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

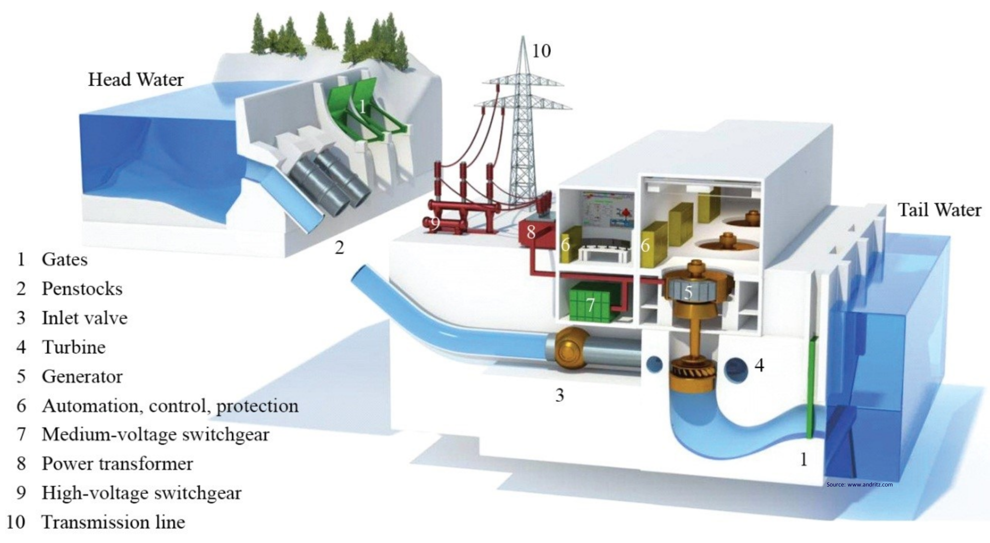
A. Müller, A. Favrel, K. Yamamoto, C. Landry and F. Avellan

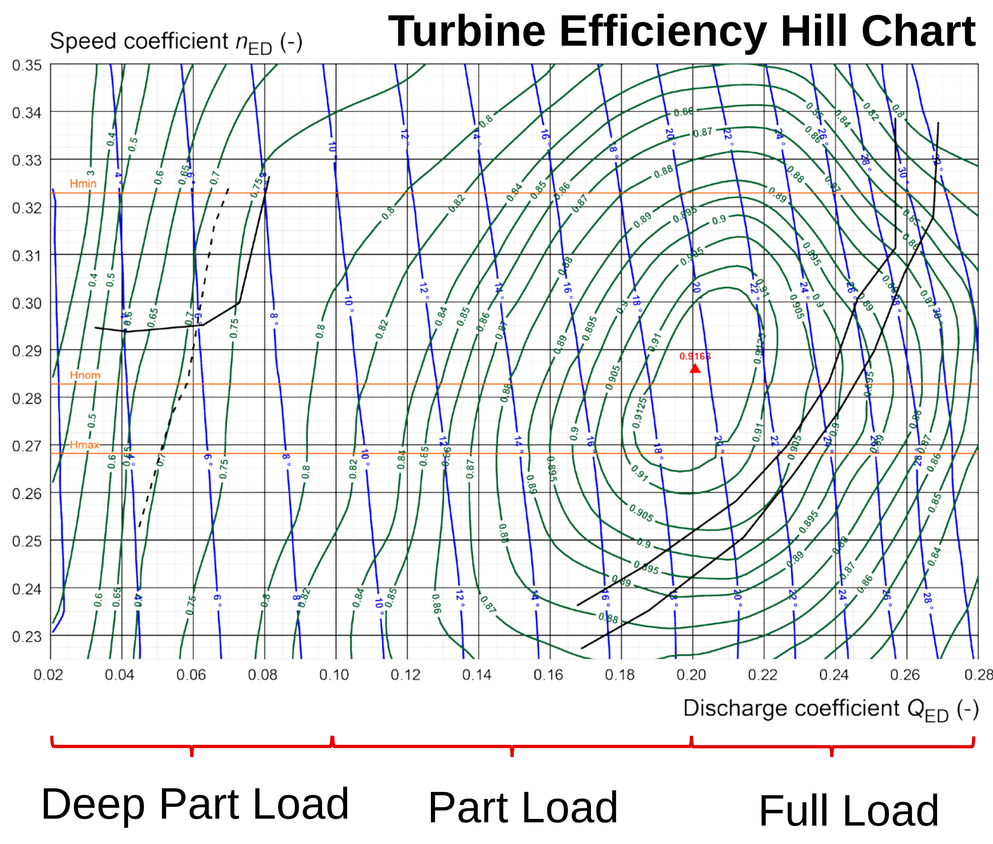
Context

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.

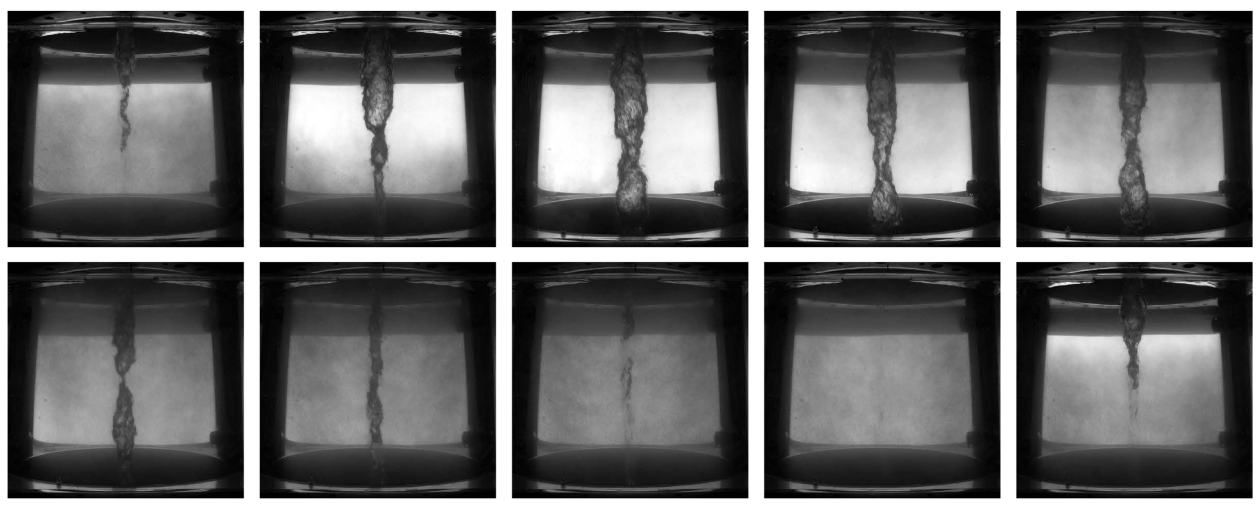
The HYPERBOLE research project (ERC/FP7- ENERGY-2013-1-Grant 608532), consisting of leading European universities and turbine manufacturers, aims at making a decisive contribution towards the smooth integration of NRE. An important objective thereof is to reach a profound understanding of the underlying physical mechanisms leading to an unstable behaviour of the unit, by per-forming 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 hydro-power plants for electrical grid regulation in the course of NRE integration.





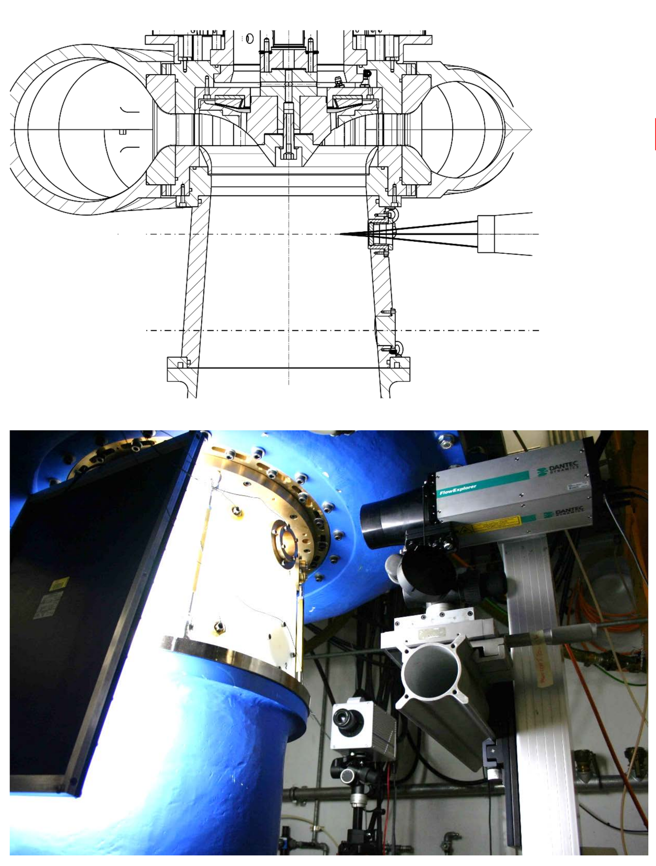
FULL LOAD



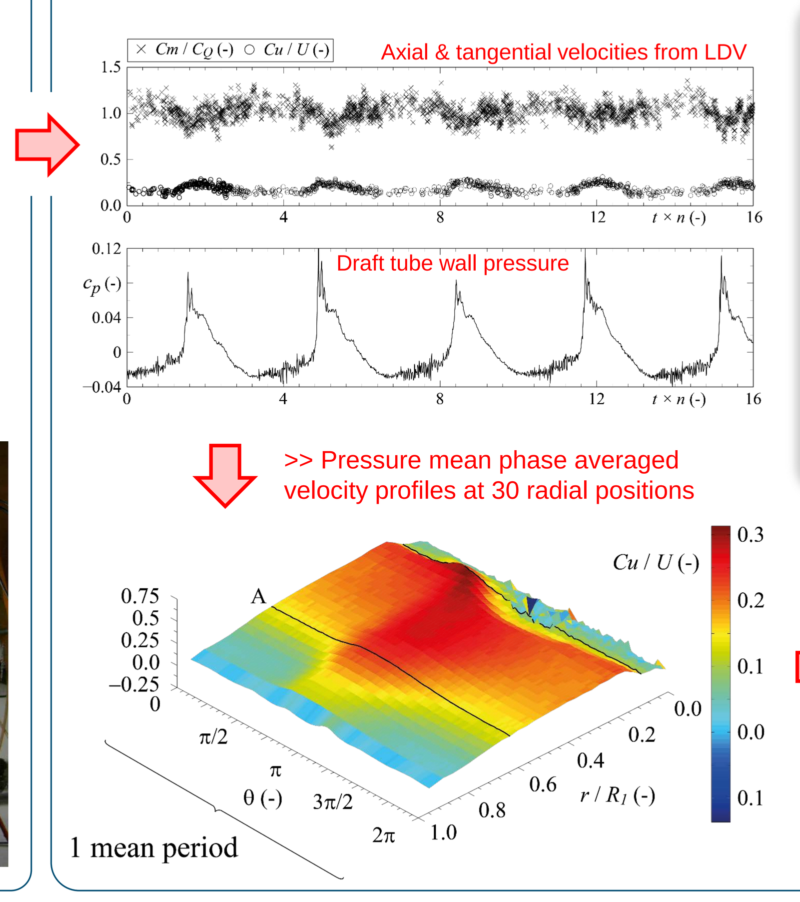
Problem: Self-excited oscillation of an axisymmetric cavitation vortex rope in the draft tube cone and of the hydro-electric system (wall pressure, mechanical torque on the runner shaft, electrical power).

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

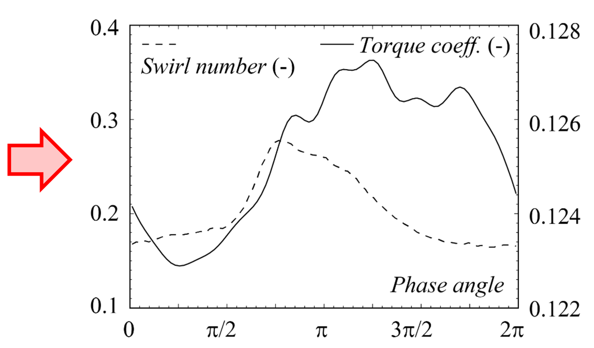
2-D LDV in the draft tube cone



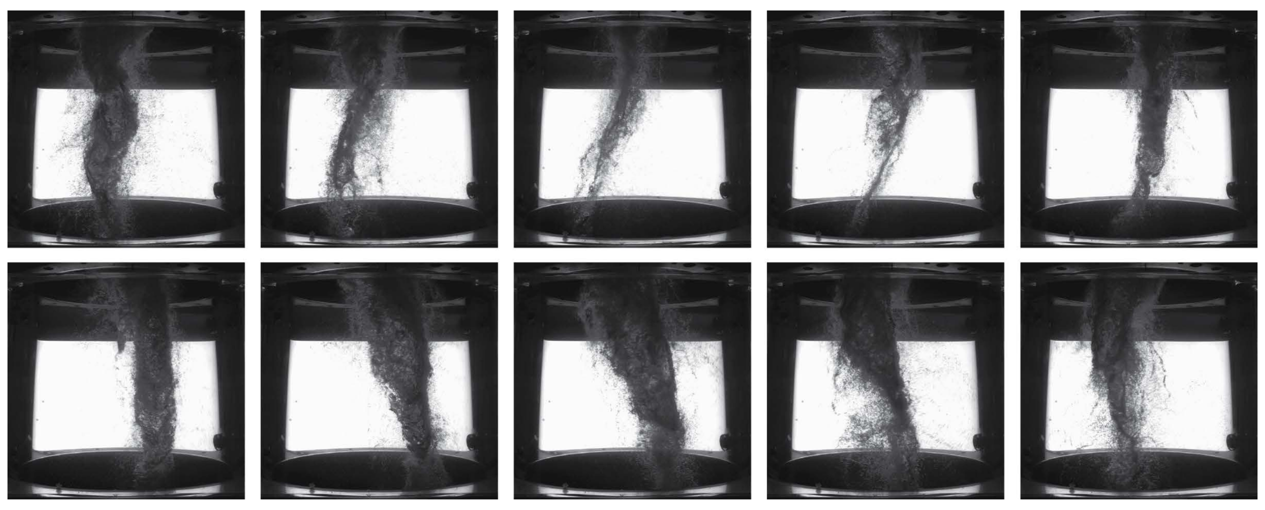
Pressure phase averaged velocity, flow swirl and torque



- ✓ 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.



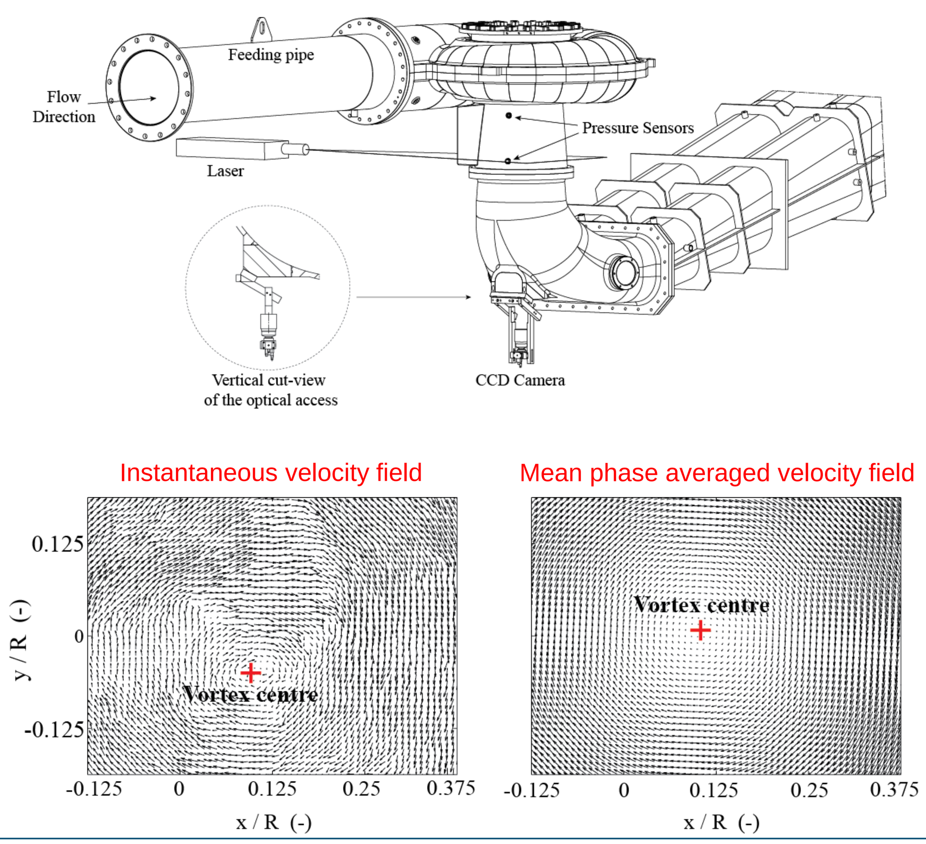
PART LOAD



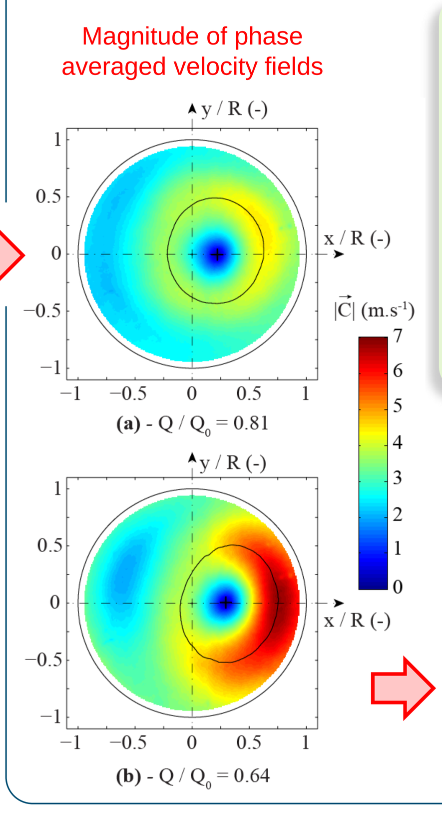
Problem: Development of a cavitation precessing vortex rope in the draft tube cone acting as an excitation source for the hydro-mechanical system >> risk of resonance jeopardizing the system stability.

