valais-Wallis, Rawyl 47, 1950 Sion, ** DSM-Consulting, Barma 1, 1973 Nax, *** Crealp, Industrie 45, 1950 Sion*

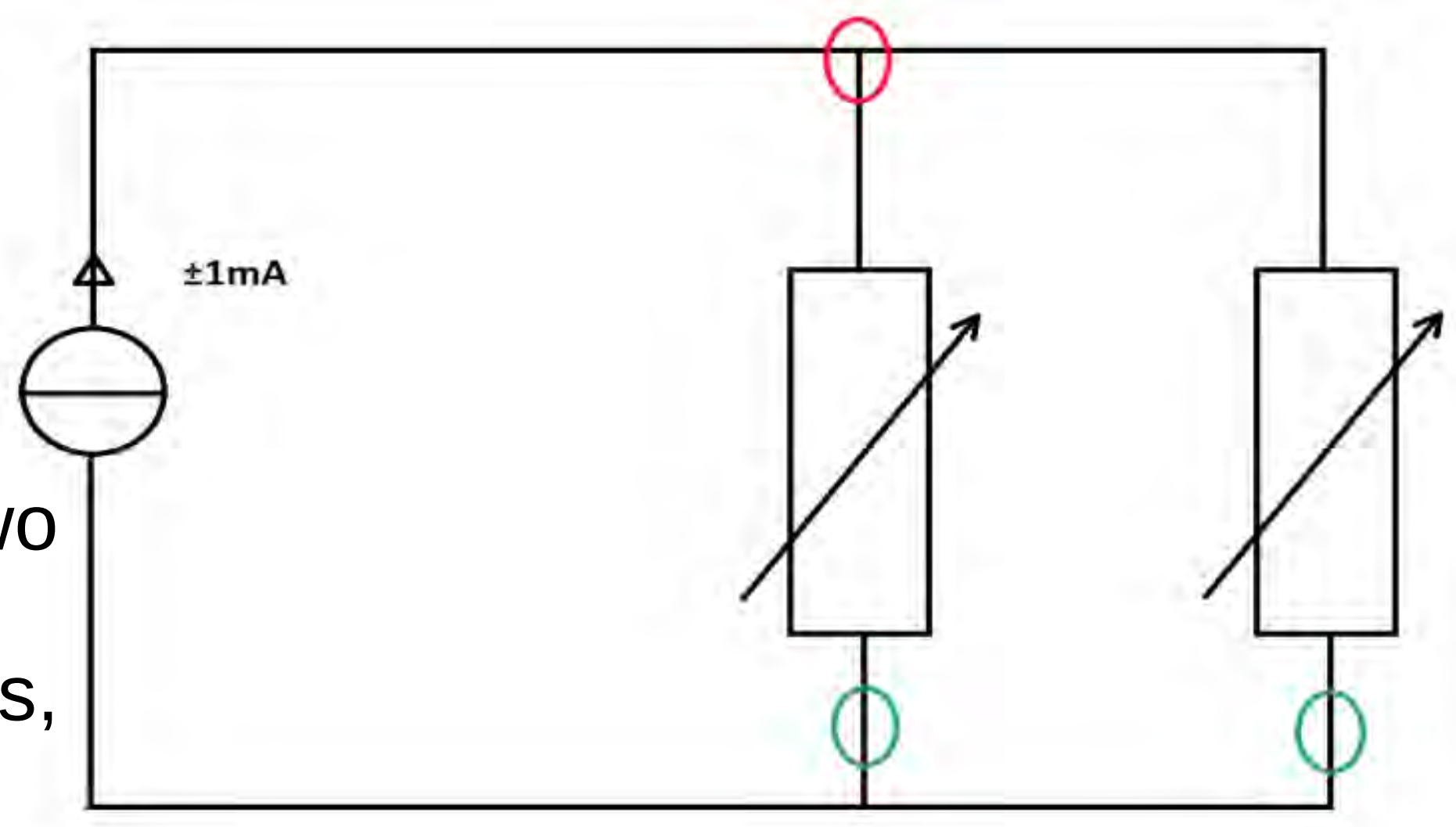
1. What is the problem?

- Mountain streams do often have a complex bed which can evolve over time, since the water transports sediments. Parts of the bed may be eroded, and sediments can be deposited in other places. The measurement of water depth is therefore not complete when the upper limit of the streams, it's interface with the air is determined, as e.g. a radar shall do. Ideally, the water bed level should also be measured. Typical mountain stream with glacial regime may show depth fluctuations of 1m during a season, sometimes even more.
- The measurement should yield an electric quantity to be able to acquire and record it with a data-logger.
- The properties of mountain waters are fluctuating, e.g. turbidity, electrical conductivity, temperature. A new measurement method should be intrinsically independent of such variations. Further on, a water depth sensor shall be robust enough to withstand the impact of solid material carried along by the water flow.

2. New limnimeter

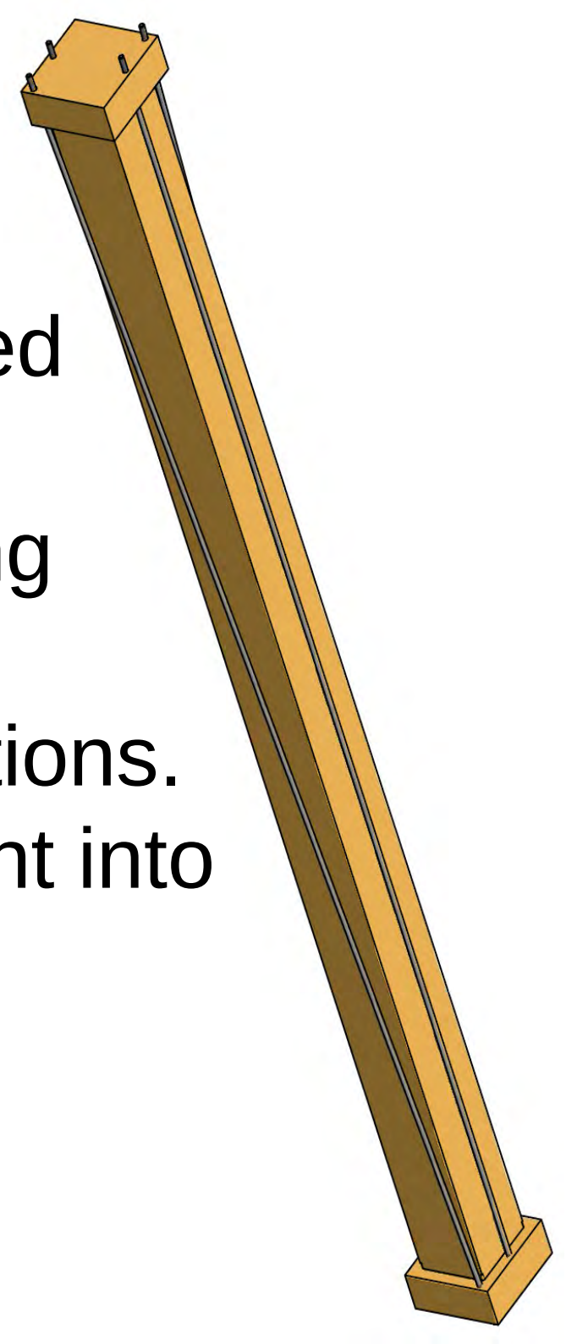
To address the requirements enumerated above, we propose to determine water and sediment levels based on the measurement of a differential electric impedance variation:

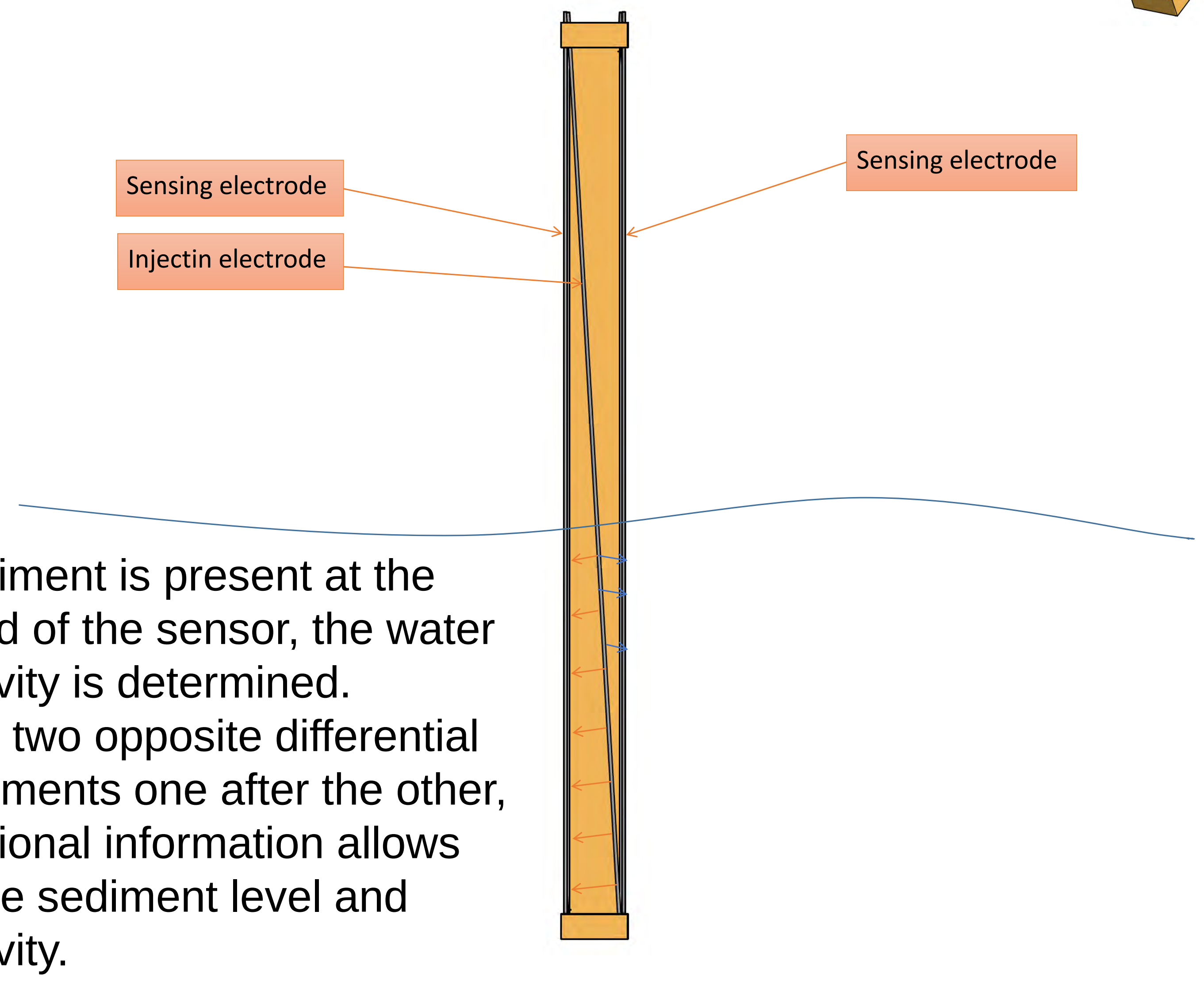
- A rectangular electric current of fixed frequency is injected into a measurement circuit made up of 2 parallel impedances.
- Depending of the variation of water and/or sediment level, the ratio of the two impedances shall vary, i.e. one increases and the other decreases.
- Because of the differential measurement, the influence of water conductivity is cancelled.
- By making two different differential measurements, two layer thicknesses with two different electric conductivities, e.g. water and sediments can be discriminated.