Experimental approach: Study of the link existing between the pressure excitation source and the vortex structure by means of 2D-PIV synchronized with pressure measurements.

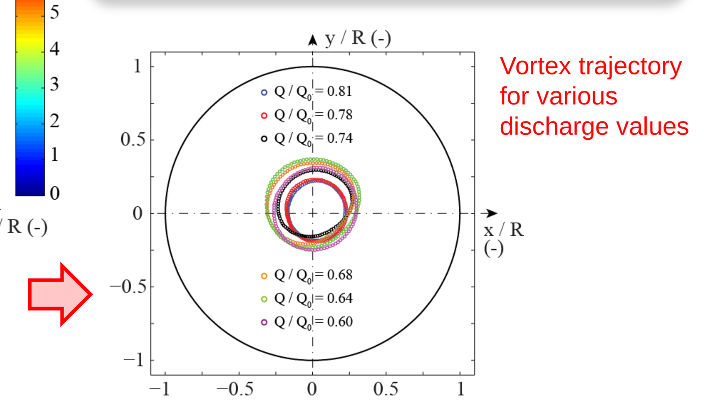
2-D PIV in the draft tube cone



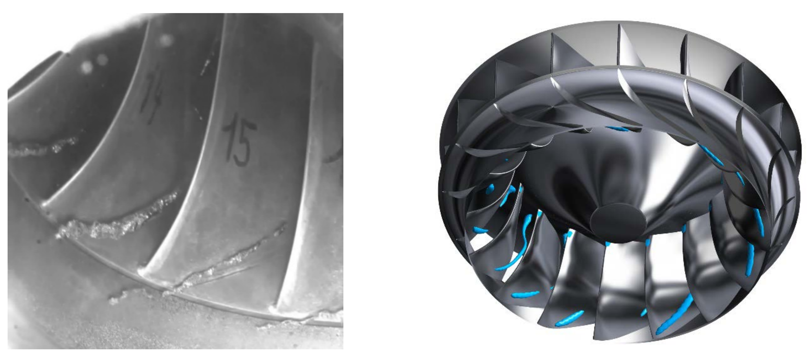
Phase averaged velocity field and average vortex trajectory



- ✓ Determination of the evolution of the vortex parameters (trajectory and circulation) with the discharge.
- ✓ Linking of the evolution of the precession frequency to excitation source strength.



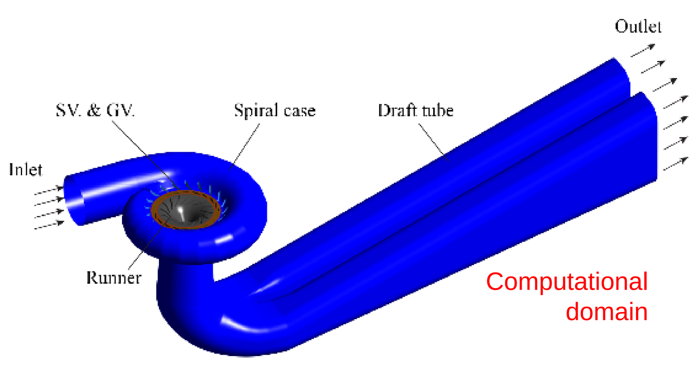
DEEP PART LOAD



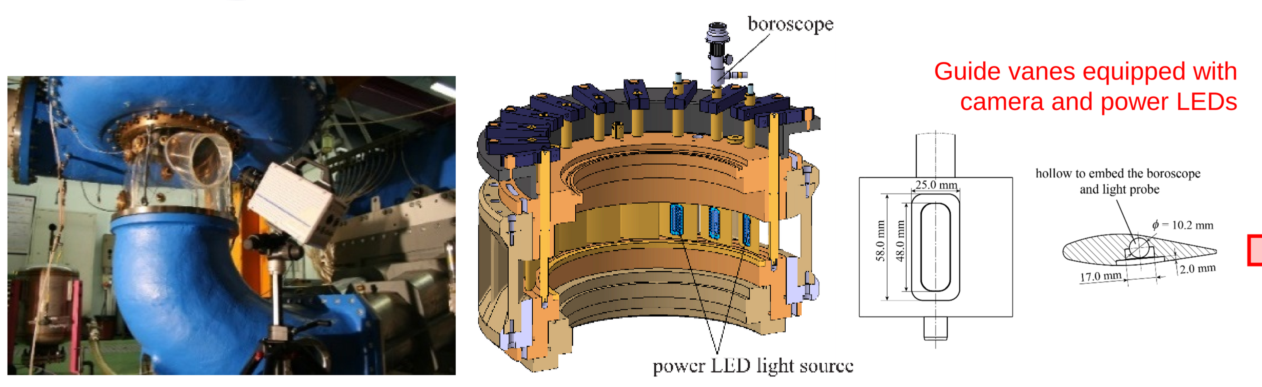
Problem: Formation of cavitation vortices in the inter-blade channels (inter-blade vortices) with unknown draft tube flow interaction and erosive potential.

Investigative approach: Detailed characterisation of the vortex dynamics by high-speed visualization and numerical simulation of the inter-blade channel and draft tube flow.

Unsteady RANS simulation and high-speed visualizations

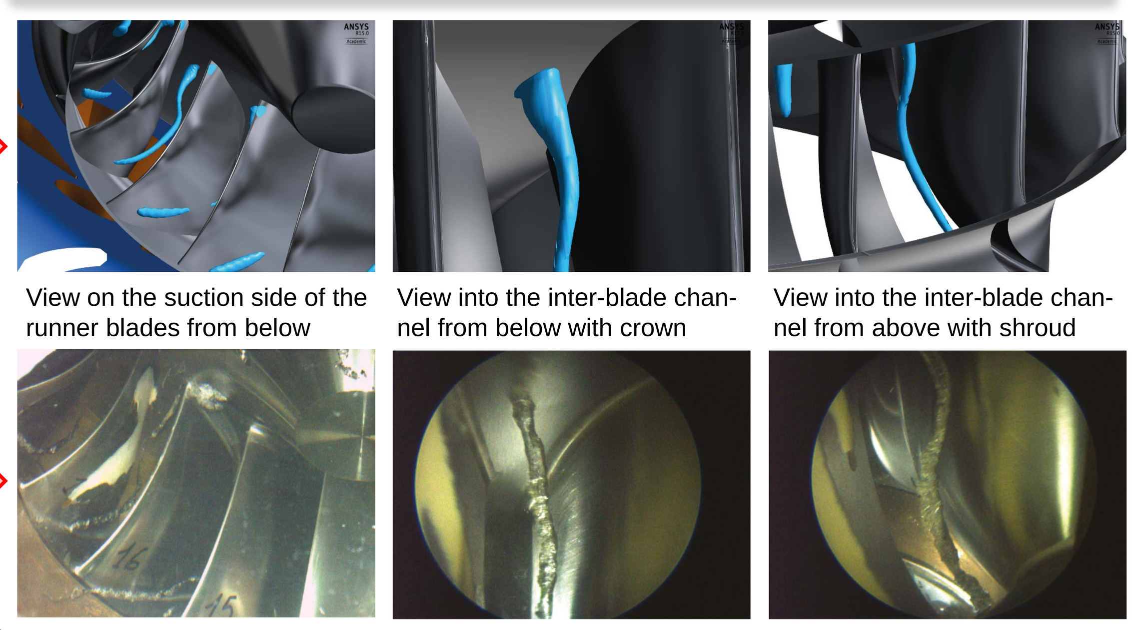


- ✓ Homogeneous fluid (water and vapour) with SST-SAS turbulence model.
- ✓ Cavitation model based on Rayleigh-Plesset equation.
- ✓ Mesh: 16 million nodes.



Successful simulation of inter-blade vortices

- ✓ Experimentally validated simulation of the vortex dynamics in the inter-blade channels by innovative visualization tools.



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Prediction of Francis turbine pressure fluctuations through hydro-acoustic modelling of a reduced scale physical model

C. Landry, J. Gomes, A. Müller, A. Favrel, K. Yamamoto 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 accurately predict and simulate off-design operating conditions. The presence of the cavitation vortex rope in the draft tube requires a numerical pipe element taking into account the complexity of the two-phase flow.

Methodology

Among the hydroacoustic parameters describing the numerical model of the cavitating draft tube flow, three unknown parameters require a special attention: the wave speed, the bulk viscosity and the pressure source. A new methodology was developed to model these parameters:

1) Identification of the natural frequency with a excitation system
2) Modelling of the experimental test rig with SIMSEN software
3) Identification of the hydroacoustic parameters
4) Transposition of hydroacoustic parameters to the full-scale turbine
5) Modelling of the hydroelectric power plant with SIMSEN software
6) Dynamic simulation and prediction of pressure pulsations for the full-scale turbine

Actual practice

Model testing (IEC 60193)

Experimental results (Pressure fluctuation, torque, …)

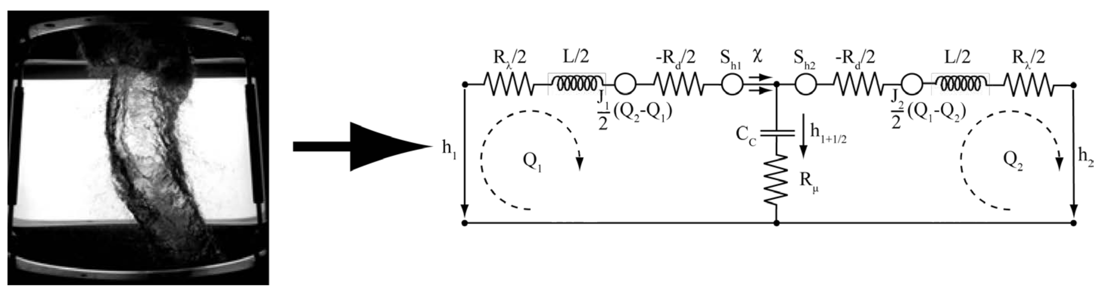
Clouds of unknown prediction quality +/-30% … +/-200%

Experimental results (Pressure fluctuation, torque, …)

Goal: prediction quality +/-20%

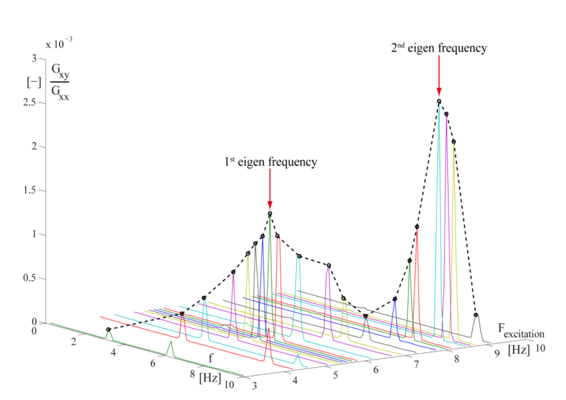
Procedure developed within HYPERBOLE

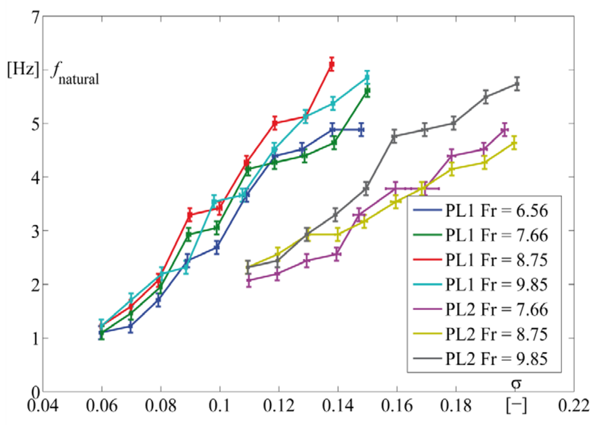
Draft tube model



- ✓ R_λ = Energy losses
- ✓ R_d = Divergent geometry
- ✓ R_μ = Viscosity term
- ✓ L = Inertia term
- ✓ C_C = Cavitation compliance
- ✓ S_h = Pressure source induce by vortex rope precession
- ✓ J = Convective term

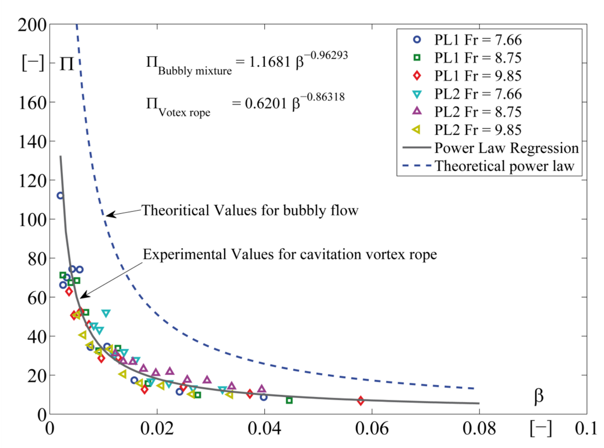
Natural frequency identification



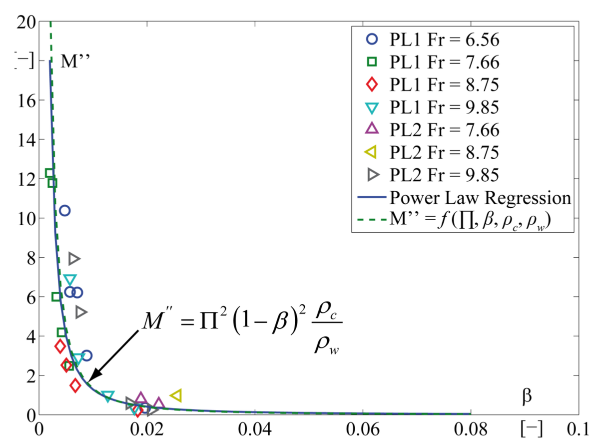


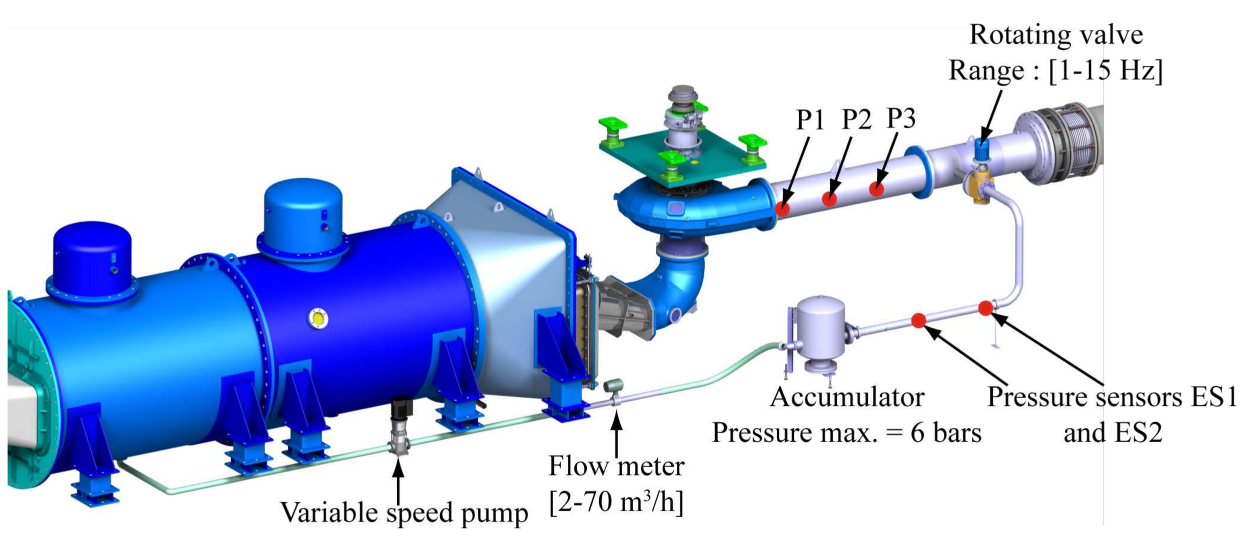
Hydroacoustic parameters

✓ Dimensionless wave speed



✓ Dimensionless bulk viscosity





Reduced-scale physical model

Transposition from the model to the prototype

The following equations are defined to transpose the draft tube wave speed and bulk viscosity from the model to prototype values:

$$a^P = a^M \left(\frac{D^P_{ref}}{D^M_{ref}}\right)\left(\frac{n^P}{n^M}\right)$$

$$\mu''^P = \mu''^M \left(\frac{D^P_{ref}}{D^M_{ref}}\right)^2 \left(\frac{n^P}{n^M}\right)^2 \left(\frac{f^M_{natural}}{f^P_{natural}}\right)$$