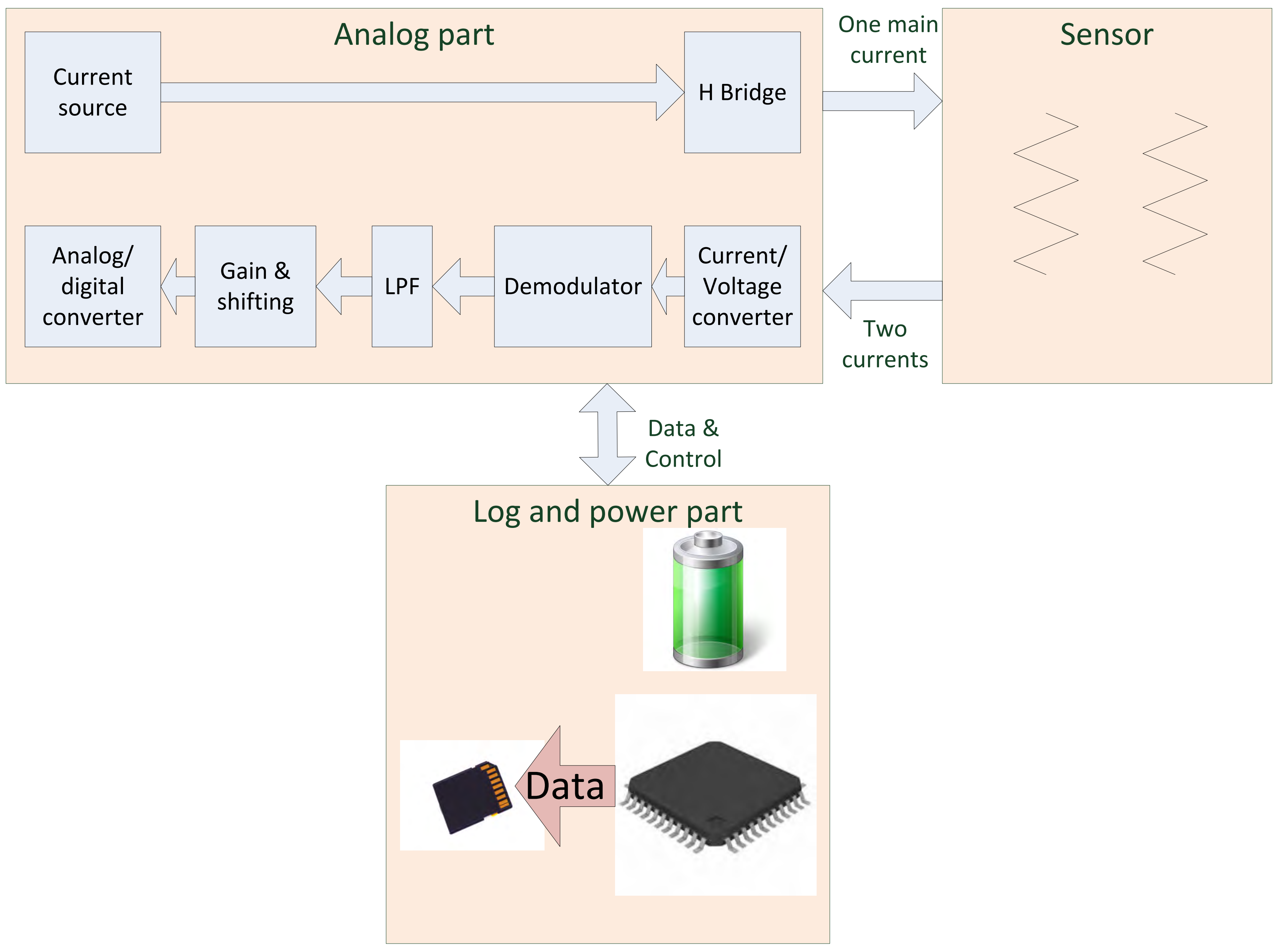
3. Sensor concept

- The sensing element is made up of 4 electrodes grouped around a central non conducting support column.
- Two of the electrodes are vertical. These are the sensing electrodes.
- The other two electrodes are inclined, in opposite directions. These are alternately used to inject the excitation current into the water.
- Depending on the water level, the ratio of the two water impedances between the electrodes is modified.





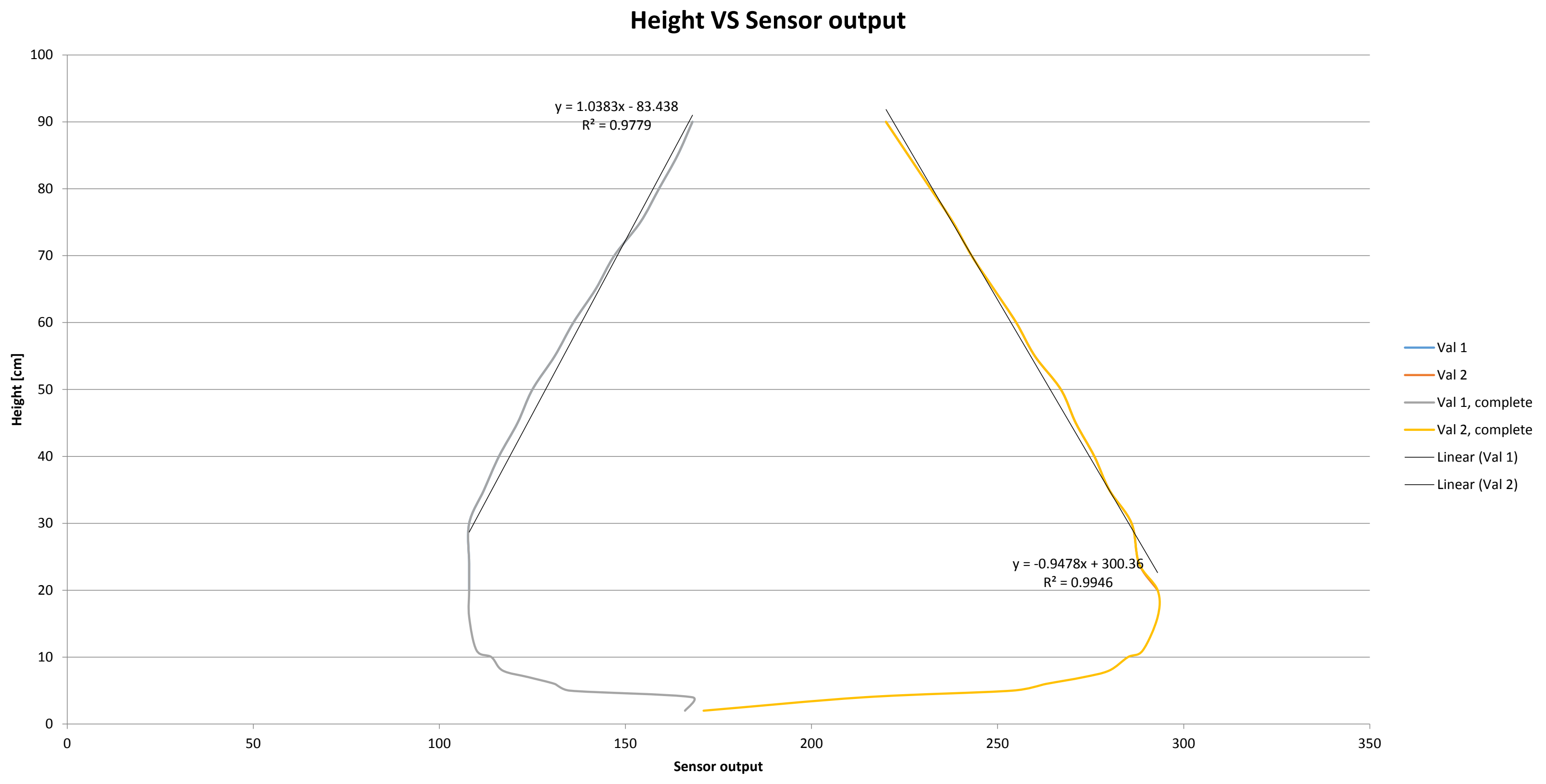
- If no sediment is present at the lower end of the sensor, the water conductivity is determined.
- By doing two opposite differential measurements one after the other, the additional information allows determine sediment level and conductivity.



The figure above shows a block diagram of the sensing acquisition, processing and recording / read-out electronics.

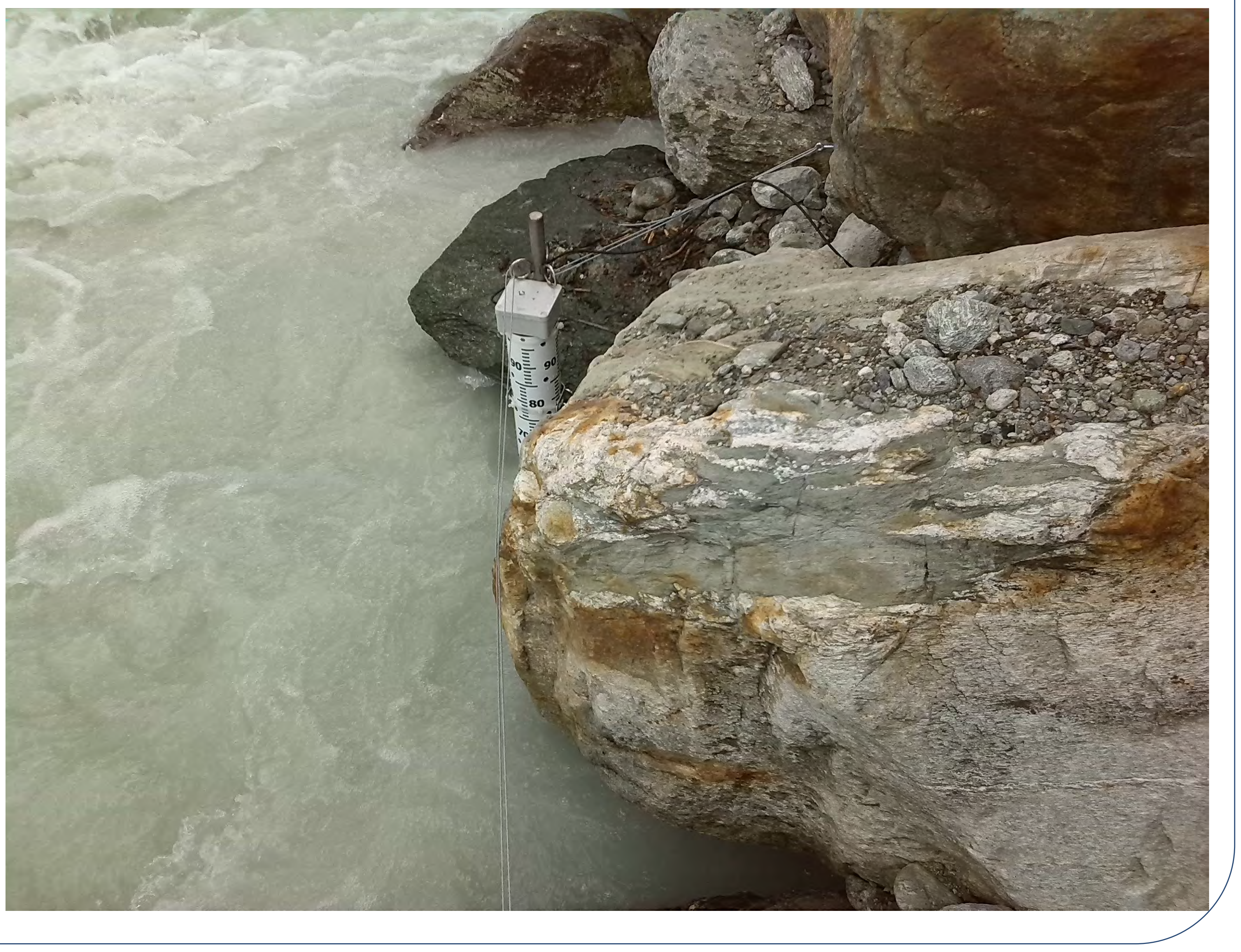
4. Limnimeter calibration

Calibration of the sensor demonstrator in a laboratory water reservoir with variable depth, shows that the sensing curve may be linearized over about two thirds of the measurement range.



5. Demonstrator installation

A demonstrator of the proposed water and sediment level sensing system is currently installed in the Naviscence river at Crealp's Zinal measurement station.



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PiezoEel: An Energy Harvester for Mountain Stream Monitoring

Grégory Emery, Sylvain Richard*,*
*Herbert Keppner**, Joseph Moerschell*, Cécile Munch-Alligné*, Laurent Rapillard**
** HES-SO Valais-Wallis, Rawyl 47, 1950 Sion, ** HE-ARC, Eplatures-Grise 17, 2300 La Chaux-de-Fonds*

Hes·so VALAIS WALLIS
School of Engineering

1. What is the problem?

Mountain streams may flow in deep valleys with little sunshine available to power a photovoltaic panel that would recharge a data-logger and sensor battery.

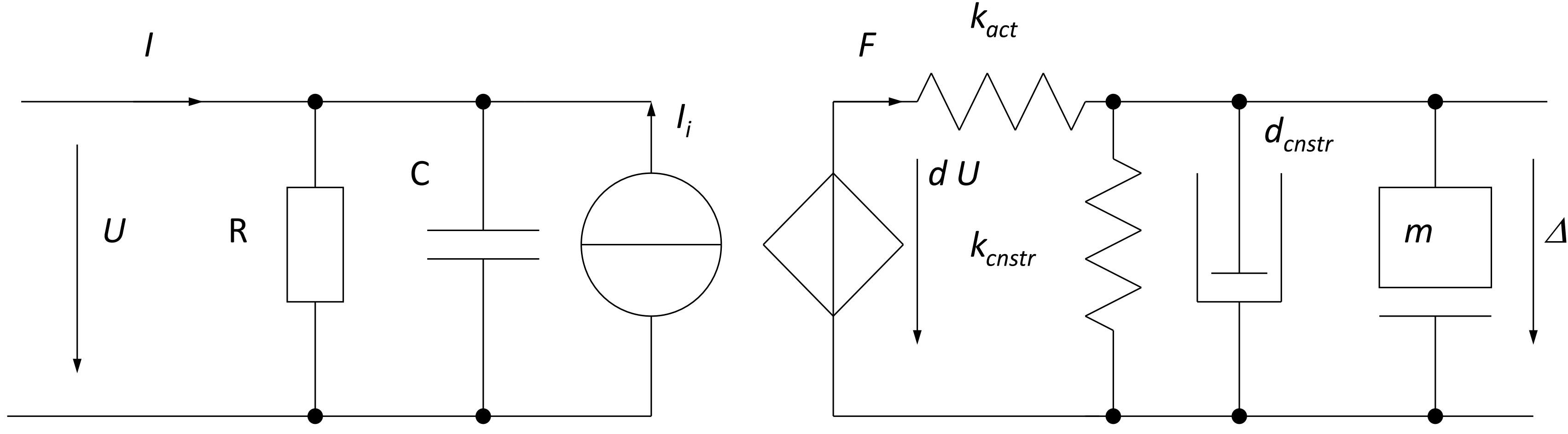
As an illustration, the picture shows the Borgne river at the entrance of Val d'Hérens.
Modern data-loggers may consume not more than 100mW typ., but depending on the number of sensors, and their sampling rate, average power consumption can increase to 1W or more. Also, GSM data communication requires several W of power.
The objective is to develop an alternative power source capable of supplying an average power of 1W. The energy shall be collected from the water flow.

2. Piezoelectric energy harvesting from water

The basic approach of this development is to use piezoelectric elements instead of a turbine / generator group as classically used. This is done for several reasons:

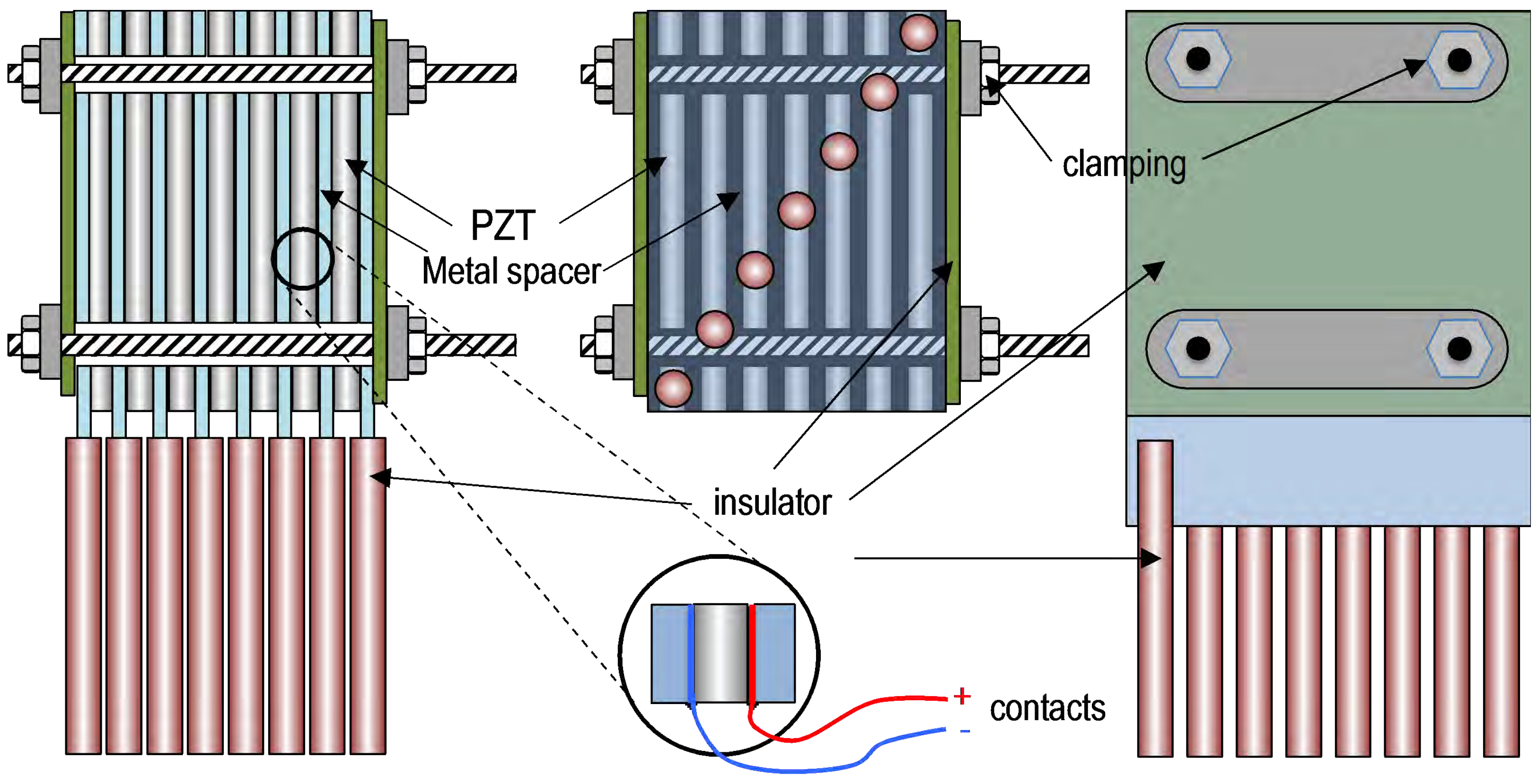
- A water channel structure (concrete or steel construction) shall be avoided to keep the system light and easy to install.
- At 1W power level, the efficiency of a turbine / generator set shall be modest.
- The energy to be harvested shall be motion energy of the water, rather than potential energy due to a water gradient.

Piezoelectric elements are very stiff, and important electric polarization occurs if high forces are exerted on them. On the other hand, water is practically not stiff, but flows over long distances with considerable speed. Between the two, the proposed harvester must therefore do an important adaptation of 'mechanical impedance'.
The schematic below shows an equivalent electric circuit model of a piezoelectric actuator.



3. Harvester concept

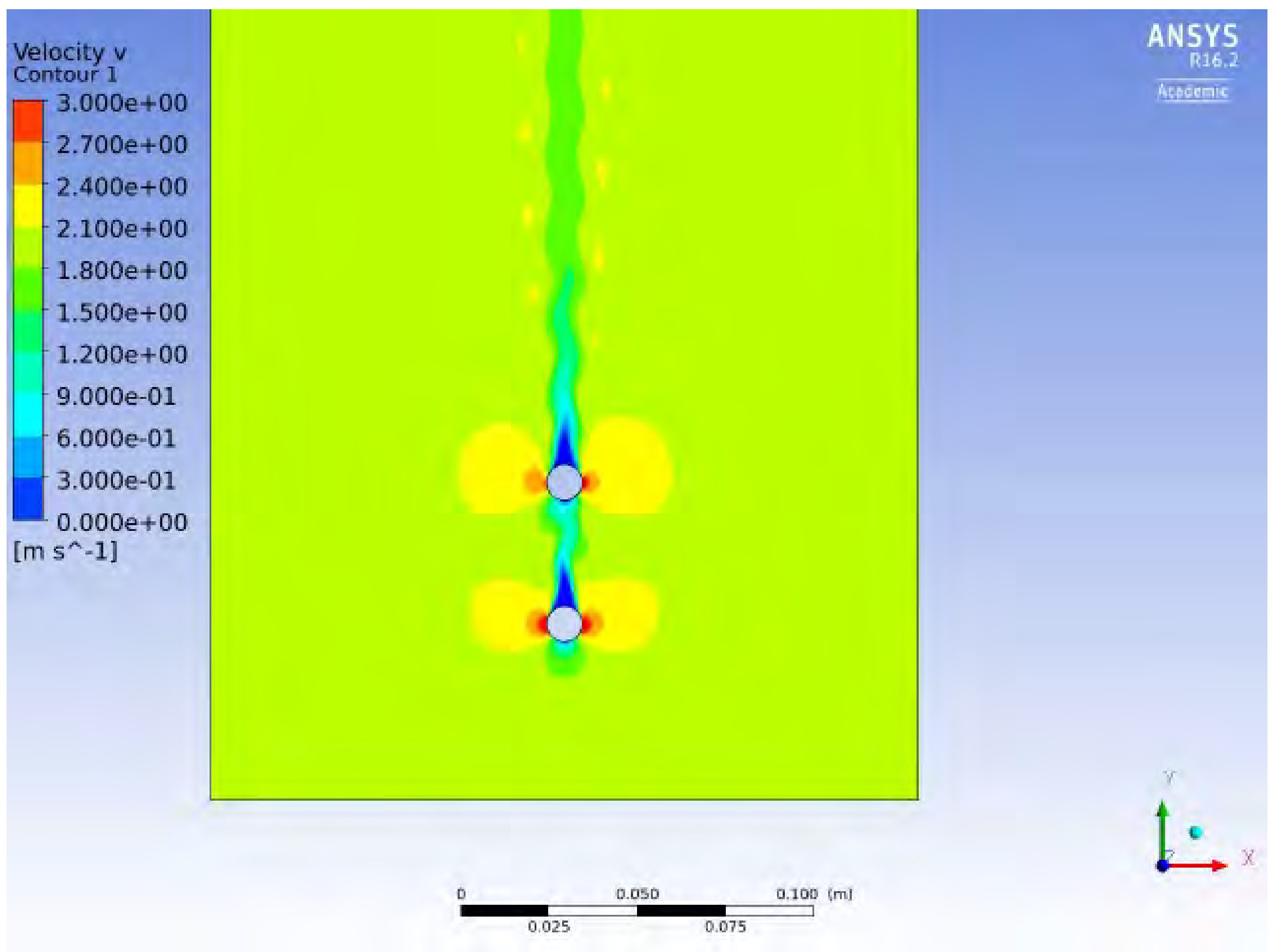
A set of piezoelectric elements is compressed within a staple of steel plates. The preconstraint is necessary since piezo elements can only work in compression. Steel rods are screwed into the steel plates. The length of these rods and their diameter shall be adapted such that their resonance frequency is excited by turbulent water flow around the tips reaching into the water stream.



4. First simulation results

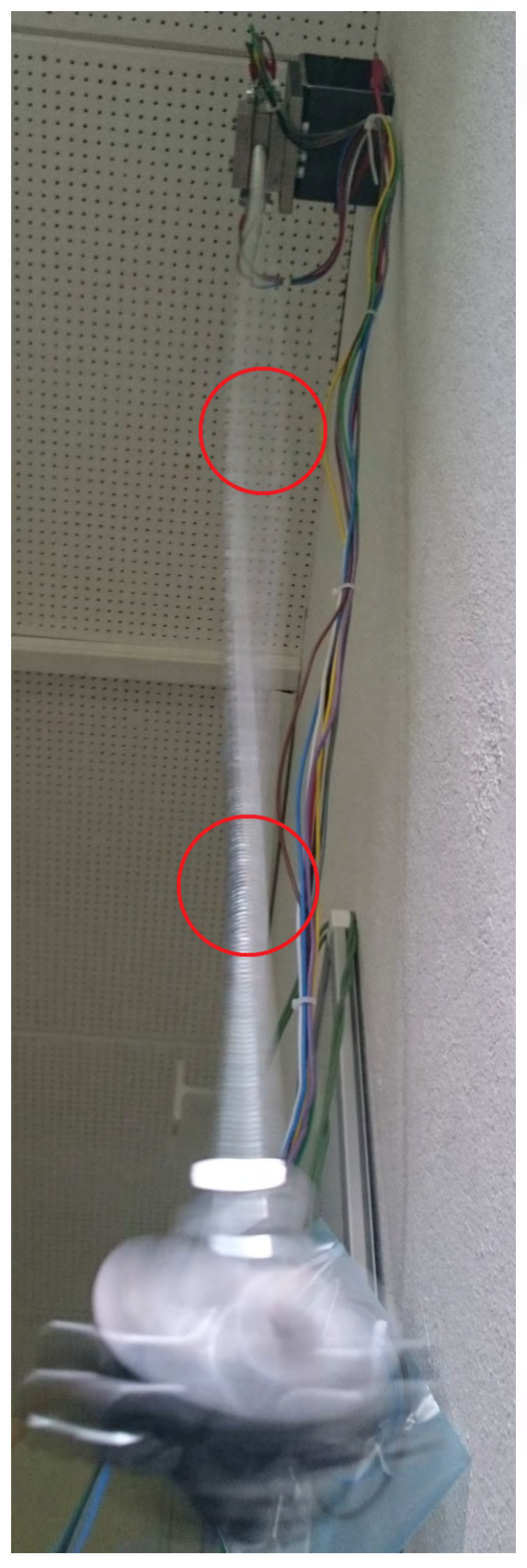
Favorable configuration of rods plunging into ware was sought. I turns out that

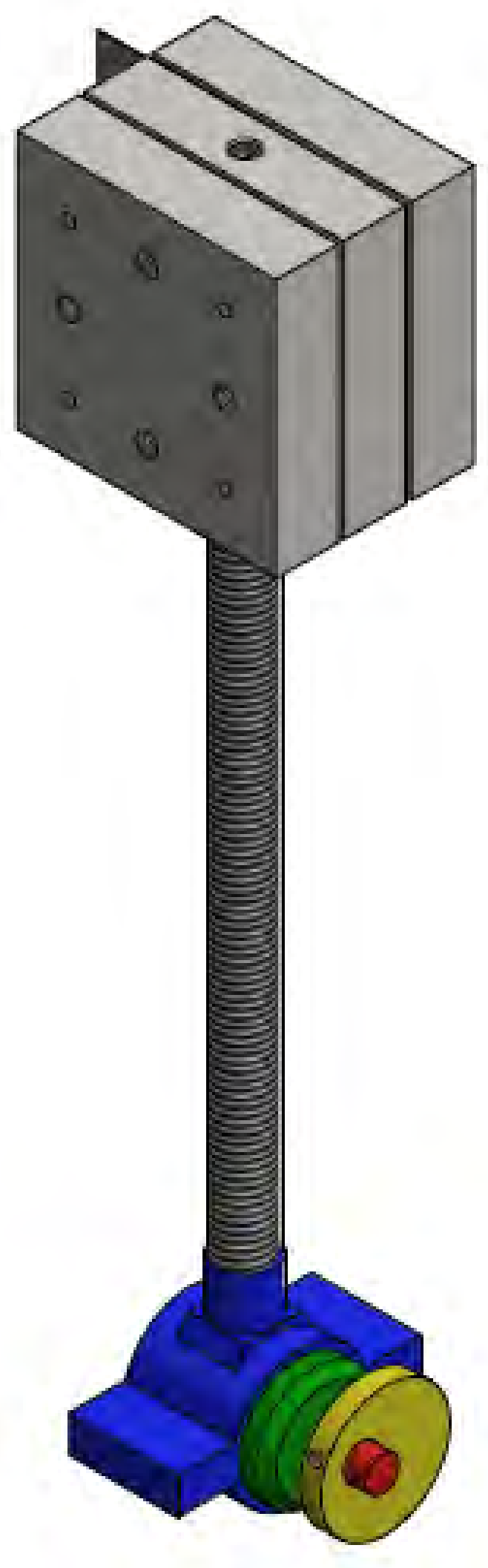
- An obstacle, typically of same diameter and spaced by one diameter should be placed in front of the vibrated rod.
- Having several rods in parallel increases the vibration force generated by turbulent water flow.
- Vibration frequencies in the range of several 10Hz, depending on rod diamter.