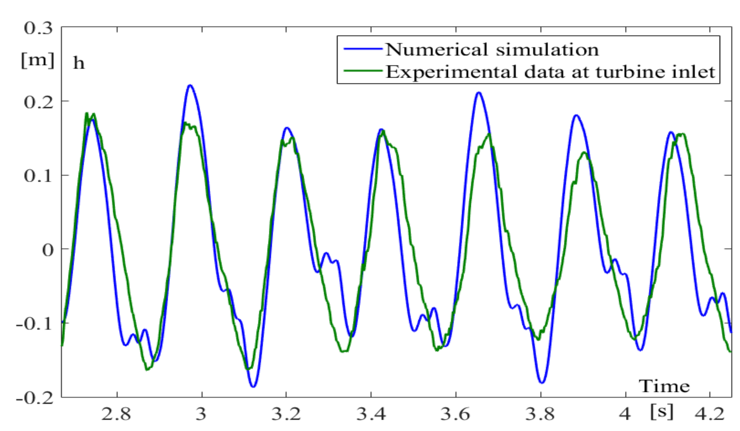
Numerical model of the hydroelectric power plant

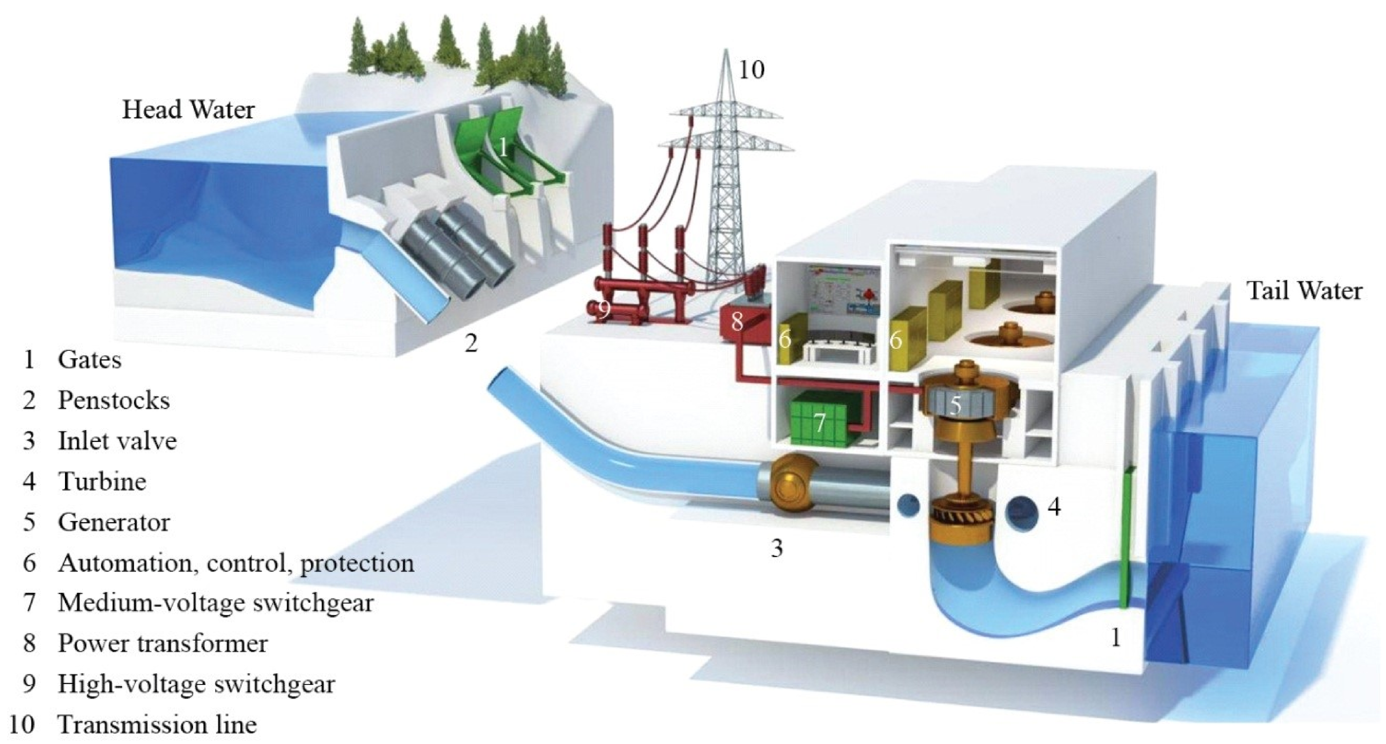
Full scale & Power units dynamic simulation

Full-scale turbine

Validation

To validate the identified hydro-acoustic parameters, a time simulation is performed at resonance conditions and the numerical results are compared with experimental data.





Conclusion and future works

This work presents a methodology to identify important parameters describing the behaviour of the cavitation vortex in a Francis turbine operating at partial load. The methodology is based on a numerical model and experimental measurements.

Transposition laws to the prototype are developed. Future works include measurements on an operational hydropower plant.

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Stability Analysis and Optimal Control of a Francis Turbine Vortex Rope

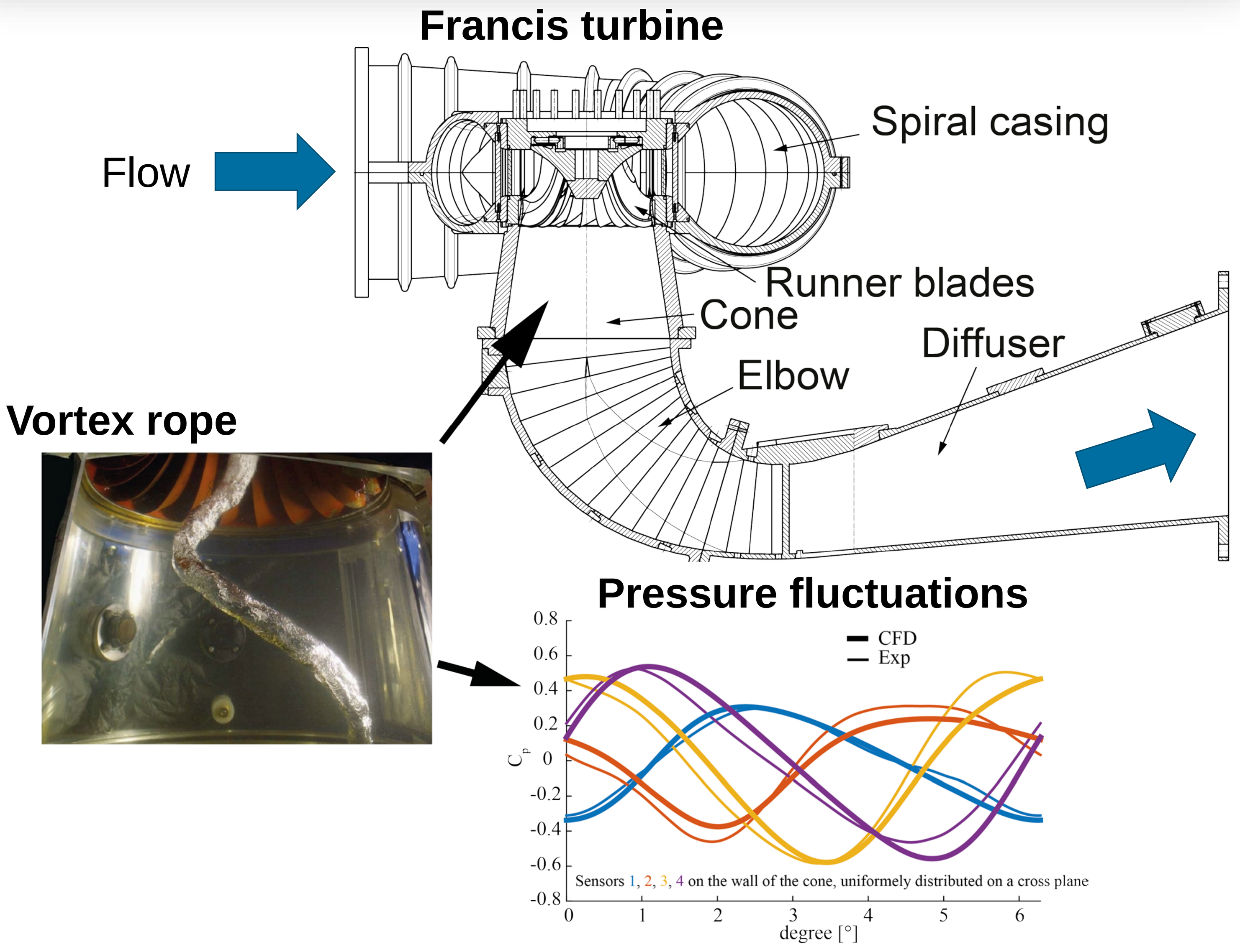
Pasche S., Gallaire F., Avellan F.

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.



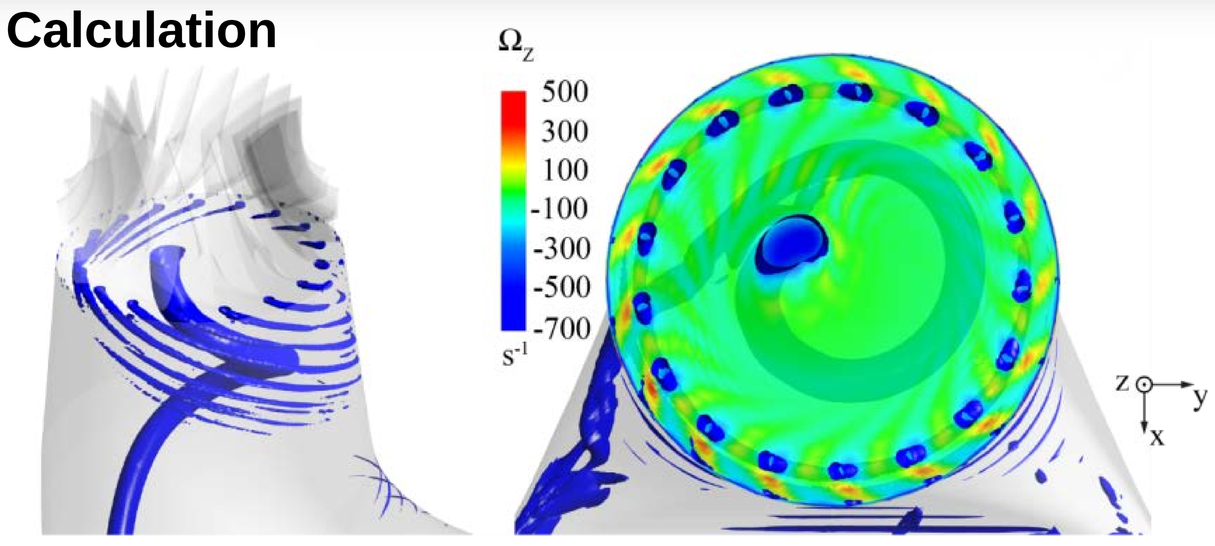
Objectives

- 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

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

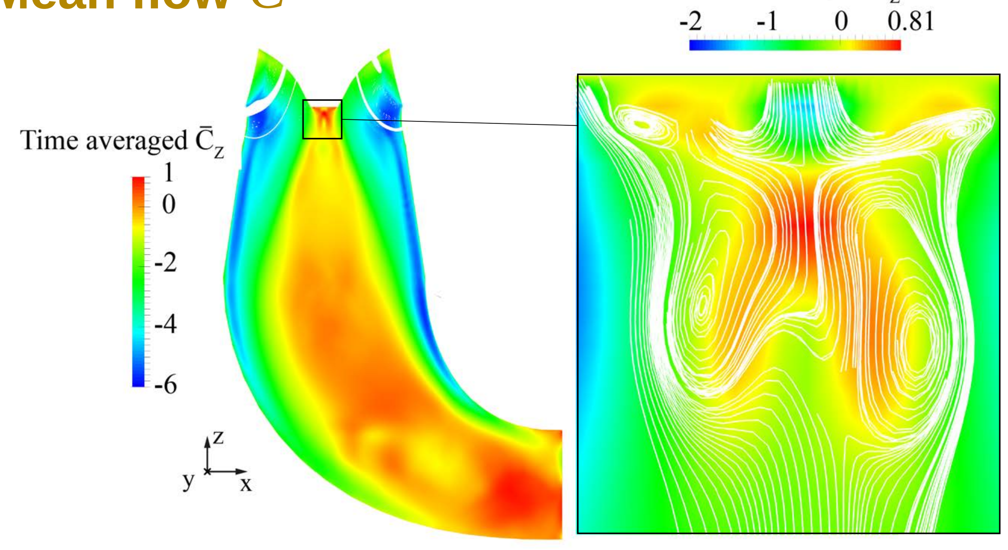
$$q'(R,\theta,Z,t)=\hat{q}(R,Z)\exp(i(m\theta-\omega t))$$

$$\nabla\cdot\hat{C}=0$$

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

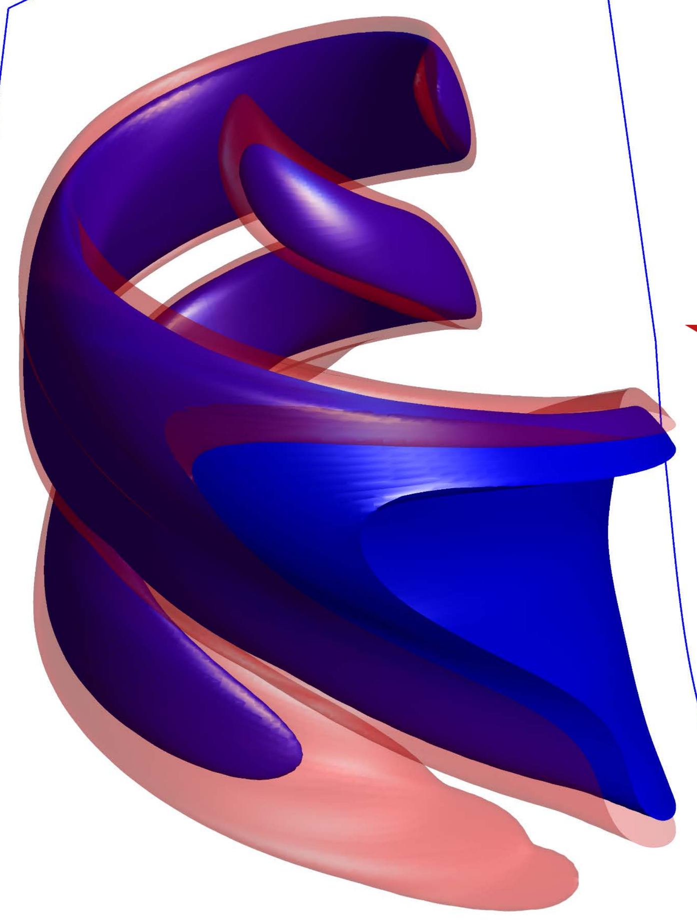
Turbulence term

Mean flow $\bar{C}$

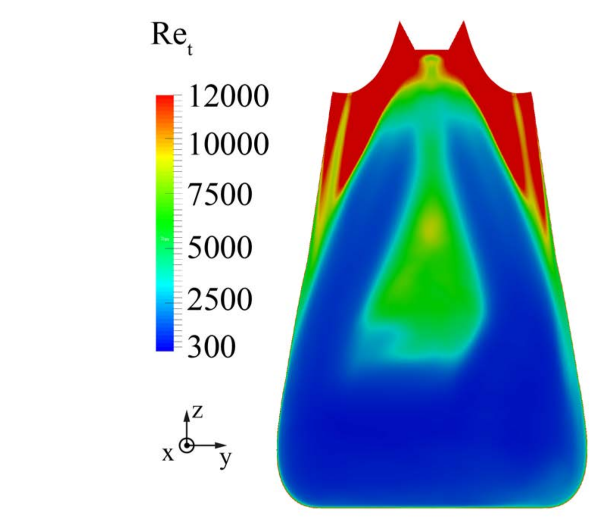


Time averaged flow field of the axial velocity of the CFD calculation and buble region