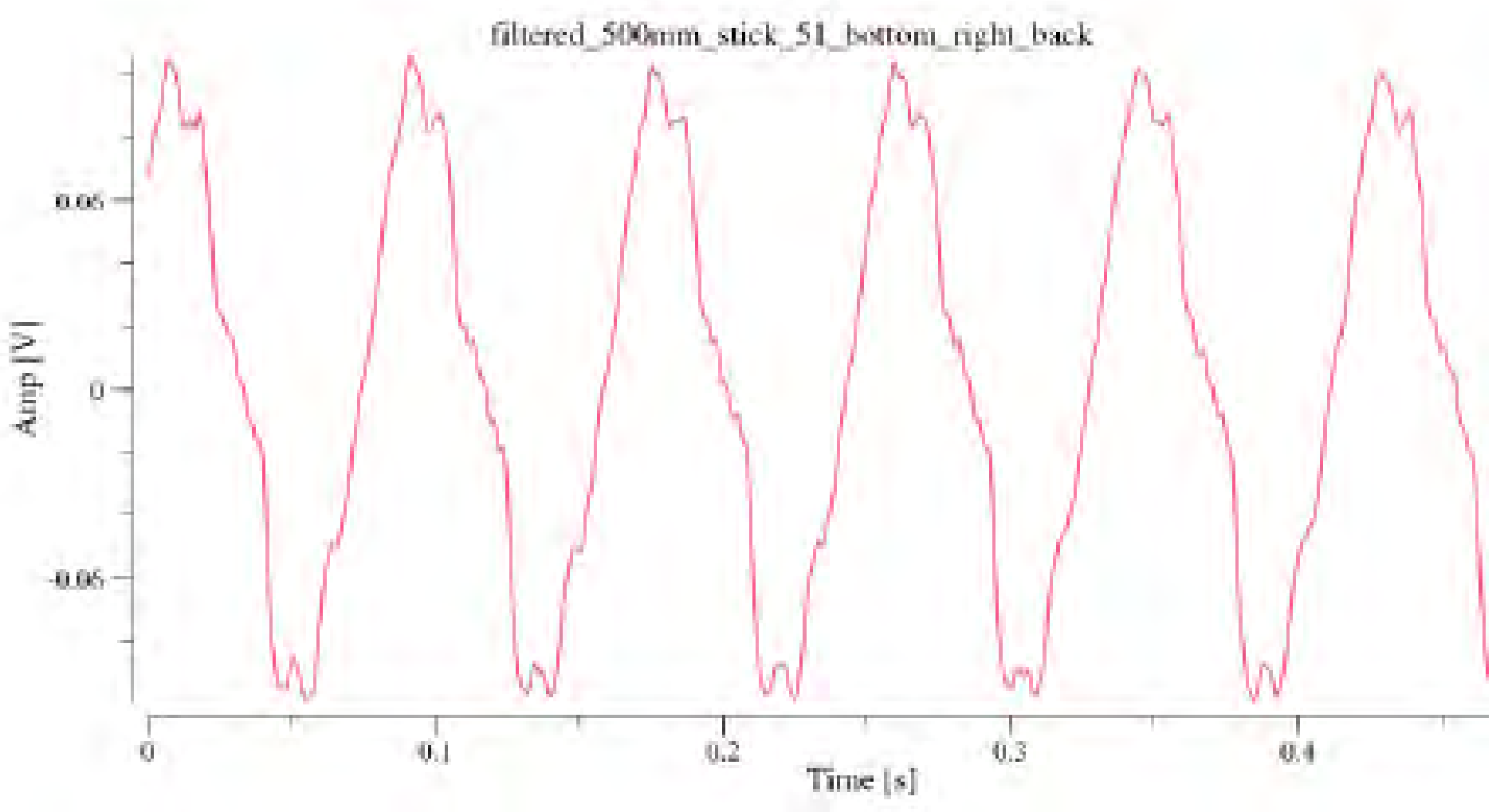


5. Preliminary tests

A test set-up was built to evaluate the energy transmission performance from rod vibration to the piezo elements. While the electric energy generation function could be successfully shown, the available electric output power is still too small. The mechanical impedance adaptation must be improved in the next iteration of the design.

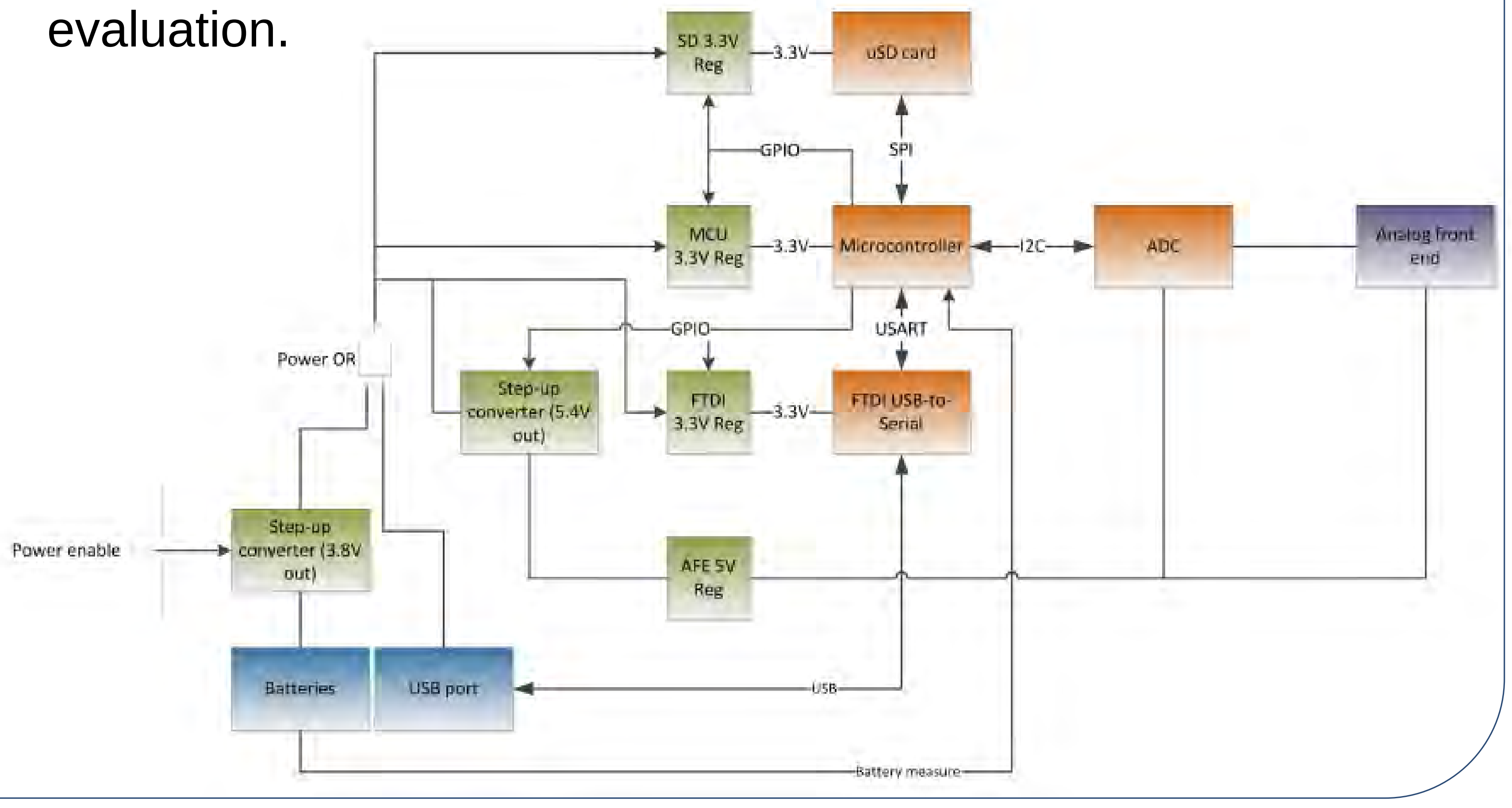






6. Block diagram of harvesting chain from water to battery

Monitoring functions are added around the chain, for performance evaluation.



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GPU-SPHEROS – Assessment of Constitutive Models for Silt Erosion Simulations

Sebastián Leguizamón, Ebrahim Jahanbakhsh, Audrey Maertens, Siamak Alimirzazadeh, François Avellan

1. General Information and Introduction

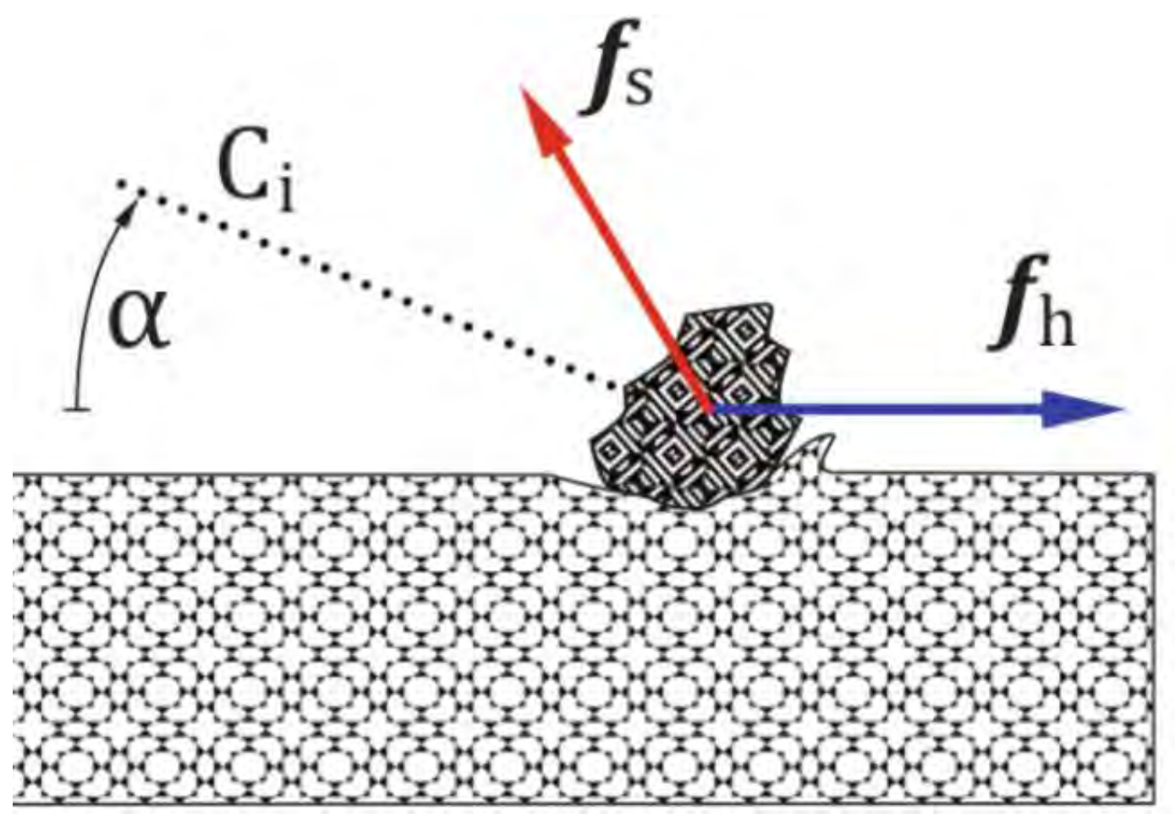
In the context of the energy strategy 2050, the optimized utilization of the available hydropower resources is a fundamental step in the restructuring of the Swiss energy system away from nuclear energy. However, the **erosion** occurring in turbomachine components, caused by repeated impact of silt particles, **decreases the efficiency** and entails frequent downtime intervals of **expensive repair**.

This investigation is part of CTI project No. 17568.1 PFEN-IW whose **objective** is to develop a numerical simulation code able to predict the erosion process. Silt erosion simulations are fundamental to **understand the phenomenon** and **quantify the effect of the governing parameters**, with aims at better design and maintenance methodologies.

GPU-SPHEROS is an implementation of the **Finite Volume Particle Method.** As a particle method it can naturally handle free surfaces and very large deformations typical of eroded surfaces, whereas as a Finite Volume Method it is both consistent and conservative. In development since 2010, the current work of the SPHEROS team has two aims. First, develop enhanced models to better capture the phenomenon at hand. Second, implement the code in the framework of graphic processing unit (GPU) architecture, which will enhance the code performance substantially. This poster covers the latest developments concerning the first of these aims.

2. Thermomechanical Modelling of Impacting Sediments

The impact of sediments against a metallic surface, illustrated below, is a **complex thermomechanical process** due to the very **high strain rates** suffered by the surface material. Such high rate of deformation entails an alteration of the material response in terms of strength and ductility. Furthermore, the heat produced by plastic deformation induces **thermal softening**, compromising the mechanical properties of the material.



To simulate the sediment impacts, a sufficiently complex constitutive model must be used to describe the solid behaviour. Such model should take into account the effect of strain rate, thermal softening, and work hardening. Additionally, a friction model must also be implemented.

3. Assessment of Constitutive Models

Several elasto-plastic constitutive models have been compared in order to chose the most appropriate one for the problem at hand:

- Linear strain hardening (**L-H**)
- Johnson-Cook (**J-C**)
- Temperature dependent Johnson-Cook (**J-C Temperature**)

An **erosion test case** involving collocated particle impacts at several impact angles and velocities has been used to **assess the constitutive models** in terms of their ability to accurately **predict the steady-state erosion rate**. The sediment transport by the water jet was not considered at this stage; the experimental data used for validation accordingly corresponds to a test rig which uses an air jet to convey the particles; the effect of the conveying jet on the sediment trajectories is therefore small.

The results of the test case, presented in **Figures 1 and 2**, confirm the importance of considering the effect of **strain rate** on the material response: The **J-C** model predicts a **much tougher material**, compared to the **L-H** model which neglects the strain rate dependence. It was also evidenced that taking into account the effect of **thermoplastic heating**, seen in model **J-C with temperature**, significantly affects the erosion rate prediction; indeed, the thermal softening of the material implies **increased ductility** and therefor higher erosion resistance. Furthermore, it was found that, in order to predict the **erosion at low impact angles**, a **friction model** is fundamental.

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[2] E. Avcu et al., *Acta Physica Polonica A* **125** 541-53 (2014)

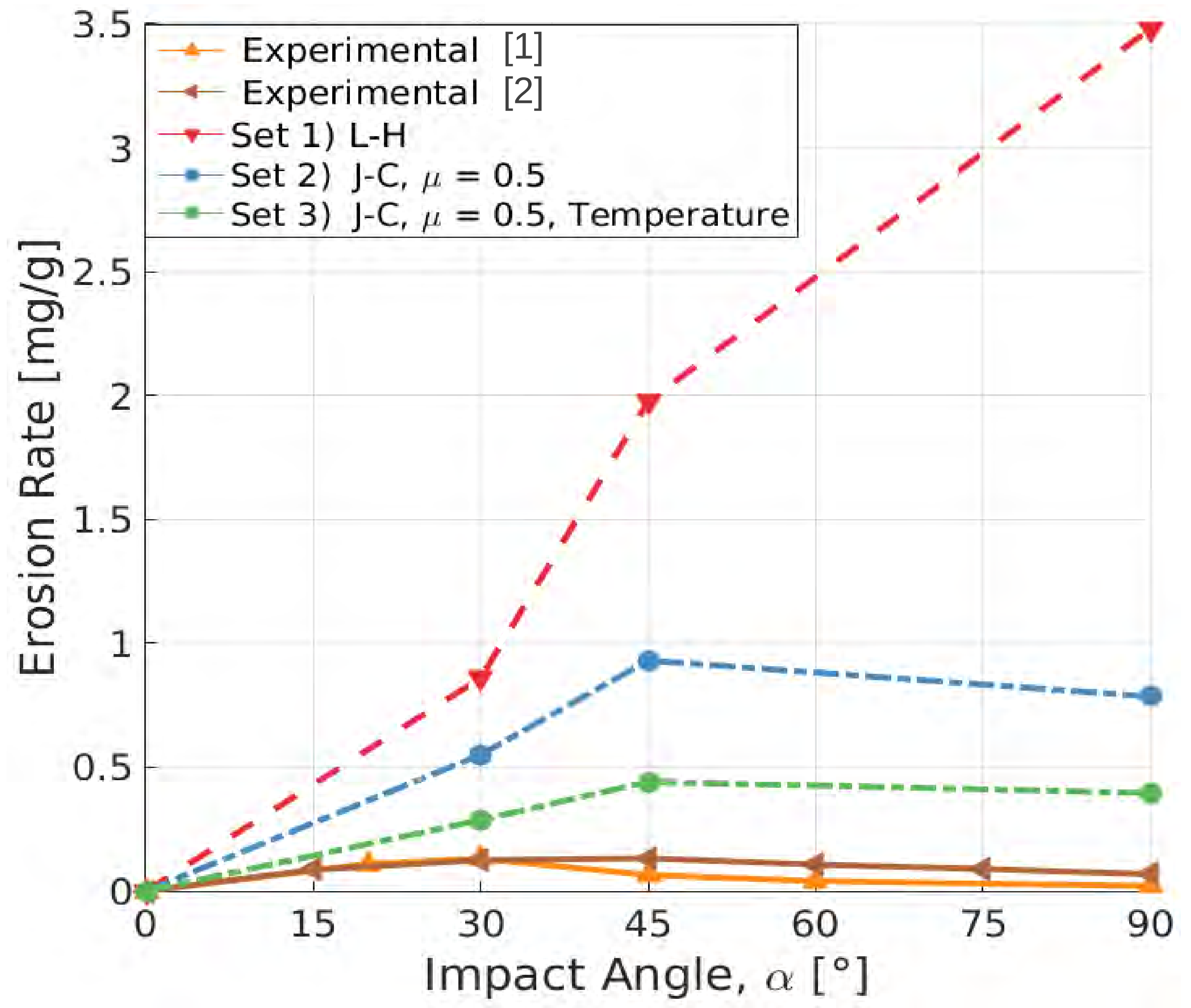
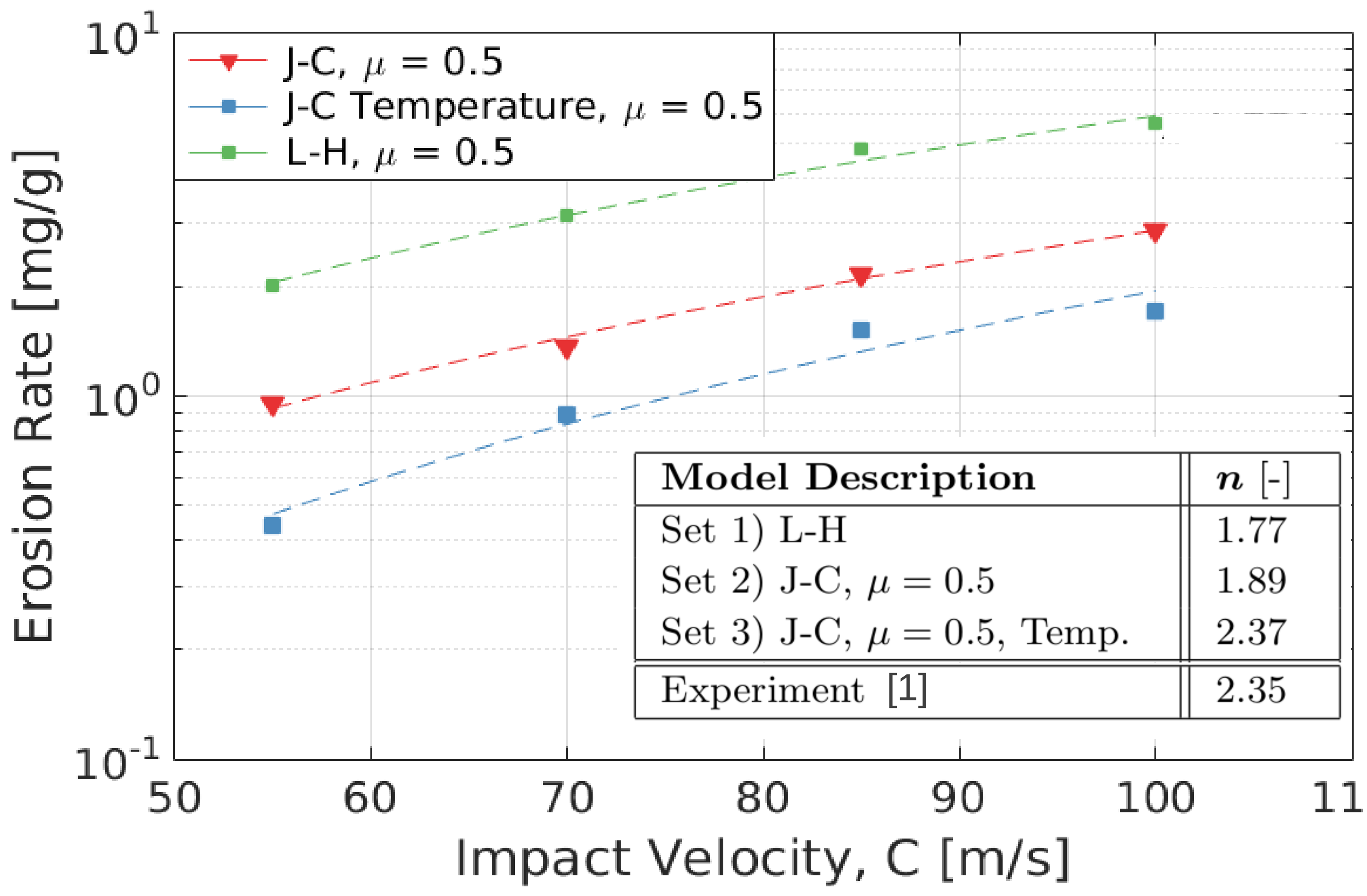


Figure 1. Erosion rate as a function of impact angle, at an impact velocity of 55 m s^{-1}.



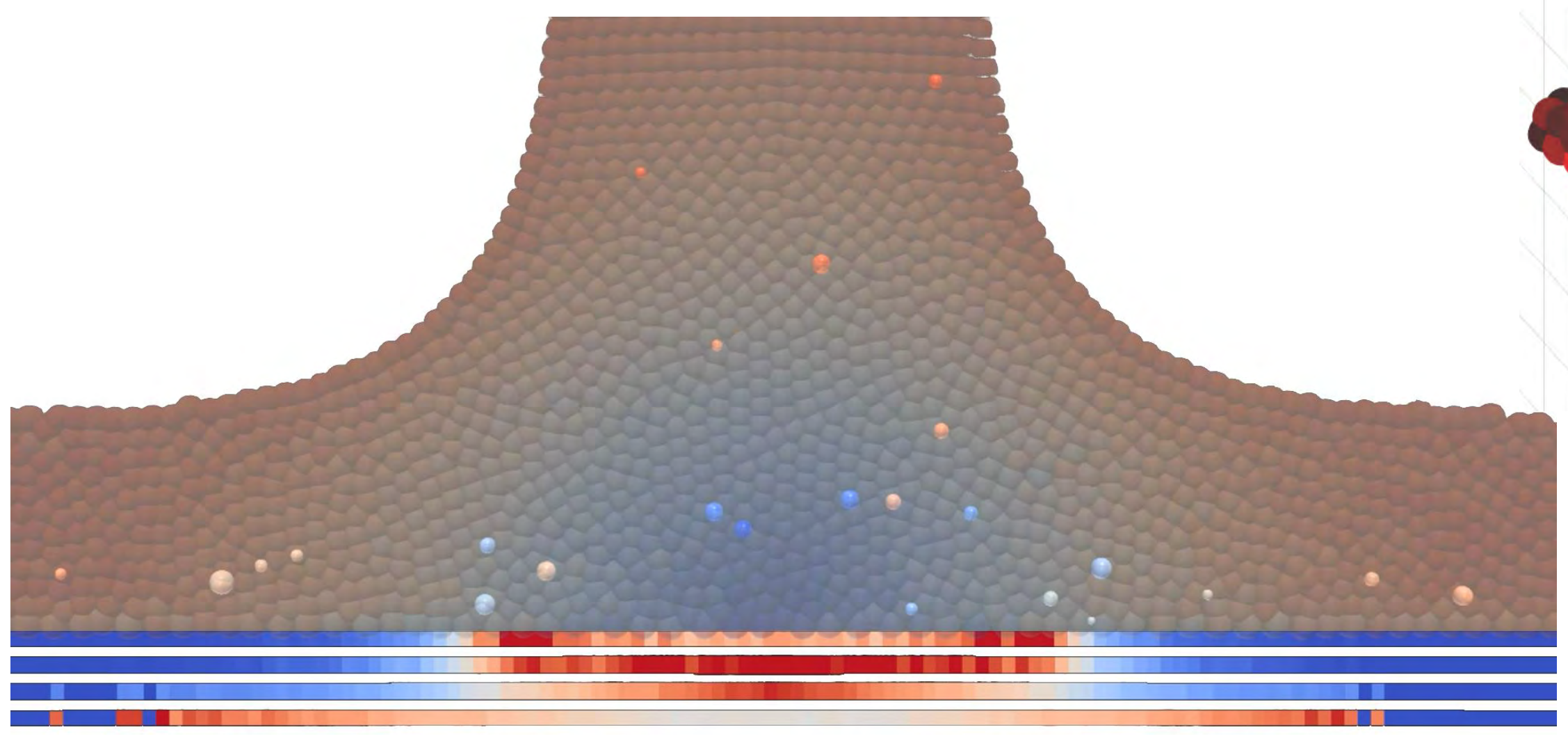
Model Description	*n* [-]
Set 1) L-H	1.77
Set 2) J-C, $\mu = 0.5$	1.89
Set 3) J-C, $\mu = 0.5$, Temp.	2.37
Experiment [1]	2.35

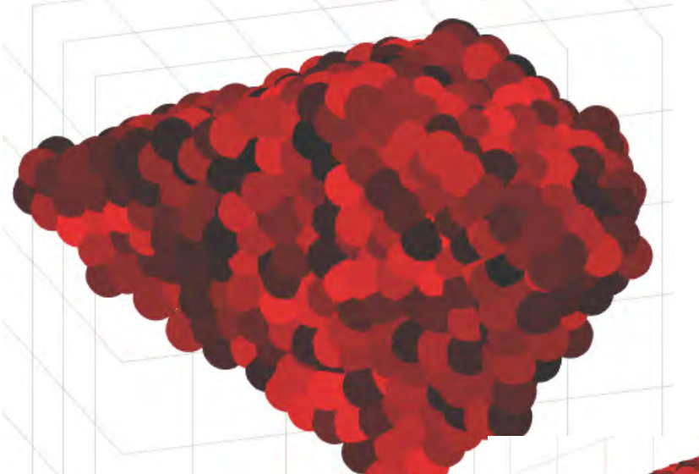
Figure 2. Erosion rate as a function of impact velocity, at an impact angle of 45°. Resulting velocity dependence exponent, *n,* presented in the table.