Vortex Rope, an Unstable Eigenmode

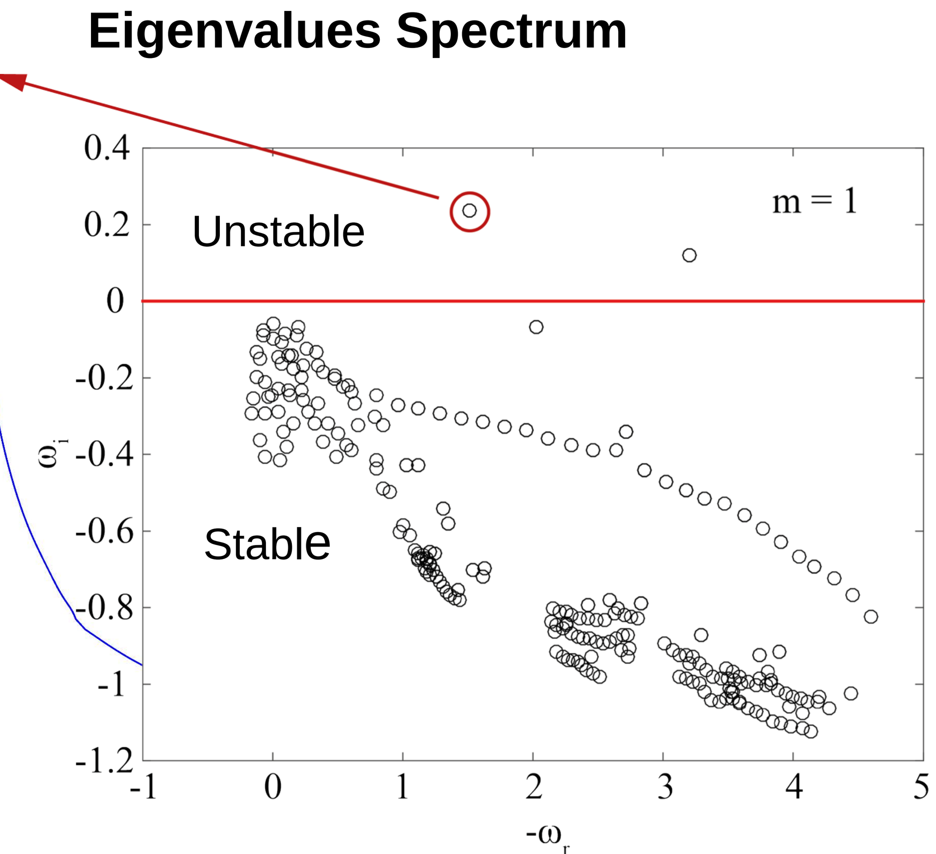


Turbulent Reynolds number Re_t



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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Versuchsanstalt für Wasserbau,
Hydrologie und Glaziologie

Supervision: Prof. Dr. Robert Boes
Dr. Ismail Albayrak
PhD student: David Felix

Effects of suspended sediment on turbine wear and efficiency

Introduction

Hard mineral particles transported in rivers (Fig. 1) cause hydro-abrasive erosion (Fig. 2) on turbines of medium- and high-head Hydro-Power Plants (HPP). Turbine wear reduces efficiency, electricity production, and revenues.

Project Goals

- Evaluate and develop techniques for suspended sediment monitoring for HPP
- Improve understanding of relations between particle load, turbine wear, and efficiency changes as basis for HPP optimizations
- Recommendations for HPP operation, e.g. temporary turbine shutdown during high sediment load

Fig. 1: Typical sediment-laden river

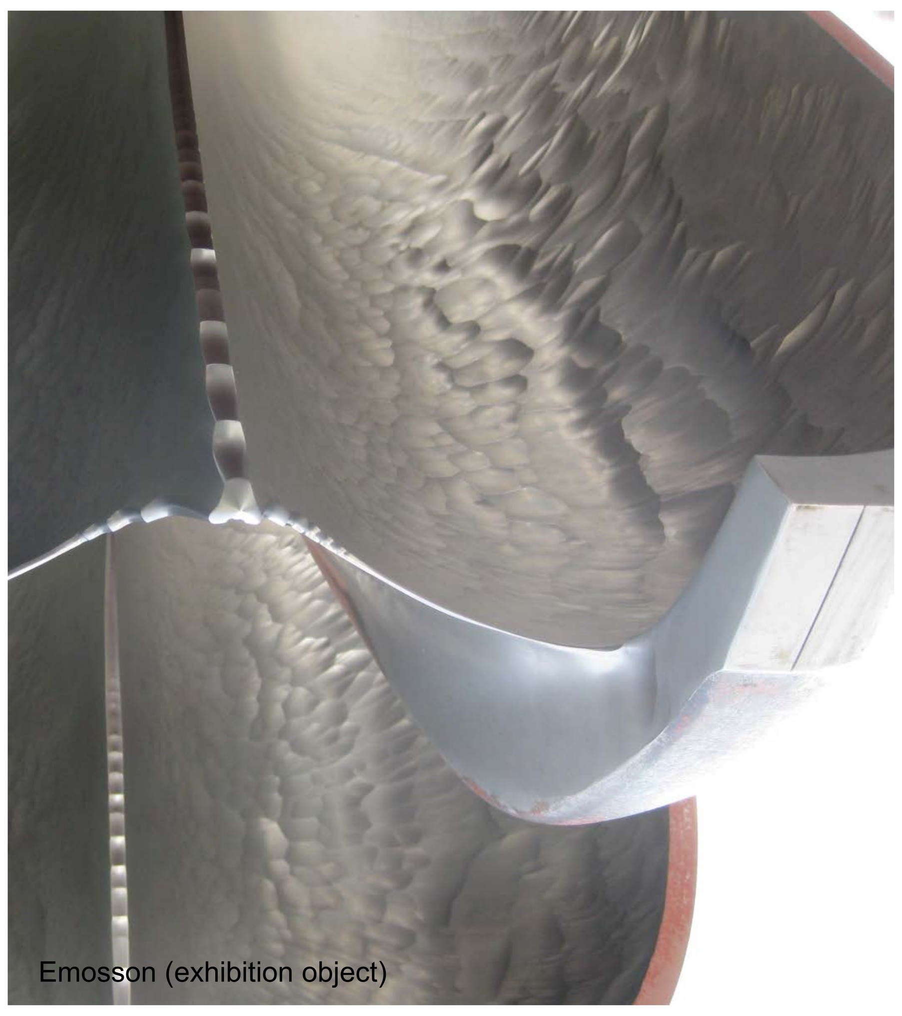

Fig. 2: Runner of Pelton turbine with abrasion damages

Methods

Suspended sediment load, turbine wear, and efficiency changes are monitored at the high-head HPP Fieschertal (Fig. 3). Prior to the field study, devices for suspended sediment monitoring were investigated in laboratory tests. An *in-situ* laser diffractometer allows not only for measuring continuously Suspended Sediment Concentration (SSC) but also particle size distribution.

The coating thickness inside buckets is measured repeatedly with an inductive thickness gauge at defined locations. Abrasion at the turbine runners is quantified by surveying selected buckets with an optical 3D-digitization system. Efficiency changes are measured by sliding needle index efficiency tests (Hochschule Luzern).

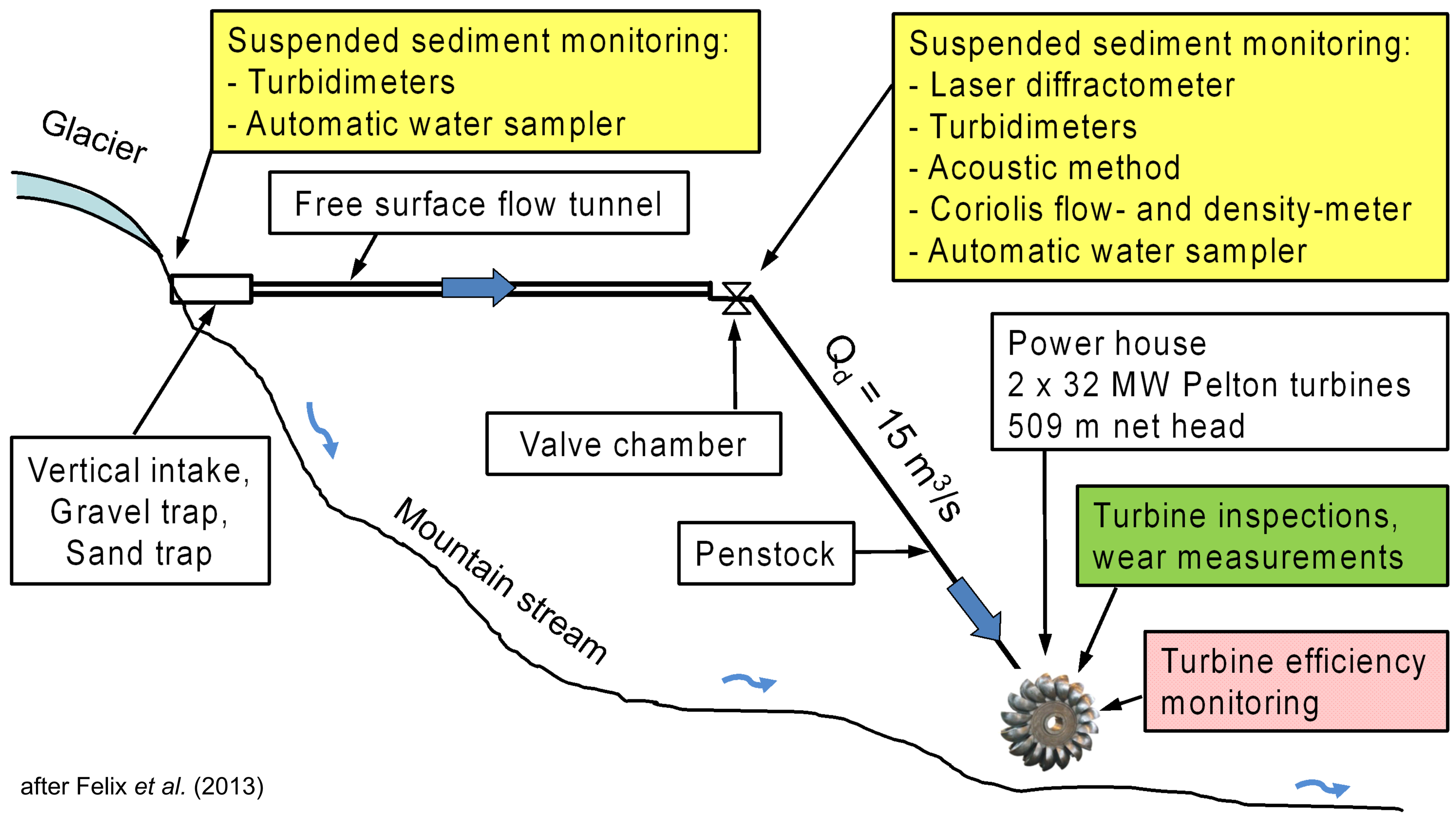

Fig. 3: Schematic longitudinal profile of HPP Fieschertal, Valais, Switzerland with investigation program

Results

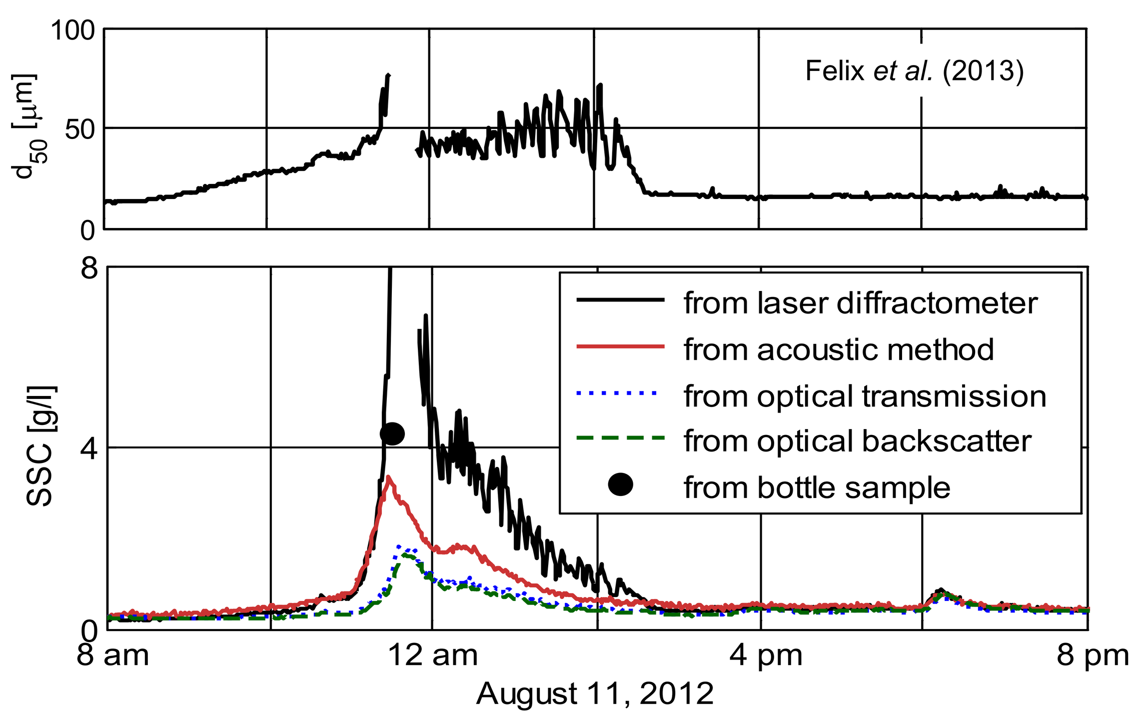

Fig. 4: Time series of suspended sediment concentration *SSC* and median particle size d_{50}, example of half a summer day

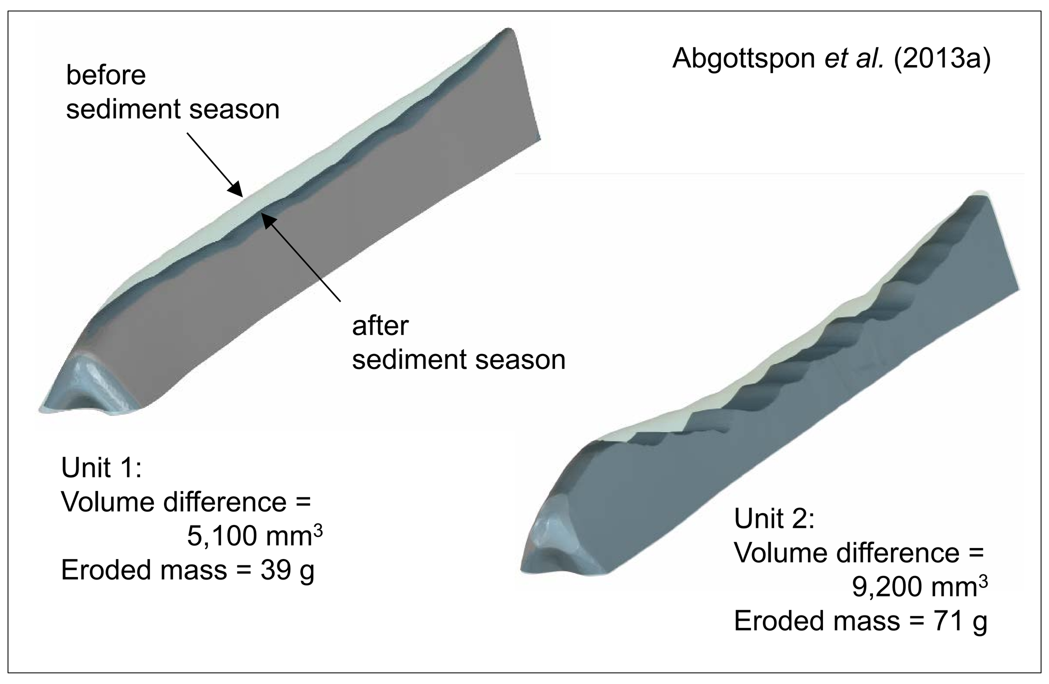

Fig. 5: Wear at splitters of Pelton turbine buckets no. 1 of both units during sediment season 2012

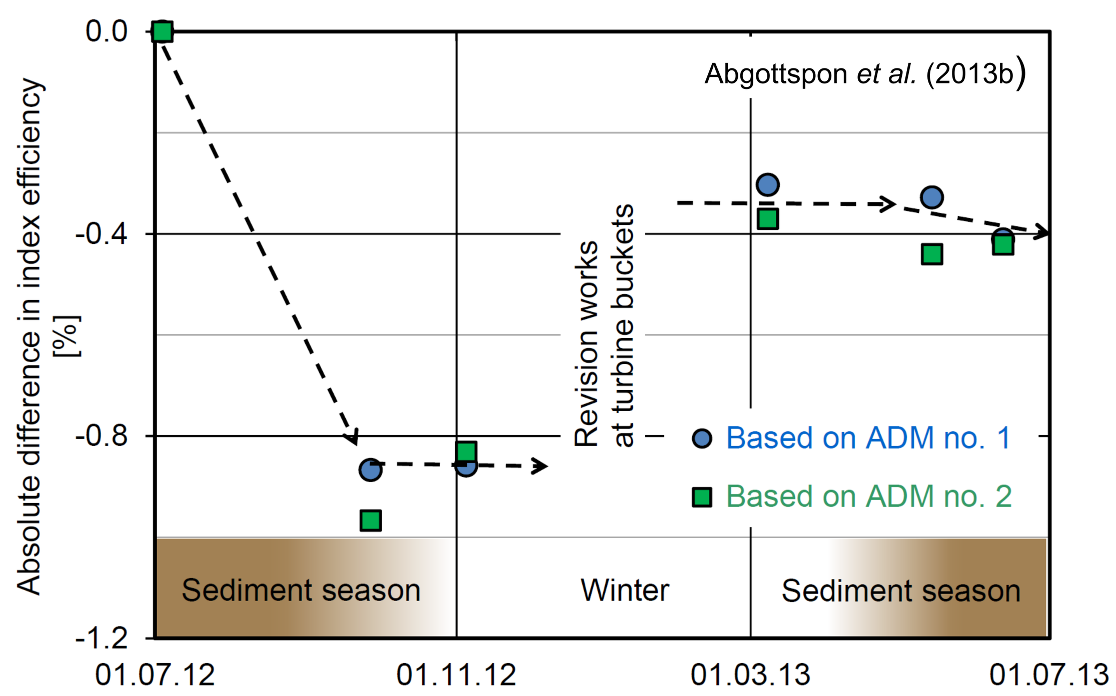

Fig. 6: History of turbine efficiency (unit 1), based on two acoustic discharge measurement sections (ADM) independently evaluated

SSC in turbine water strongly and quickly vary, not only due to precipitation but also due to reservoir operation (Fig. 4). High SSC is often associated with the transport of coarser particles. Instrumentation was calibrated based on gravimetrical analysis of periodic bottle samples. A comparison of calibrated SSC time series indicates that turbidimeters and the acoustic method underestimate SSC during peaks because of varying particle size. This effect is accounted for by the laser diffractometry, however.

Extensive hydro-abrasive erosion was observed at the splitters of the Pelton turbine buckets (Fig. 5). Differences in the wear pattern and material loss between the turbine units arise primarily from different splitter geometries at the start of the sediment season.

During two thirds of the sediment season 2012, the turbine efficiency dropped by 0.9% (Fig. 6). Due to on-site revision work (grinding and re-coating), the turbine efficiency increased by 0.5%.

The recording and analysis of suspended sediment load, turbine wear, and efficiency changes are continued. This contributes to an energy- and cost-efficient use of the hydropower potential worldwide.

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GPU-SPHEROS: Massively Parallel Finite Volume Particle Method Solver

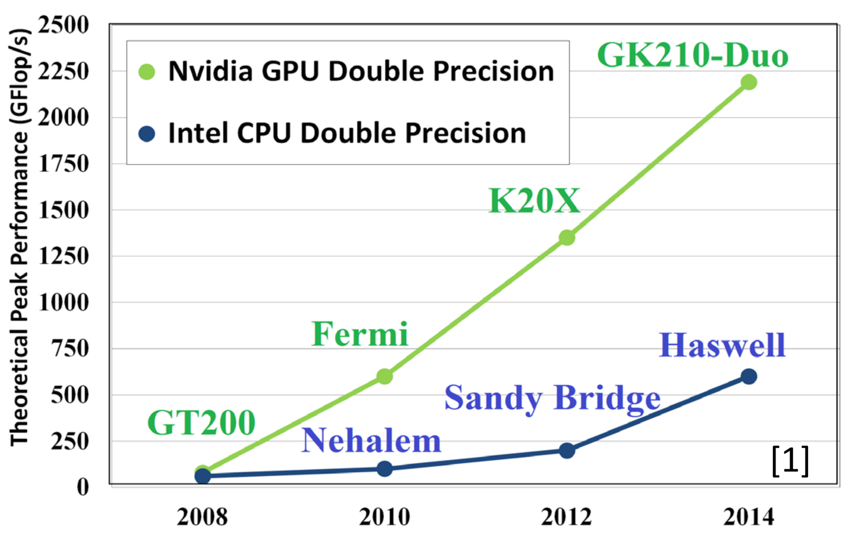
Siamak Alimirzazadeh, Ebrahim Jahanbakhsh, Audrey Maertens, Sebastian Leguizamon, François Avellan

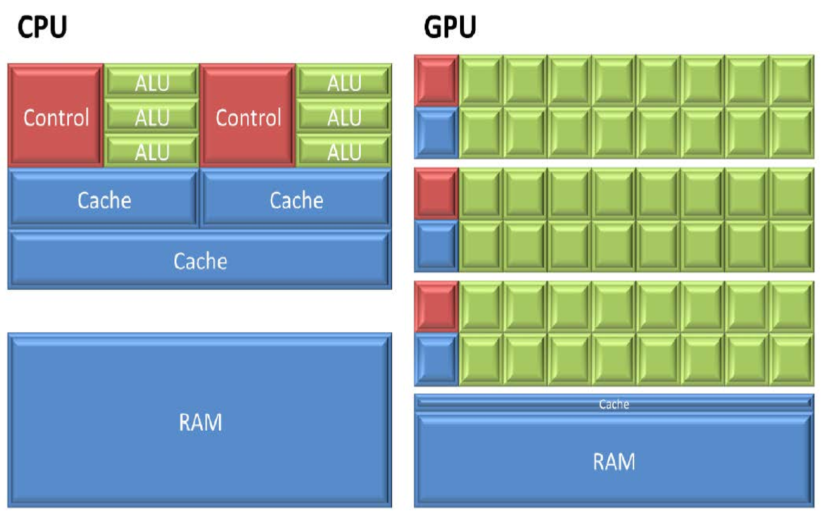
1. Introduction

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 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 designs and maintenance methodologies.

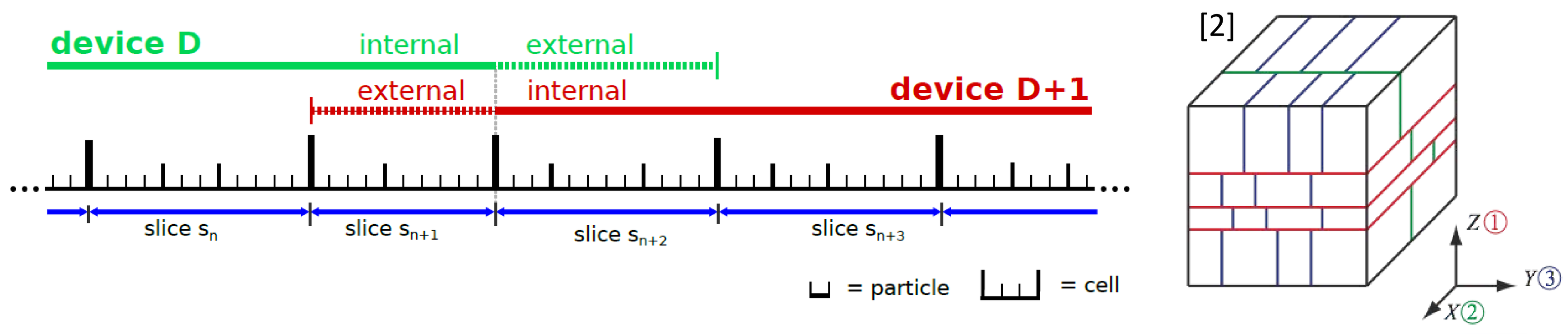
General purpose computing on graphic processing unit (GPU) has a wide application in high performance computing (HPC). GPU-SPHEROS is an implementation of the Finite Volume Particle Method (FVPM). As a particle-based method it can naturally handle free surfaces and very large deformations typical of 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 of the code in the framework of GPU architecture, which will enhance the code performance substantially. This poster covers the 2nd of these aims.





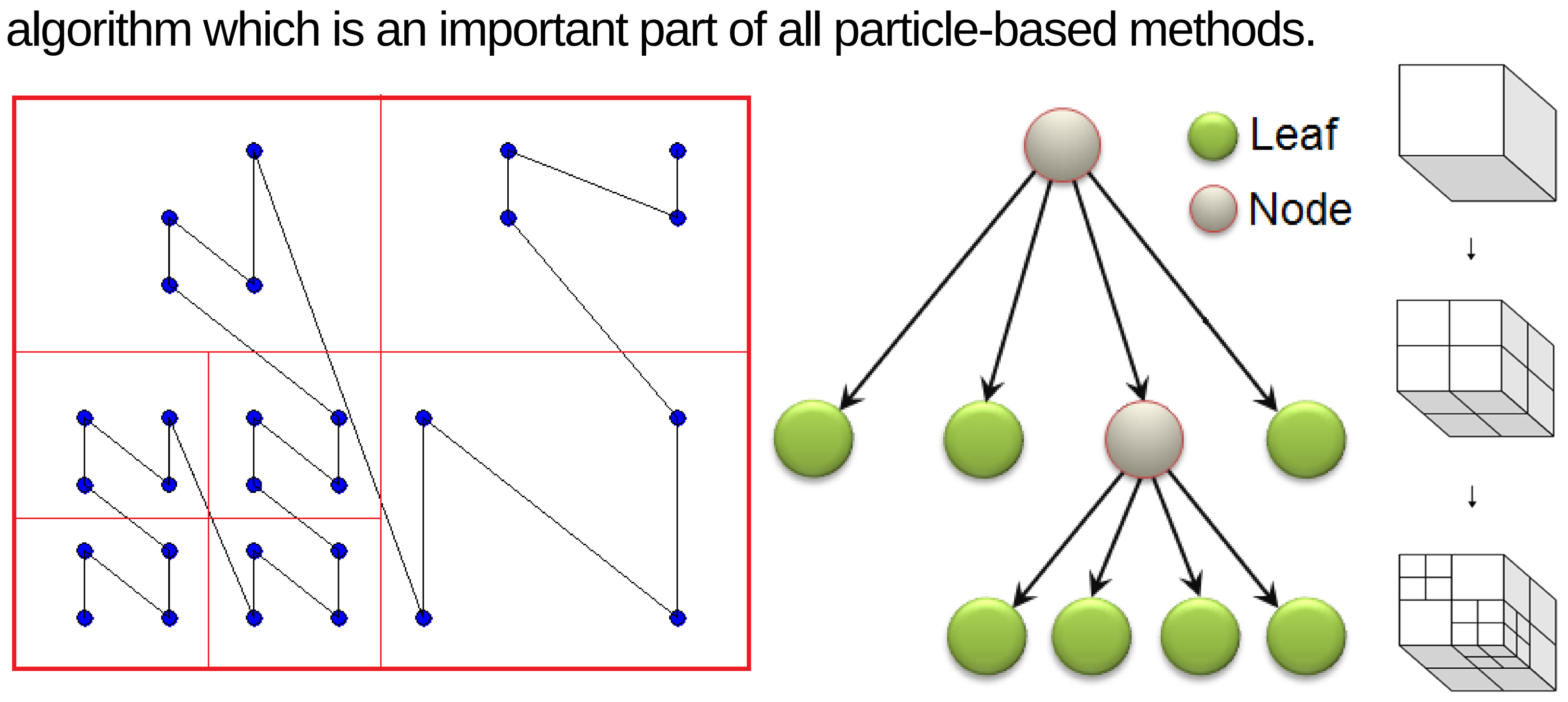
2. Adaptive Domain Decomposition

In order to run SPHEROS on massively parallel GPU clusters, the domain is decomposed such that each graphic card computes only one subdomain. Communication between the subdomains is kept to a minimum by including an overlap region around each subdomain in such a way that all particles within the interaction distance are also stored on GPU global memory.

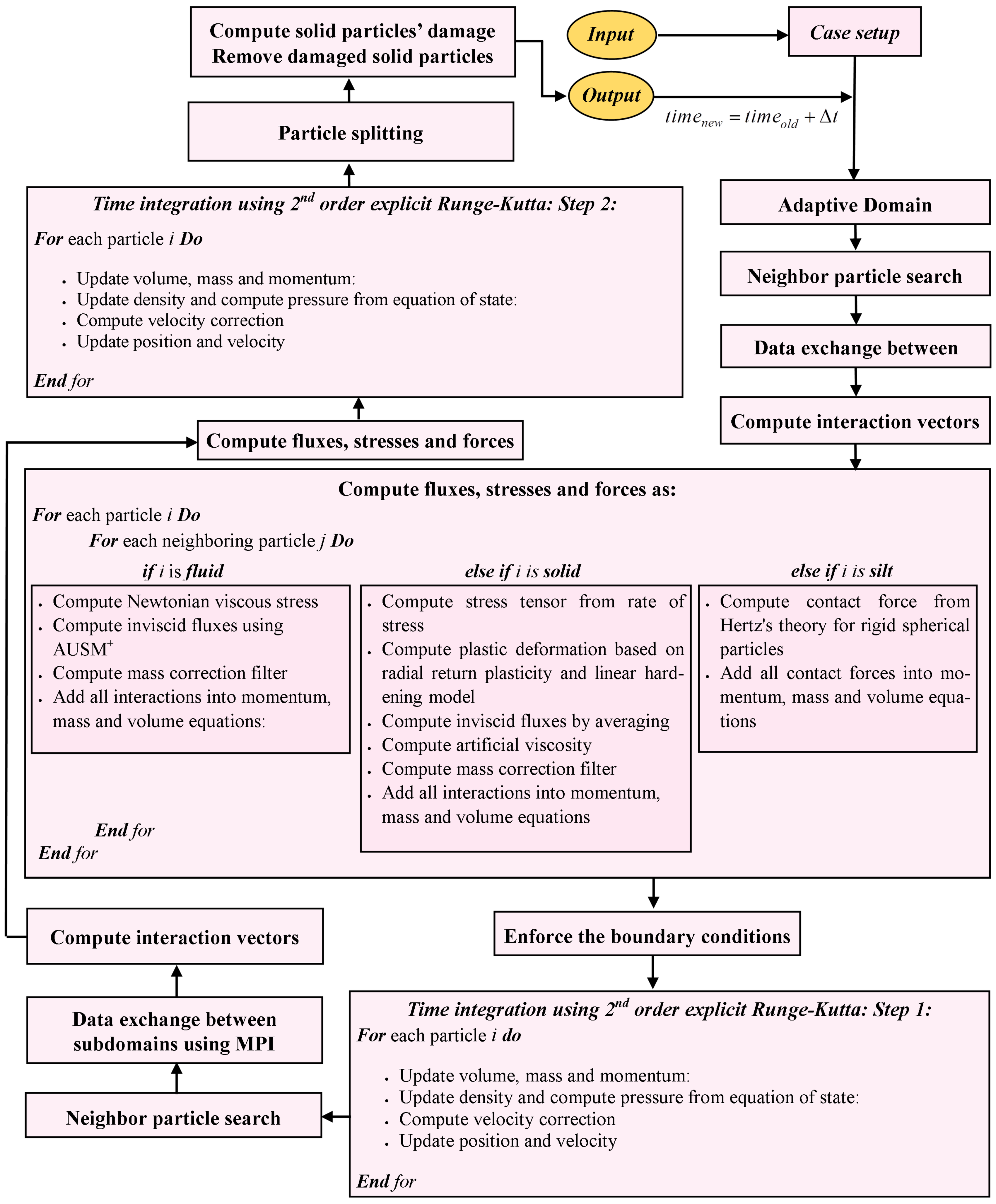


3. Data Reordering

The key point to reach high performance in GPU programming is to adapt the data structure to the unique requirements of the GPU architecture. In this regard, reordering the particles data using space filling curves (SFCs), e.g. z-curve, can improve the code performance by providing more efficient memory access. Besides, SFCs can be utilized for massively parallel octree search algorithm which is an important part of all particle-based methods.