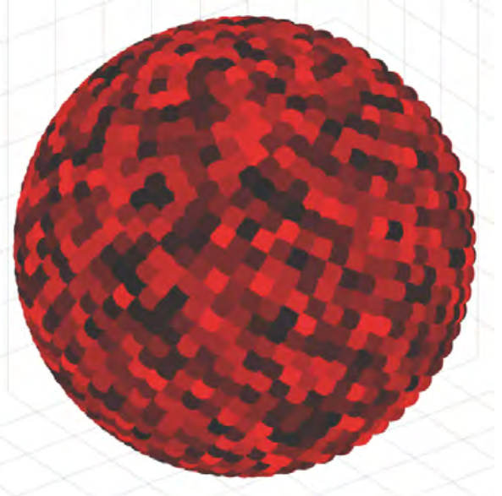
4. Discussion and Future Work

The **J-C model** considering temperature variation and friction **greatly improves the accuracy of GPU-SPHEROS** with regard to the simulation of the erosion phenomenon, compared to the original L-H model. This is evidenced both in the angle dependence, **Figure 1**, and the velocity dependence, **Figure 2**. Indeed, in both cases the improved modelling leads to predictions much closer to the experimental values.

Nonetheless, as presented in Figure 1, there is a **persistent discrepancy** in the erosion rate prediction as a function of impact angle. Even though we found that by changing the constitutive model parameters it is possible to precisely fit the experimental data, such fitting procedure was judged premature. Instead, **current work** is being performed to account for the **shape and elasticity of the sediment particles**, assumed spherical and rigid in the current study, as well as the **transport of the sediments by the fluid**. Preliminary results indicate that these improvements will render more accurate erosion rate predictions without the need for tuning the constitutive model parameters.







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SismoRiv *: An innovative system for bedload monitoring based on the measurement of seismic noise through river banks*

Travaglini Eric *, Ornstein Pascal *, Louis Mayencourt **, Joseph Moerschel **, Thierry Schneider ***

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crealp

Context

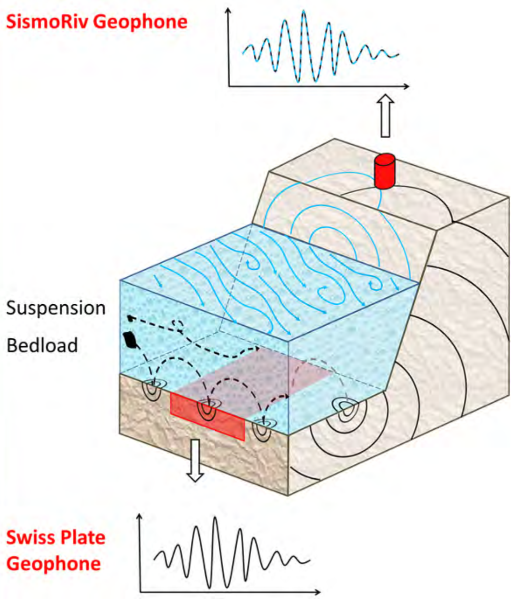
Sediment transport in watercourses results from bedload and/or suspension processes. Quantification of sediment transport is classically achieved through numerical equations that postulate a constant relation between sediment and water discharges. While this relation appears consistent over long period of time it doesn't in the short term, due to high variability, that making them poorly suited for analyzing sedimentary dynamics.

Within the current legal requirements of water protection in relation to revitalisation of watercourses, the monitoring of sediment transport, in space and time, represents a planning step for evaluating the disturbance of the bedload budget. Bedload real time monitoring could also help to prevent damages to hydraulic structure related to hydropower plants (intakes, tailwater reservoir).

Measurement Methods

In 2011, an experimental installation for measuring sediment transport based on the "Swiss Plate Geophone" technology developed by the WSL (Rickenman et al., 2012, 2014), was installed on the site of Zinal (VS). While transporting, sediment impact the river bed and generate vibrations. The latter are recorded by a set of geophones fixed underneath steel plates placed across the river channel. After a calibration process carried out in 2012, this station is now established as a reference measurement.

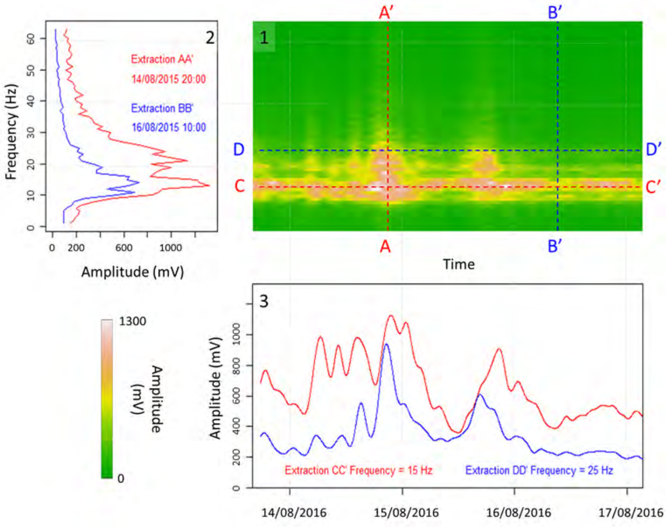
Based on work of Burtin et al. (2008, 2011), the CREALP proposes an innovative system for bedload monitoring based on the measurement of low-frequency seismic signal through river banks. With the support of the "Promotion des technologies environnementales" program founded by OFEV, a new measurement system was designed, implemented and tested during summer 2015 (SismoRiv project UTF 505.08.15)

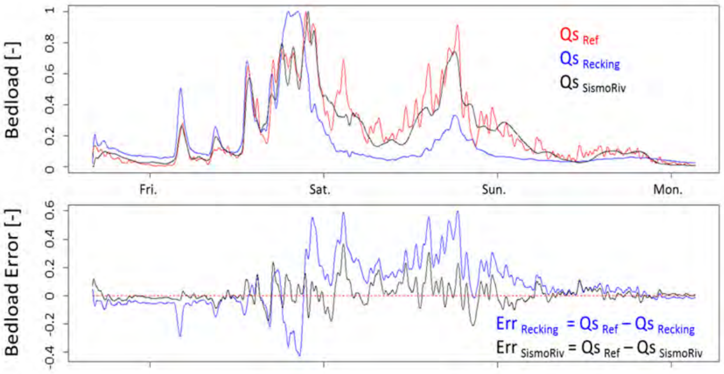


Preliminary Results

The spectrogram (1) decomposition shows :

- In the frequency domain (2) shows peak of high amplitude in frequency range of 10 to 30 Hz as reported by Gimbert et al. (2014)
- In the time domain (3) shows daily fluctuations that are coherent with the flow regime of the Navisence River (glacio-nival regime)





A preliminary analysis of results confirms the occurrence of frequency components representative for sediment and water discharges. Estimated bedload values inferred from seismic measurements ($Qs_{SismoRiv}$) show strong analogy with values provided by the reference station (Qs_{Ref}).

Furthermore the SismoRiv measurement system also allows to significantly minimize the error with respect to the estimations obtained from literature ($Qs_{Recking}$). These first results are promising and highlight the potential of SismoRiv system to monitor sediment transport.

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Prediction of a Power Plant stability while operating with a Francis turbine at partial load

J. Gomes, C. Landry, S. Alligné, C. Nicolet and F. Avellan

Introduction

This work is part of the HYPERBOLE research project (ERC/FP7-ENERGY-2013-1-Grant 608532), consisting of leading European universities and turbine manufacturers. The aim of the project is to contribute to the smooth integration of New Renewable Energies (NRE) through increasing the flexibility of hydropower plants.

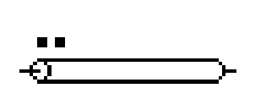
In order to extend the operating range of Francis and pump-turbines and avoid high levels of pressure pulsations and resonance, the better understanding of the physics behind its cavitation vortex rope is a mandatory step.

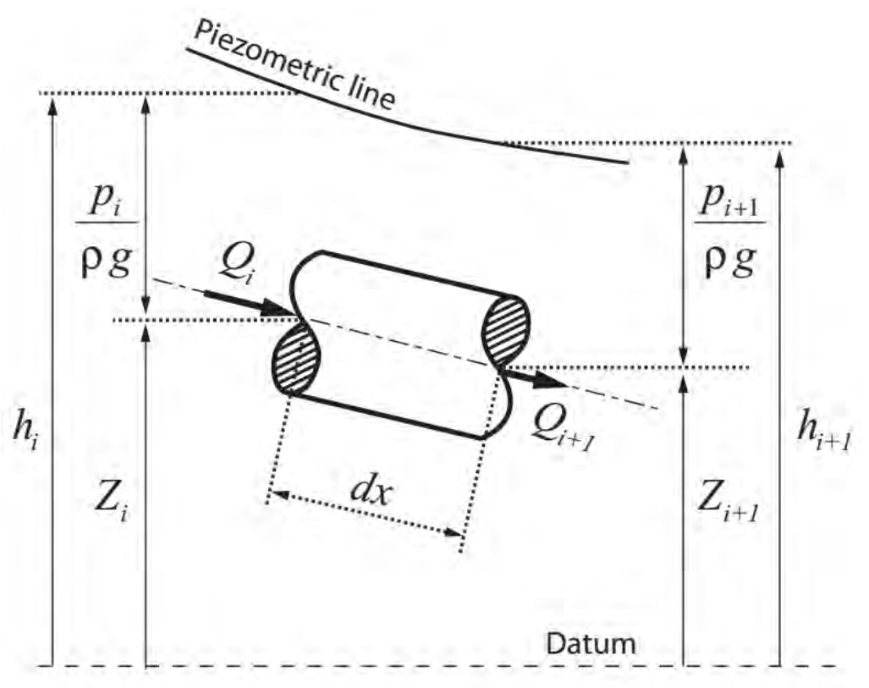
In this work, the most important properties of the cavitation vortex are obtained by testing the reduced scale model in a test rig. The results are then transposed to the prototype scale and the stability of the power plant is assessed.

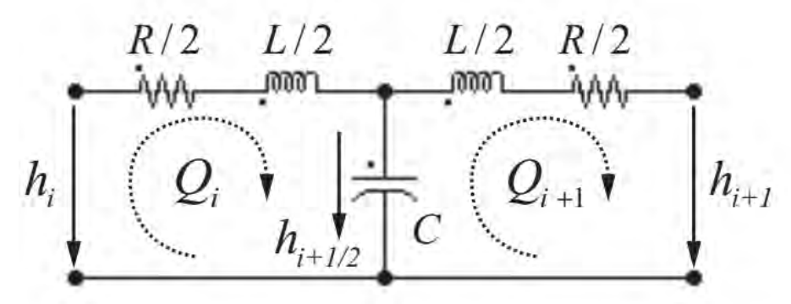
SIMSEN Modelling

Transforming the equations for conservation of mass and momentum into its electrical equivalent.