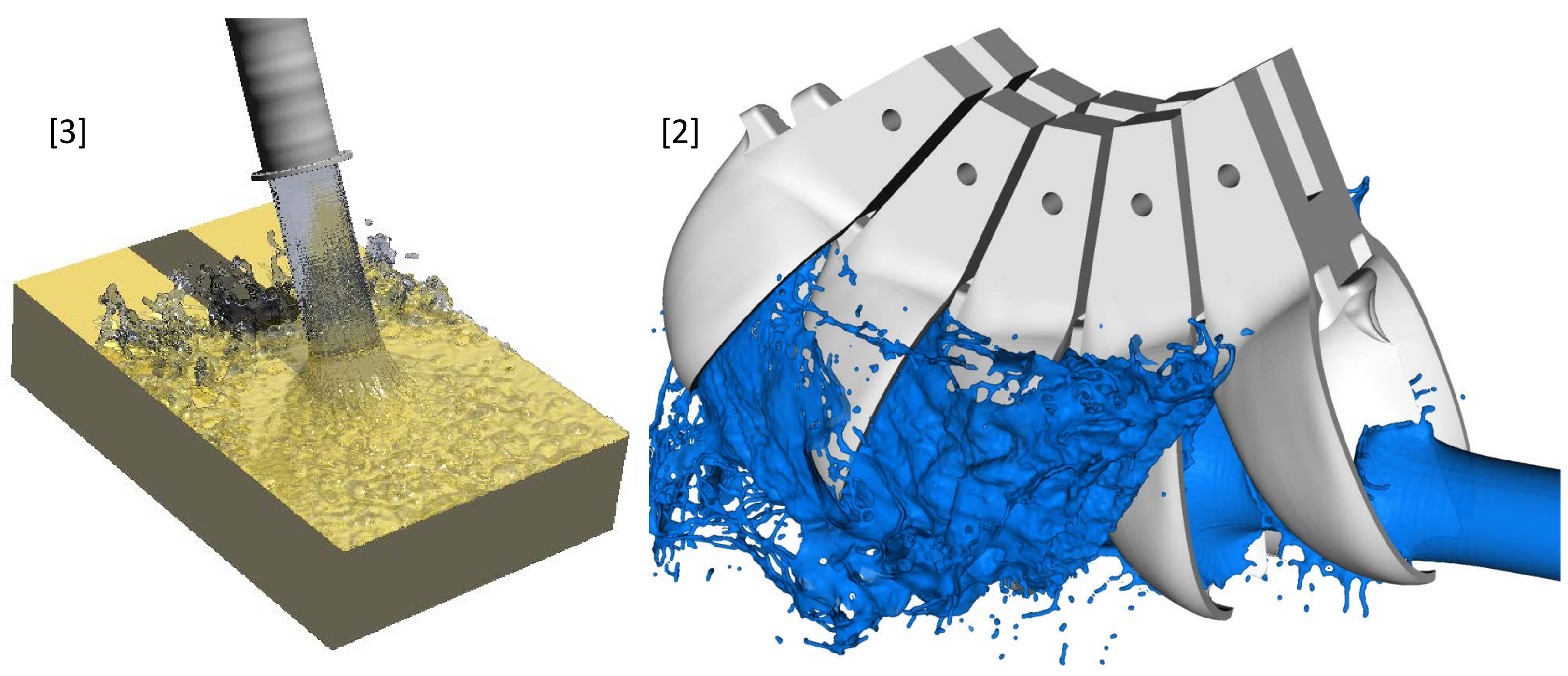


4. SPHEROS Algorithm



5. Validation and Applications

SPHEROS have been successfully validated against a series of test cases including lid-driven cavity flow, fluid-structure interaction, free surface flow, silt erosion, etc. For instance, the impinging jet and the flow through a rotating Pelton turbine simulations are shown below:



References

[1] Nvidia's technical webpages (http://docs.nvidia.com)
[2] C. Vessaz, "Finite Particle Flow Simulation of Free Jet Deviation by Rotating Pelton Buckets", EPFL PhD Thesis Nº 6470 (2015)
[3] E. Jahanbakhsh, "Simulation of Silt Erosion Using Particle-Based Methods", EPFL PhD Thesis Nº 6284 (2014)

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GPU-SPHEROS – Enhanced Material Modelling 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 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 designs 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 first of these aims.

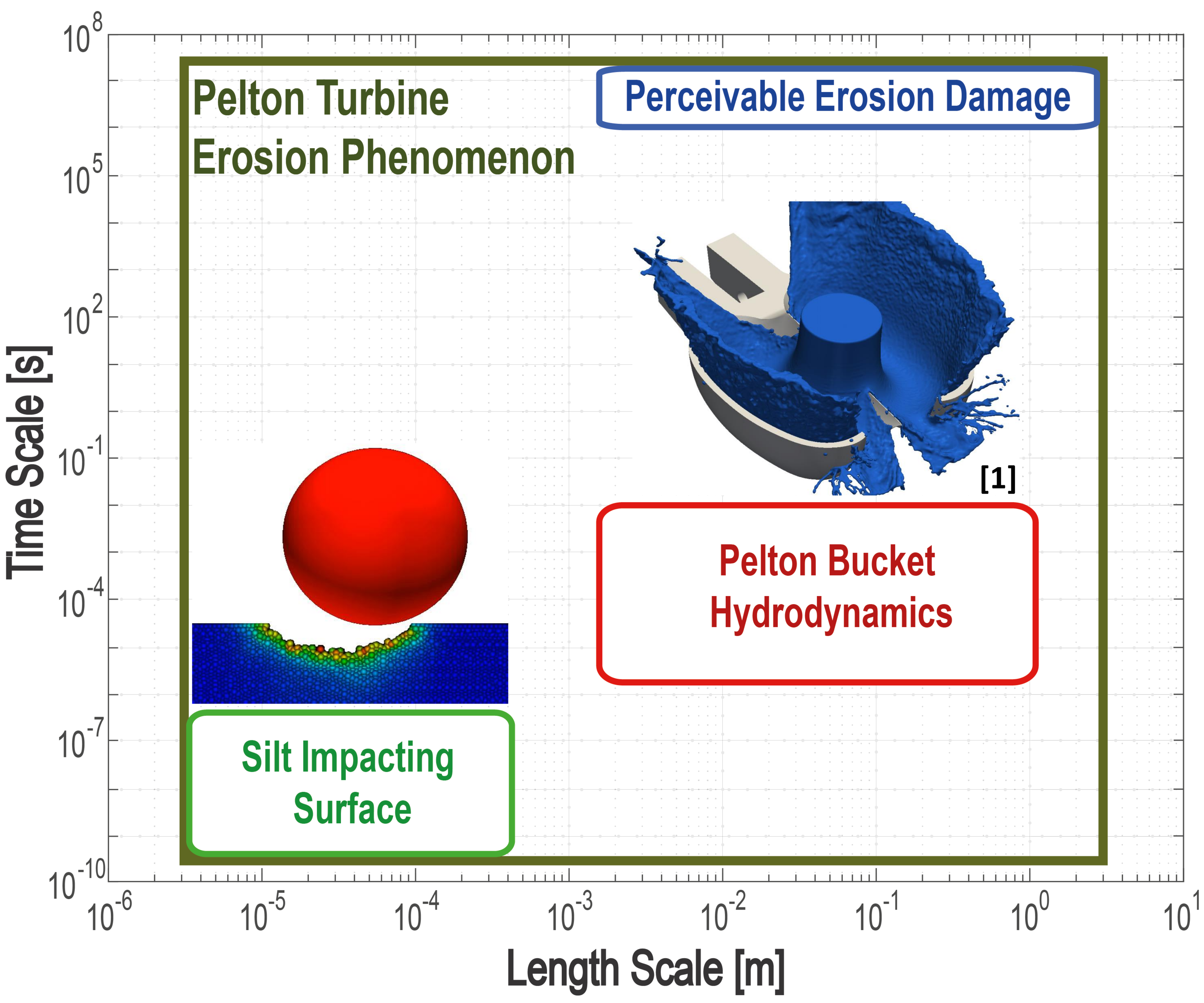
2. Multiscale Problem

The silt erosion of a Pelton turbine implies interactions among very different length and time scales. Therefore, it is an **inherently multiscale problem**, covering 6 and 17 orders of magnitude in space and time, respectively.

The interacting phenomena include:

- **Silt particle impacts** on the surface
- **Hydrodynamics** in the Pelton bucket
- **Erosion damage** to the turbine in the long-term

The **interactions** among phenomena render this a very challenging problem. Silt impacts are extremely brief, but they determine the erosion damage behaviour which occurs after thousands of hours. The Pelton bucket hydrodynamics determine the distribution of impacting particles at the surface, but simultaneously depend on the slow alteration of the surface due to erosion damage.



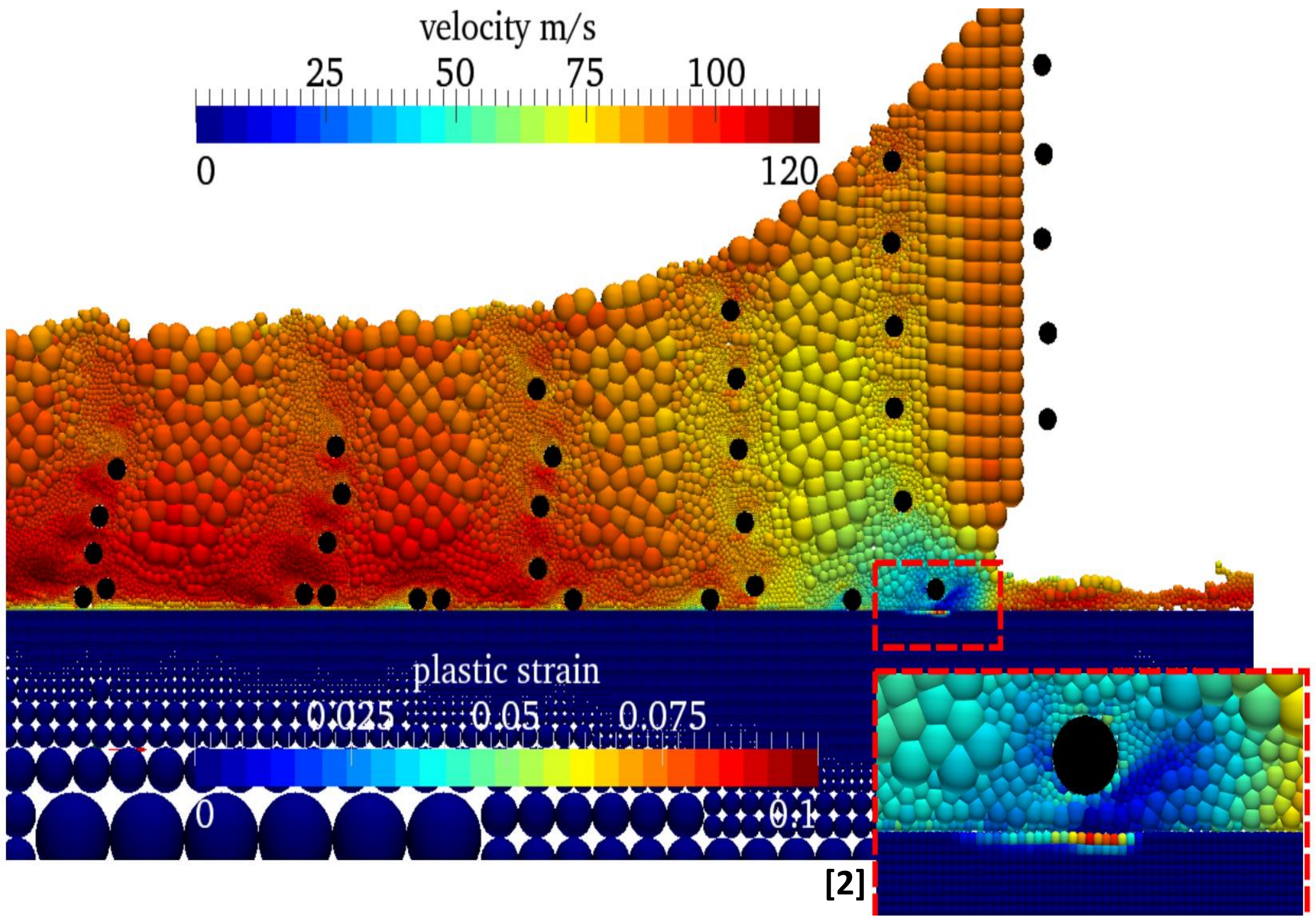
3. Current Modelling Capabilities

SPHEROS includes three interacting **materials**:

- **Silt**, assumed rigid and spherical
- **Fluid**, modelled as weakly compressible and viscous
- **Solid**, as elasto-plastic with linear strain hardening law

The **interaction** between silt and fluid is given by the viscous stress and pressure integration on the silt's surface; the contact between silt and solid is determined by Hertz's contact theory. The material removal takes place once a given plastic strain threshold is reached.

An example of an **erosion test case** performed with SPHEROS is shown next:



[2]

4. Enhanced Modelling

Several improvements are required in order to perform accurate silt erosion simulations applicable to industrial problems:

Material Constitutive Model

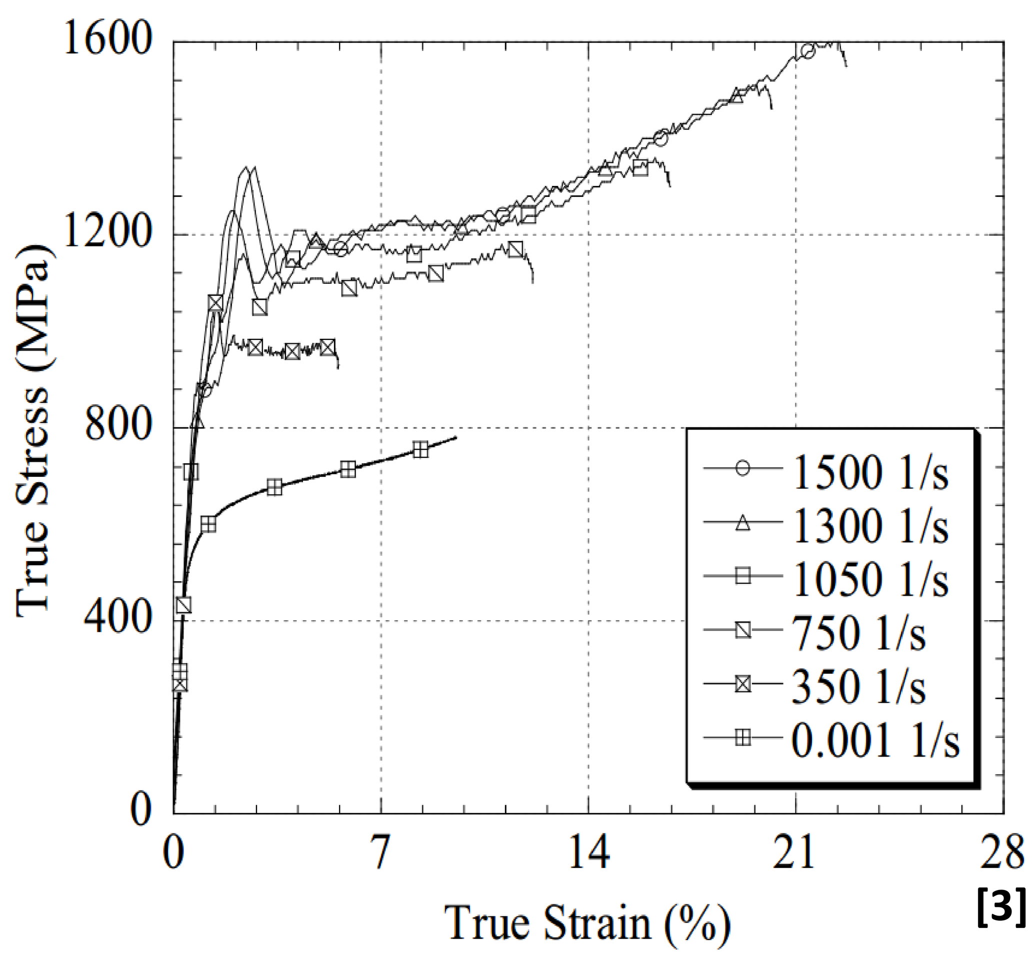
High velocity impacts such as the ones present in silt erosion entail **very high strain rates** on the material. Such strain rates modify the response of the material considerably, as seen on the stress-strain curve shown below on the left.

For this reason, two constitutive models able to capture the strain-rate dependence are being implemented: the **Cowper-Symonds** and the **Johnson-Cook** models, which will be compared and assessed to determine their accuracy and performance in the problem at hand.

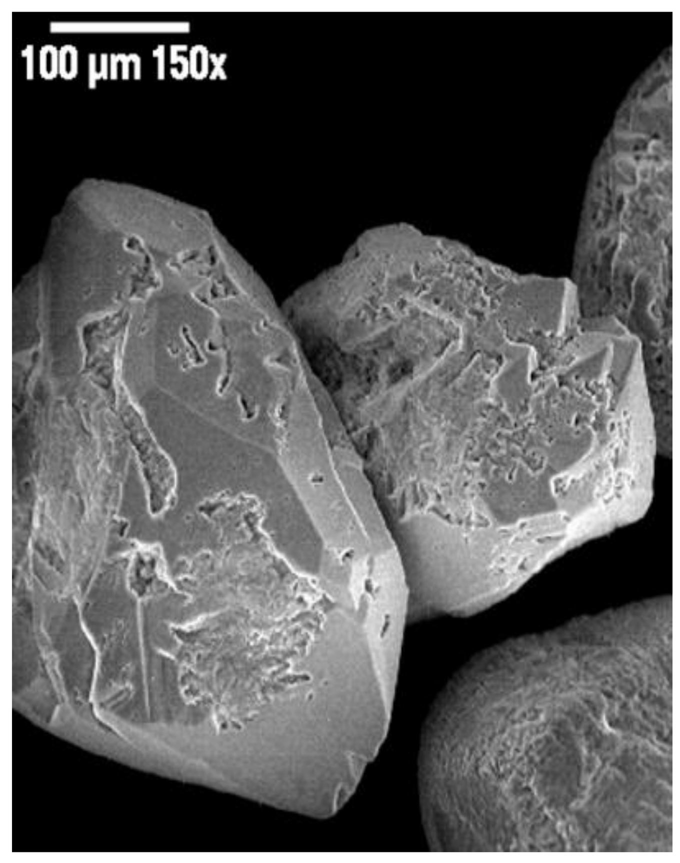
Non-Spherical Silt Particles

The erosion rate is very dependent on the silt particle's shape. As seen on the figure below, real silt particles have sharp edges and other features that affect their aggressiveness against the surface.

For this reason, we envision implementing an **arbitrary-shape capability** for SPHEROS, together with a relevant **contact model.**



[3]



[4]

References

[1] C. Vessaz, "Finite Particle Flow Simulation of Free Jet Deviation by Rotating Pelton Buckets", EPFL Thesis Nº 6470 (2015).
[2] E. Jahanbakhsh, "Simulation of Silt Erosion using Particle-Based Methods", EPFL Thesis Nº 6284 (2014).
[3] A. K. Behera, N. K. Singh and M. K. Singha, "Compressive Behavior of AISI-416 Stainless Steel at Different Rates of Loading", WCE Vol III (2012).
[4] NASA, "Ottawa Sand for Mechanics of Granular Materials", MIX Database (2000).

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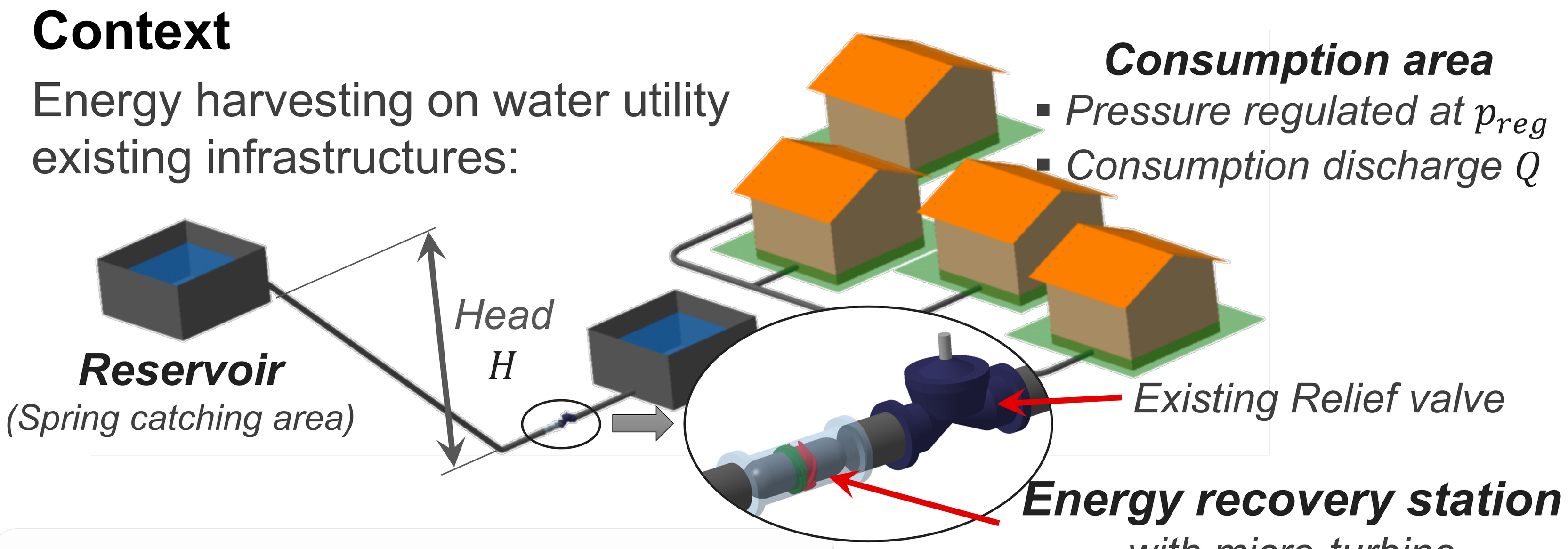
DuoTurbo :Providing Industrial and Competitive Family of Low-CAPEX energy recovery stations

Loïc Andolfatto, François Avellan , Cécile Münch-Allígné

Context

Energy harvesting on water utility existing infrastructures:



Key facts

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

Available hydraulic power:

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

CTI Project *n.17197.1 PFEN-IW*

DUO TURBO

The project focuses on turning a ***counter rotating micro-turbine*** *proof of concept into a range of* ***standard energy recovery stations (ERS)*** *able to harvest energy on drinking water networks.*

The concept to be developed will have a ***minimal environmental impact*** *and will require a* ***low investment*** *for the final customers, reaching economic feasibility in a power range between 5 kW and 25 kW. A new part of the Swiss and international* ***renewable energy potential*** *will then be targeted and* ***profitably exploited****.*

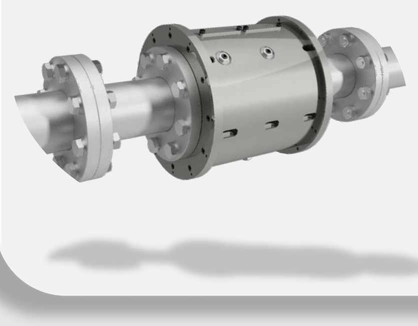
Roadmap from *proof of concept* to *product*

Technology Readiness Level

8
7
6
5
4
3
2
1

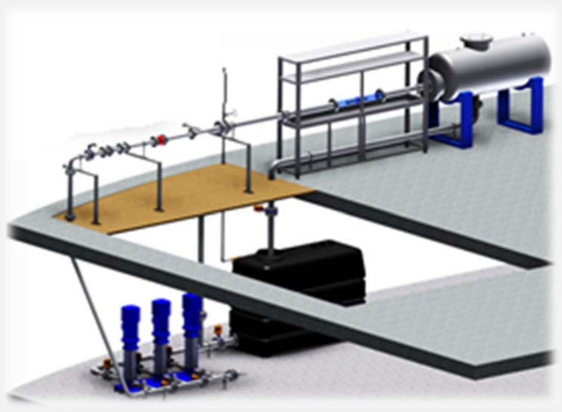
2015 2016 2017

Final target



- ERS family addresses 70% of the 5-25 kW sites
- Lean connection to electricity and water networks
- Operator payback period targeted below 10 years

Tests on *"Prototype v0"*



First prototype is built and tested on laboratory test rig

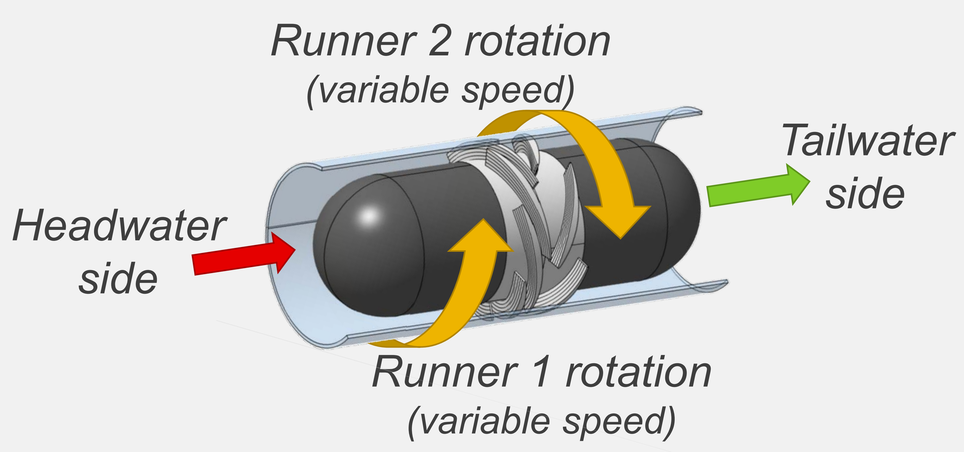
***Product v0* Milestone**

***Prototype v0* Milestone**

Installation of *"Product v0"*

First product demonstrated in operating conditions on an instrumented pilot site

Initial proof of concept



Micro-turbine with counter rotating runners

An estimated potential of **35 GWh per year** – currently dissipated – can be **harnessed in Switzerland** with the **developed technology**.

Research partners:

Hes·so VALAIS WALLIS
Haute Ecole d'Ingénierie
Hochschule für Ingenieurwissenschaften

D. Biner, S. Gabathuler, D. Violante, V. Hasmatuchi, S. Richard, C. Cachelin, L. Rapillard, S. Chevailler, C. Münch-Allígné

LMH Laboratory for Hydraulic Machines
EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

L. Andolfatto, F. Avellan

Project staff in brief

- 11 researchers involved
- Multidisciplinary engineering
  - Hydraulic machinery
  - Mechanical design
  - Electrical machinery
  - Manufacturing

Implementation partners:

TELSA ELECTROTECHNIQUE

Jacquier & Luisier SA
Atelier mecanique

VALELECTRIC FARNER SA

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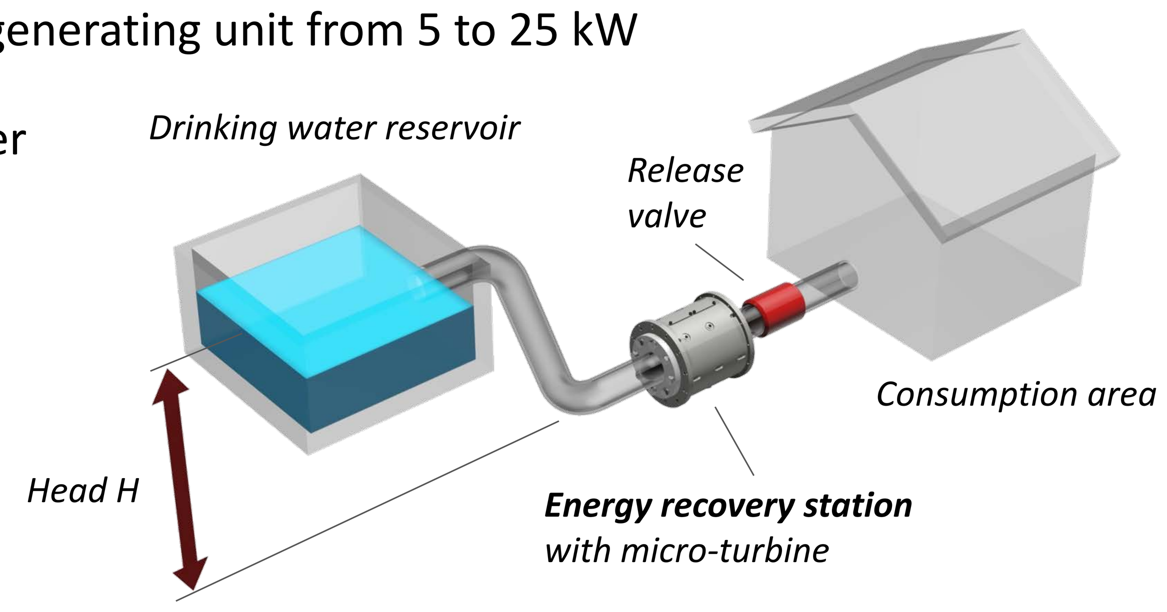
Concept & hydraulic design of a counter-rotating micro-turbine

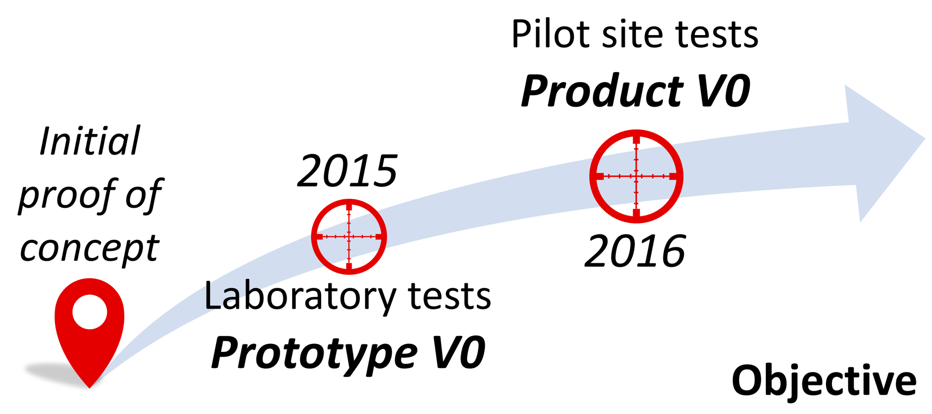
D. Biner, L. Andolfatto, F. Avellan, C. Münch-Alligné

Context

- Energy Recovery in drinking water networks
- Modular in-line "water to wire" generating unit from 5 to 25 kW
- No environmental impact
- Low investment for final customer



Project

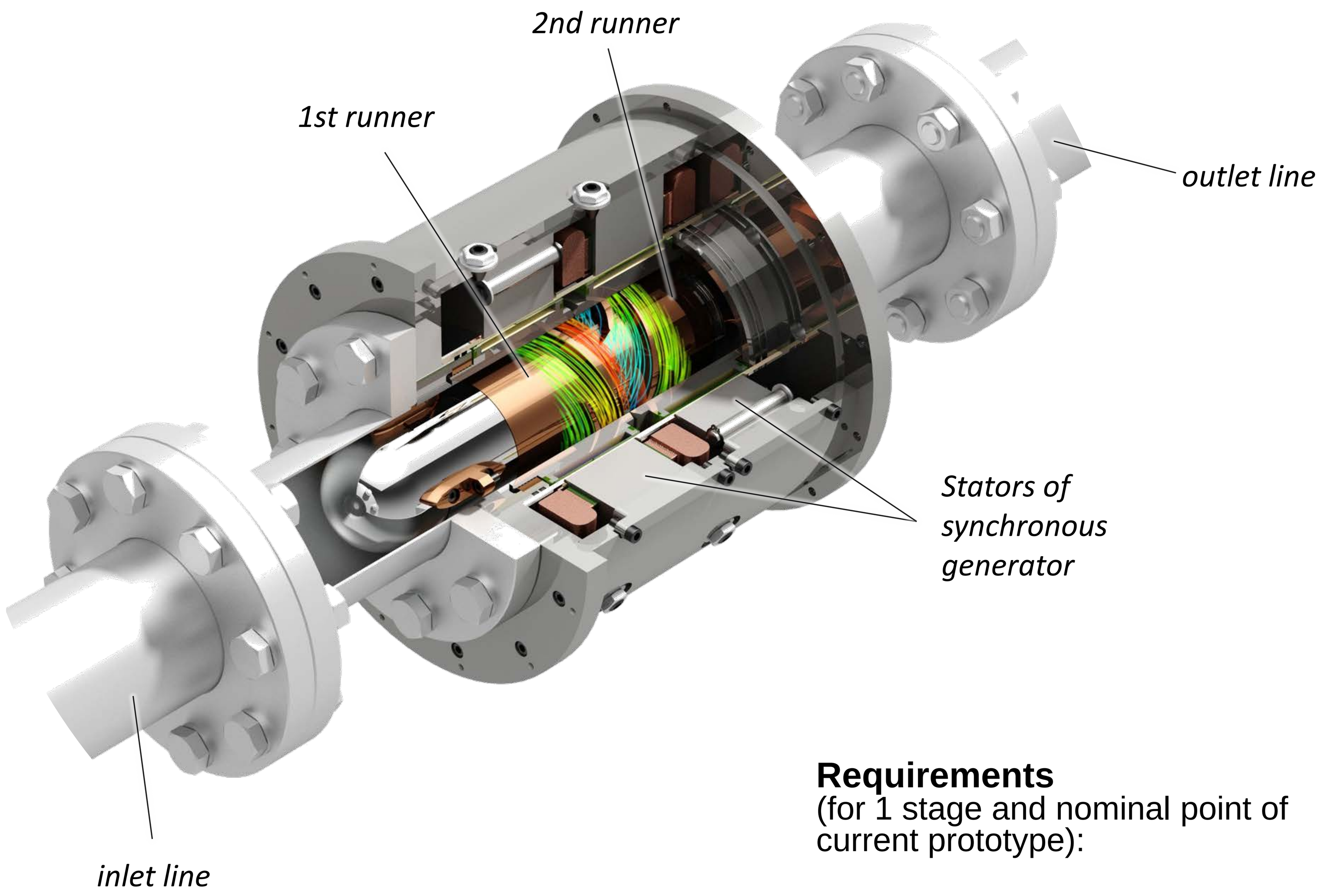


Objective

- *Family of modular ERS*
- *Harness Swiss potential around 35 GWh per year*

Concept

- Two axial counter-rotating runners per stage
- Compact permanent magnet synchronous generator straflo-design
- Individual runner speed regulation for best efficiency
- Multi-stage concept for a wide power range