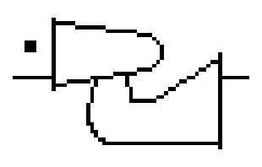
- Pipes

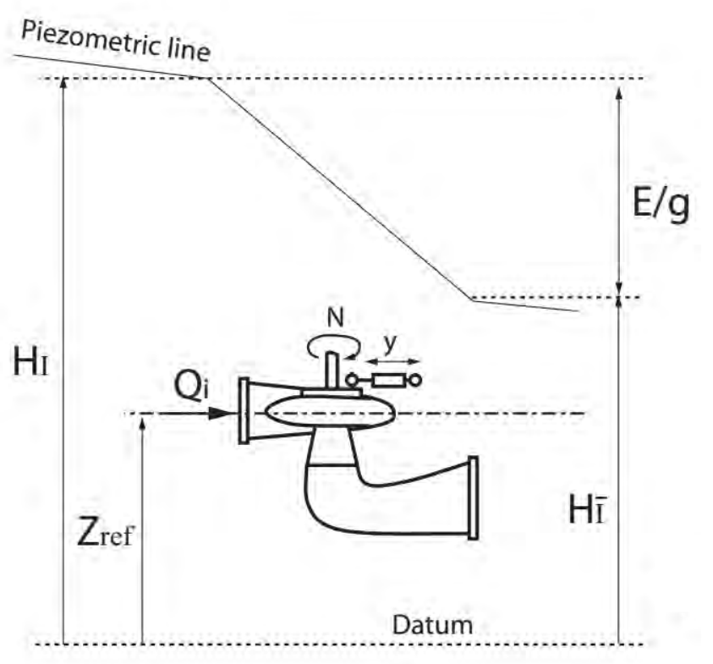


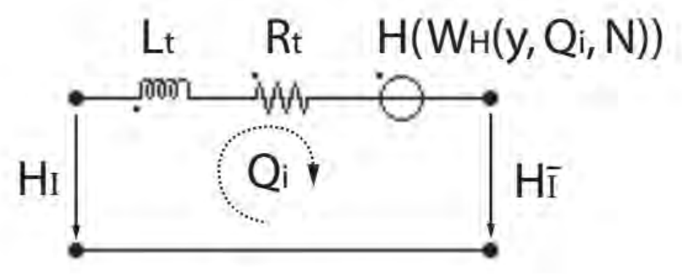




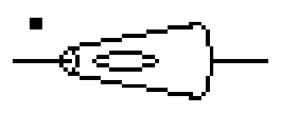
- Turbine

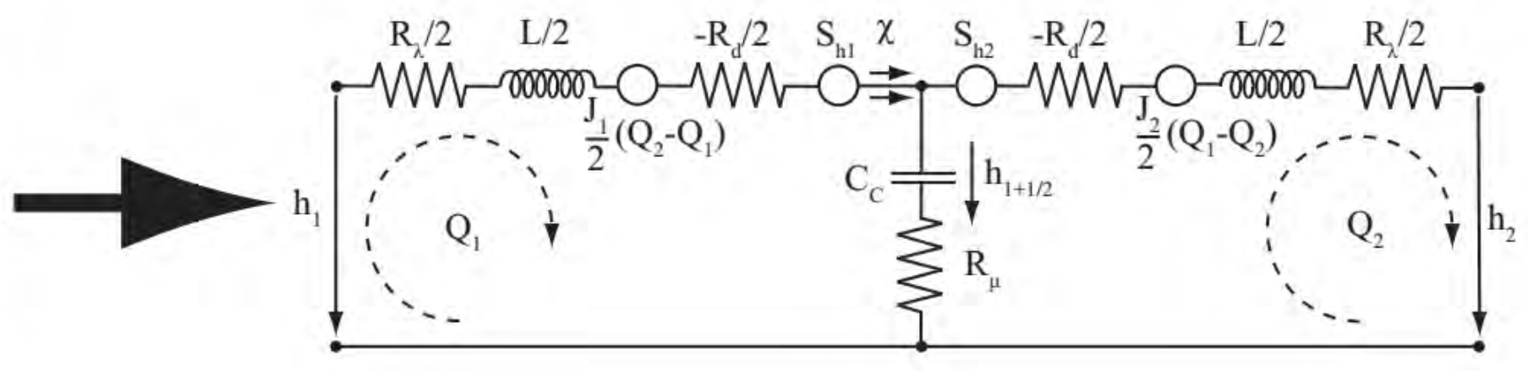






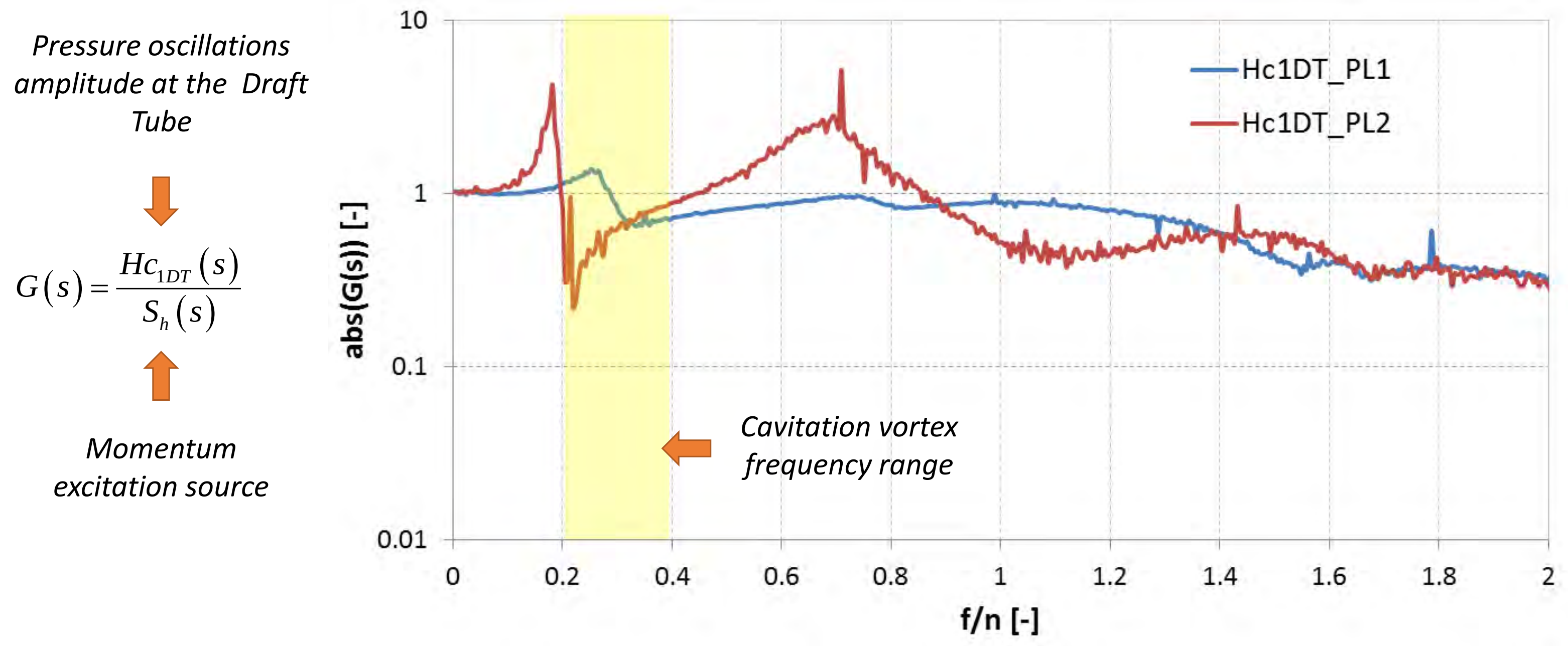
- Draft tube with cavitation vortex rope





Results

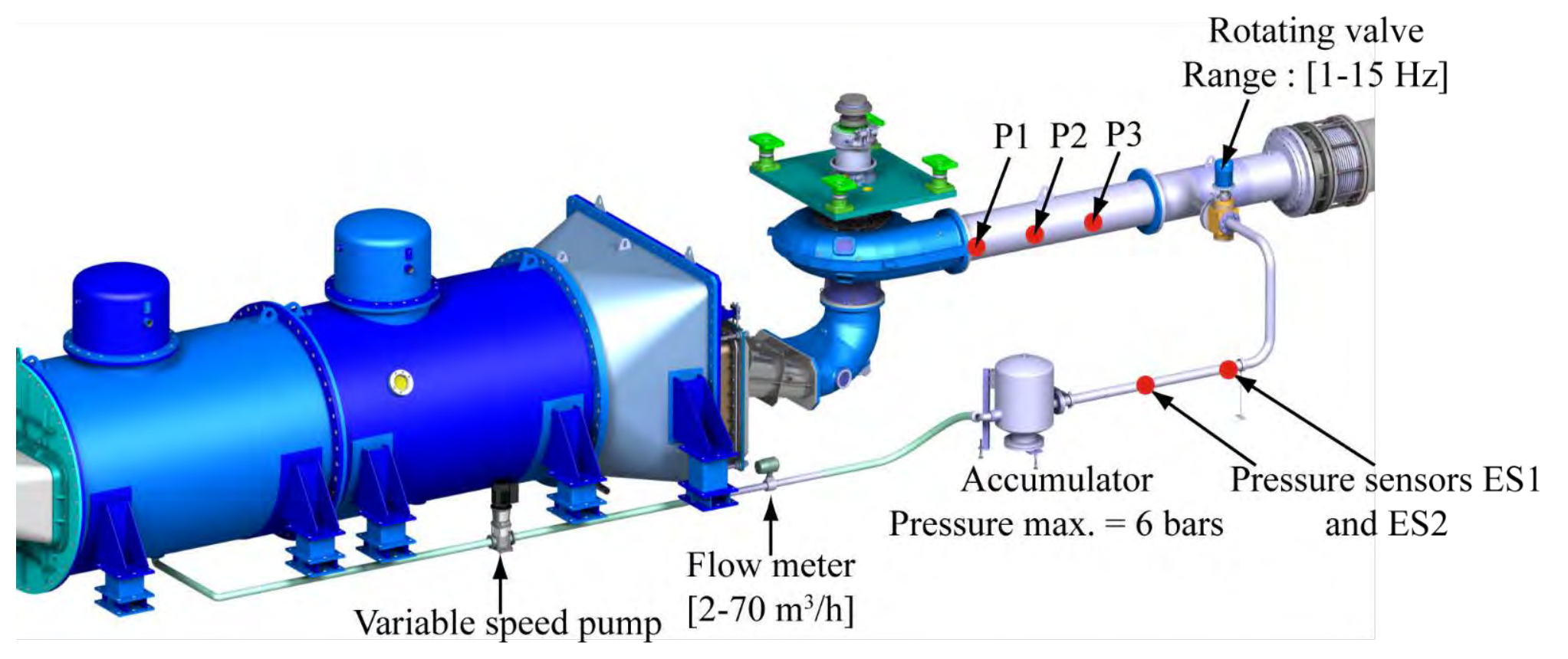
- ✓ Two operating conditions at part load were considered.
- ✓ For the operating point PL1, the first natural frequency of the hydro-mechanical components of the plant is excited by the cavitation vortex, but the pressure oscillations amplification is rather small.
- ✓ For the operating point PL2, the resonance frequencies are not excited by the cavitation vortex.



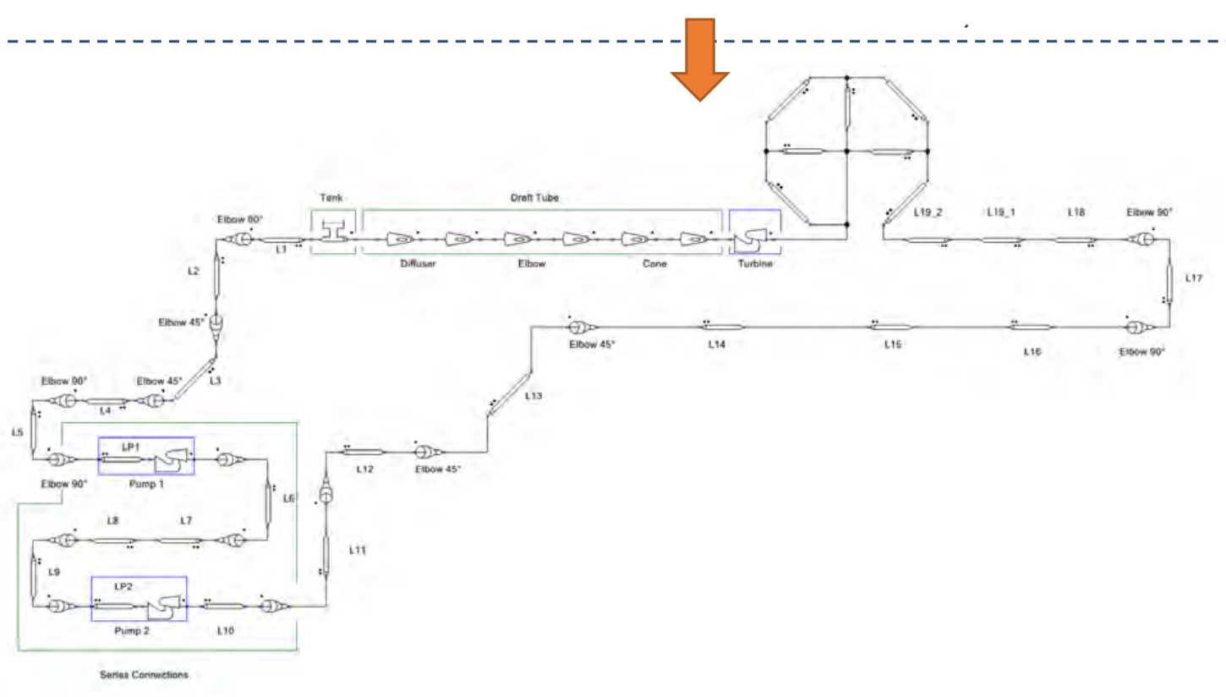
$$G(s)=\frac{Hc_{1DT}(s)}{S_h(s)}$$

Methodology

Model testing



SIMSEN model of the test rig



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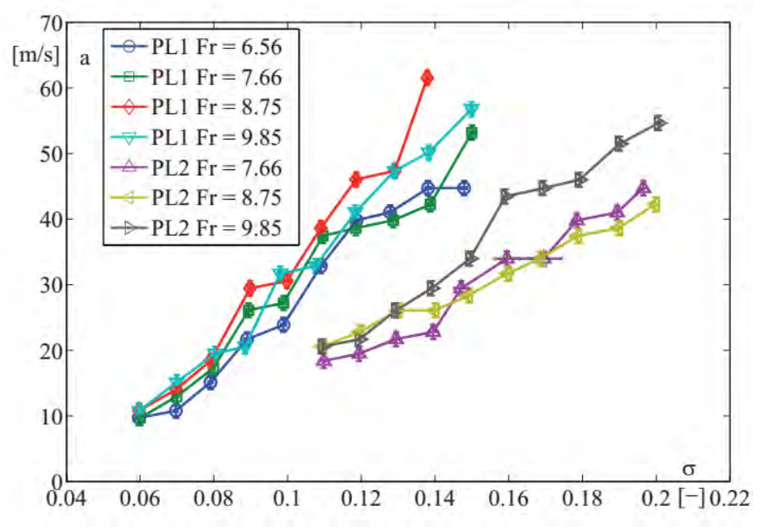
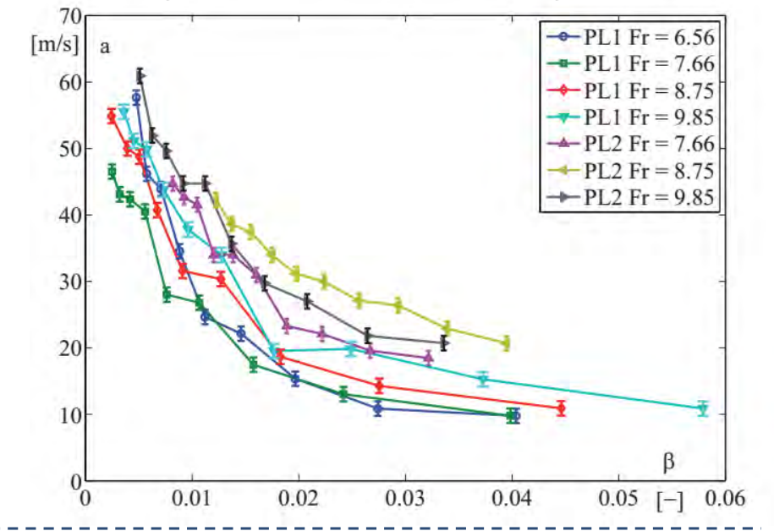
Cavitation vortex parameters determination

Wavespeed as a function of the Thoma number σ.

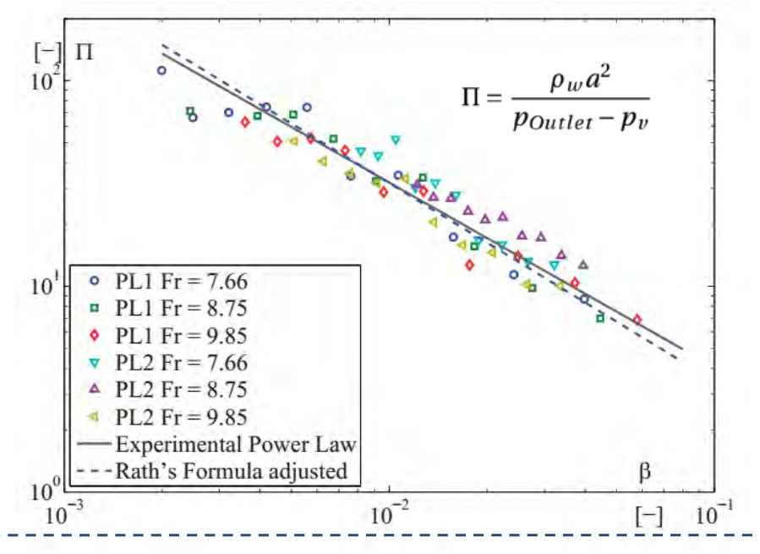


Wave speed as a function of void fraction in the draft tube.

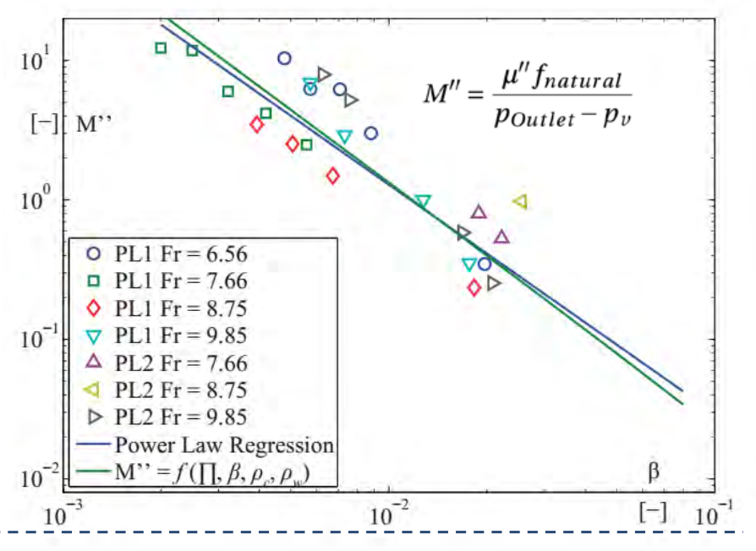


Parameters transposition to prototype scale

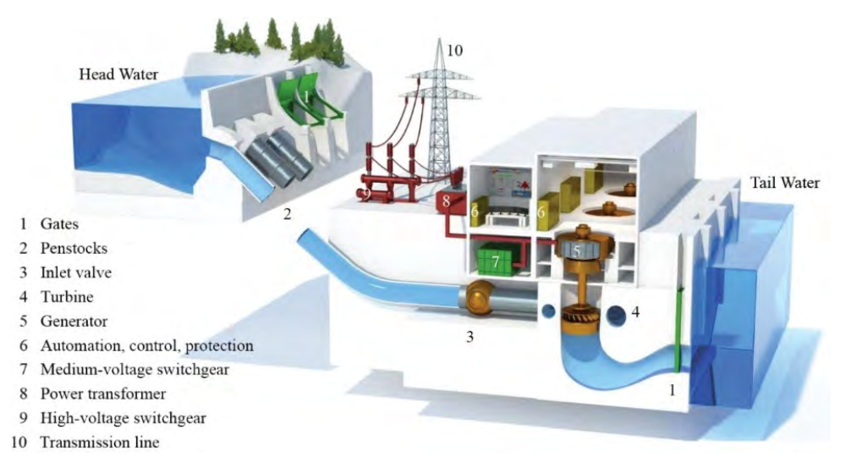
Dimensionless wave speed number as a function of the void fraction.



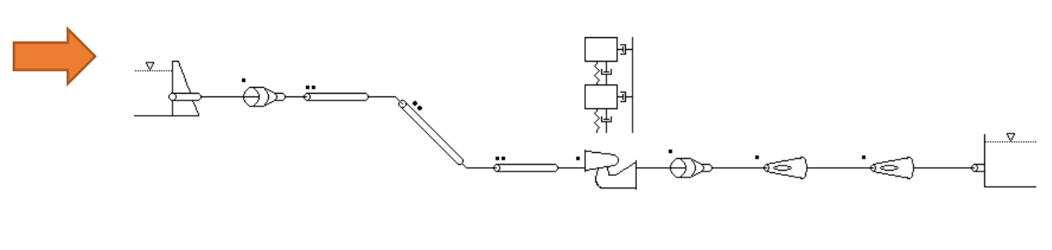
Dimensionless viscosity number as a function of the void fraction.



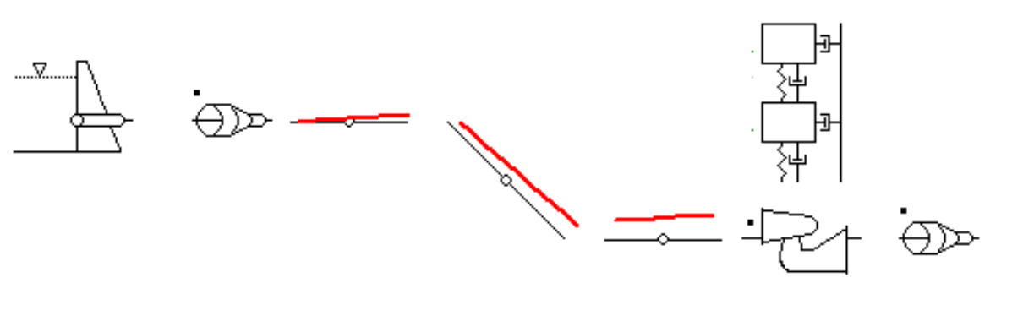
SIMSEN model of the power plant



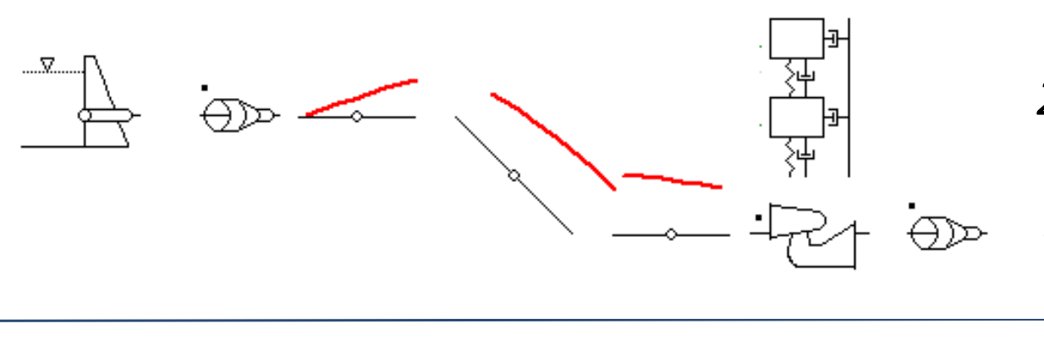
Modeling of the hydro-mechanical components in SIMSEN



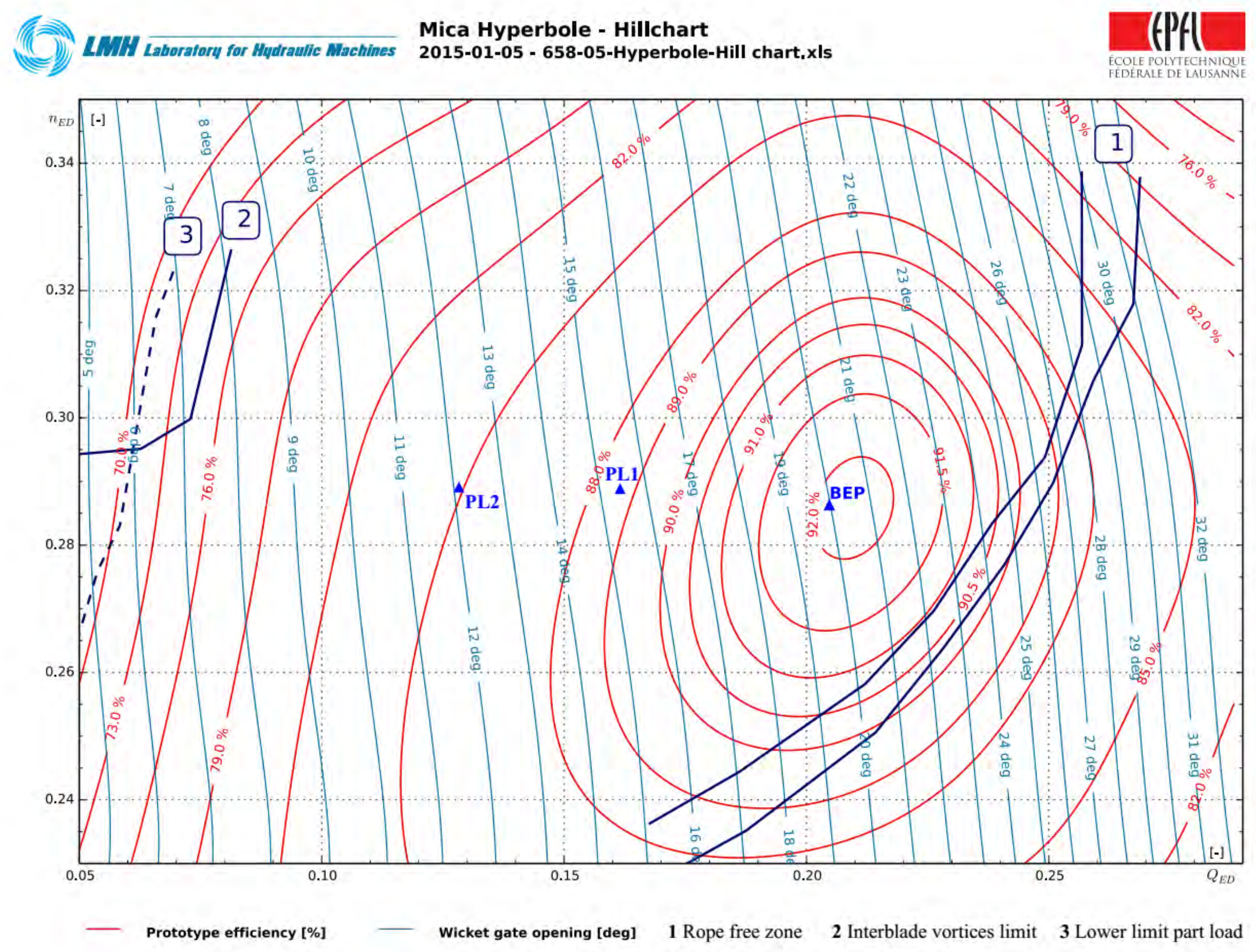
Assessment of the power plant stability



1st. pressure eigenmode



2nd. pressure eigenmode



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