Requirements
(for 1 stage and nominal point of current prototype):

Mass flow	*9*	$kg \cdot s^{-1}$
Pressure drop	*2.4*	*bar*
Rotational speed	*2500*	*rpm*
Hydraulic efficiency	*>80*	*%*
Mechanical power	*>1728*	*W*

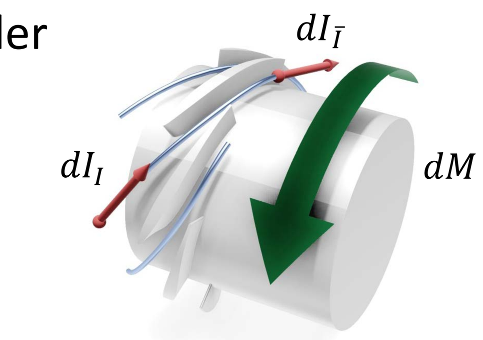
Hydraulic Design

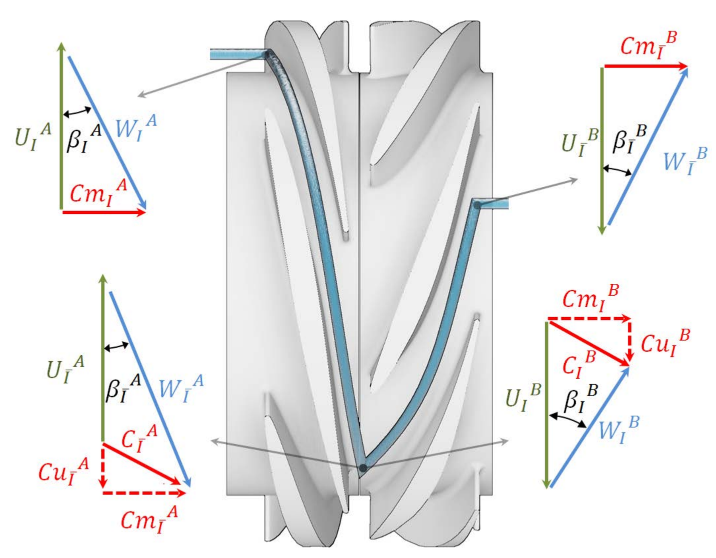
1 Rated specific hydraulic energy E

$$E = \frac{p_{\mathrm{I}} - p_{\bar{\mathrm{I}}}}{\rho} + \frac{C_{\mathrm{I}}^2 - C_{\bar{\mathrm{I}}}^2}{2} + g(Z_{\mathrm{I}} - Z_{\bar{\mathrm{I}}})$$

2 Runner angular momentum balance yields Euler equation for the specific hydraulic energy conversion:

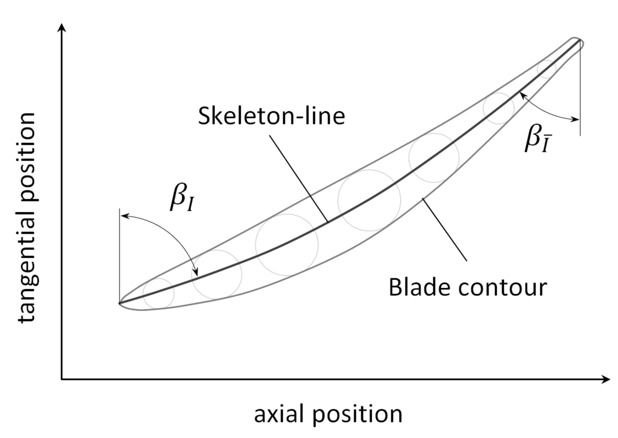
$$\eta_h \cdot E = U_I C u_I - U_{\bar{I}} C u_{\bar{I}}$$





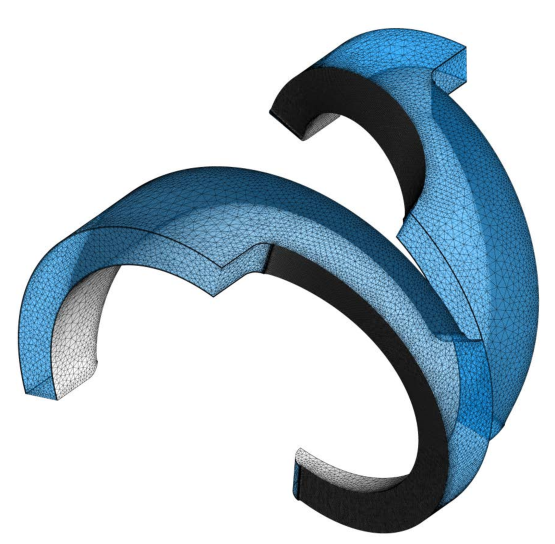
3 Velocity triangles at both the inlet and outlet runner blades yield the relative flow angle β

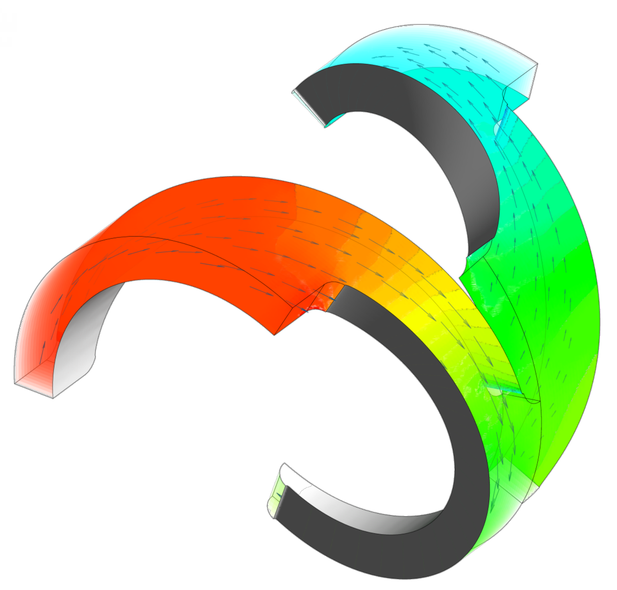
4 Blade camber-line and shape are defined as a function of β



CFD Simulations

- ANSYS CFX numerical flow simulations are performed to achieved optimized performance of the micro-turbine


Unstructured, tetrahedral mesh


Pressure field and velocity vectors

Simulation Results
(nominal point 2500 min^{-1}, 9 l/s)

Total Pressure	***2.35***	*bar*
Hydraulic efficiency	***90.2***	*%*
Mechanical power	***1'908***	*W*
Hydraulic power	*2'115*	*W*
Torque 1st runner	*3.54*	*Nm*
Torque 2nd runner	*3.75*	*Nm*

Perspectives

- Multi-stage configuration investigations with numerical flow simulations
- Fabrication of the straflo-prototype until October 2015
- Experimental tests of the straflo-prototype on the hydraulic test rig until end of 2015

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

HES-SO Valais//Wallis:

D. Biner, S. Gabathuler, D. Violante , V. Hasmatuchi, S. Richard, C. Cachelin, L. Rapillard, S. Chevailler, C. Münch-Alligné

EPFL LMH:

L. Andolfatto, F. Avellan

Industrial partners:

Telsa SA, Jacquier-Luisier SA, Valelectric Farner SA

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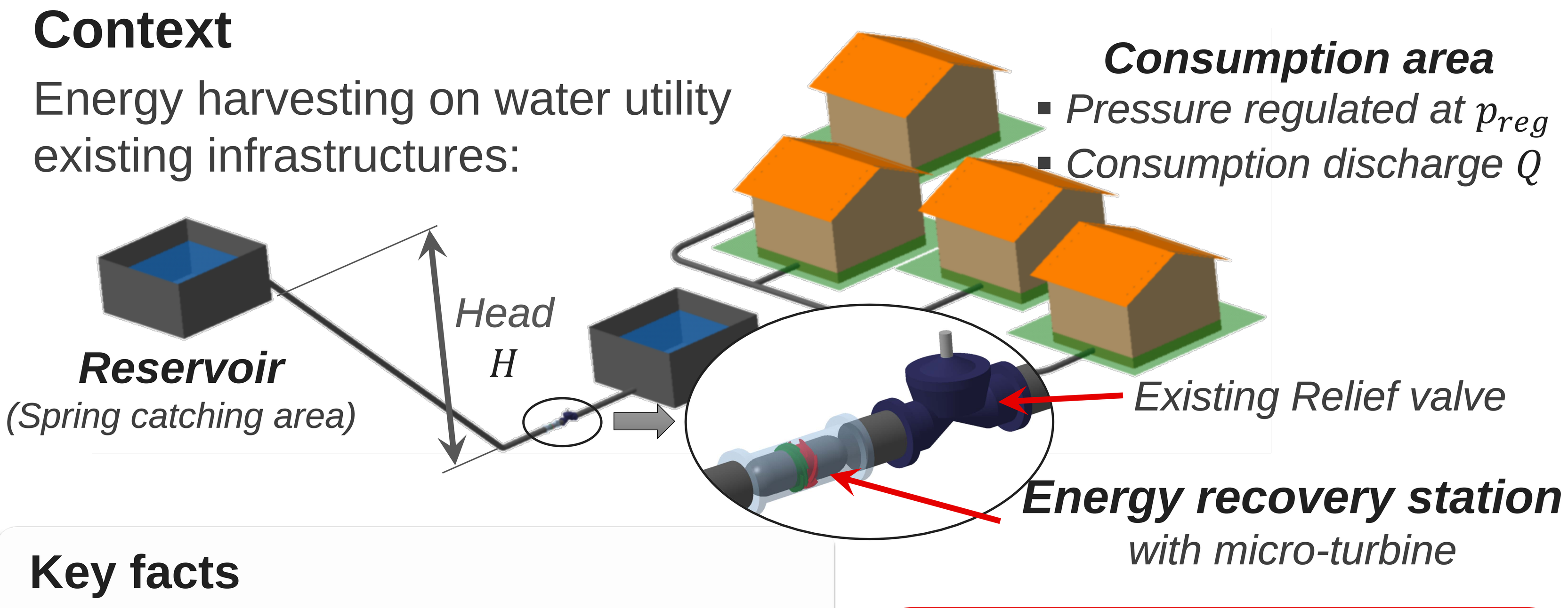
Experimental investigation of the velocity fields in a counter rotating micro-turbine

Elena Vagnoni, Loïc Andolfatto, Cécile Münch-Alligné & François Avellan

Context

Energy harvesting on water utility existing infrastructures:



Key facts

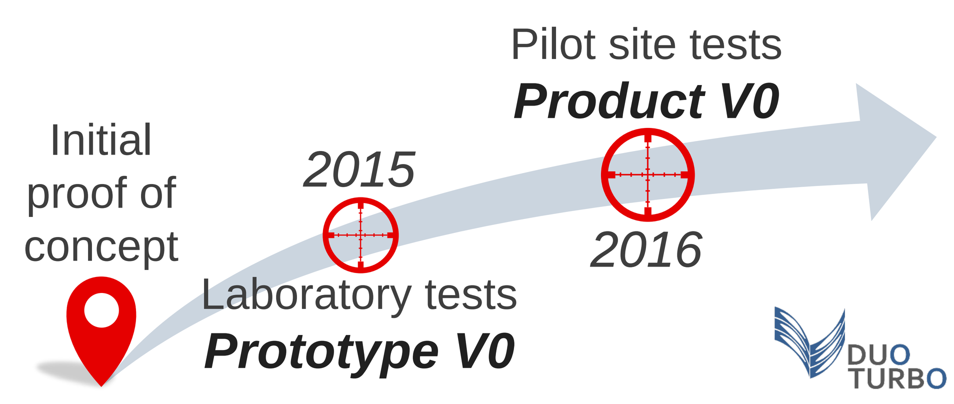
- *Modular concept from 5 to 25 kW*
- *Low environmental impact*
- *Lean water to wire installation*
- *Limited capital expenditure*

Available hydraulic power:

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

Project

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



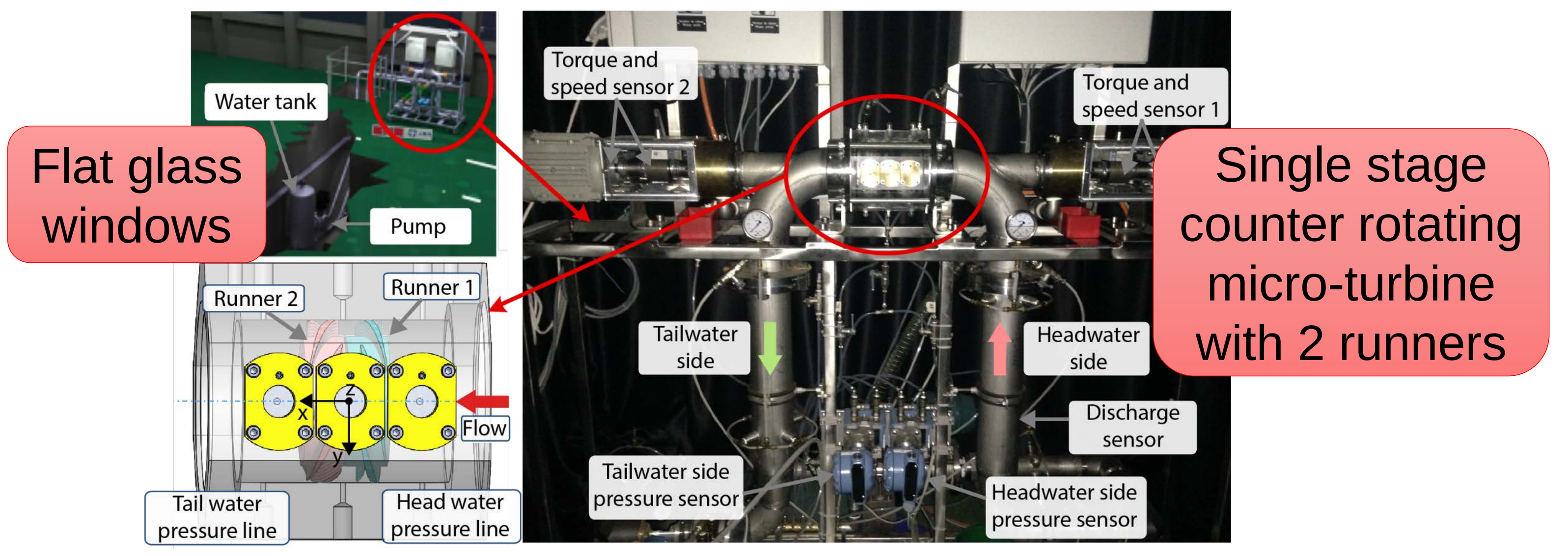
Objective

- *Family of modular ERS*
- *Harness Swiss potential around 35 GWh per year*

Research partners: Hes·so Valais Wallis; LMH Laboratory for Hydraulic Machines; EPFL

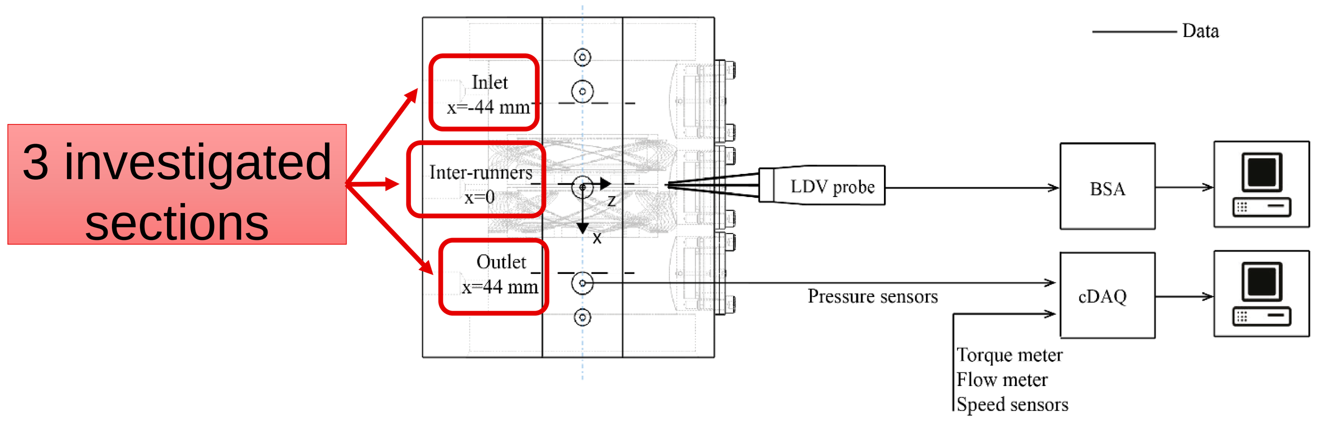
Implementation partners: Telsa Electrotechnique; Jacquier & Luisier SA Atelier mecanique; Valelectric Farner SA

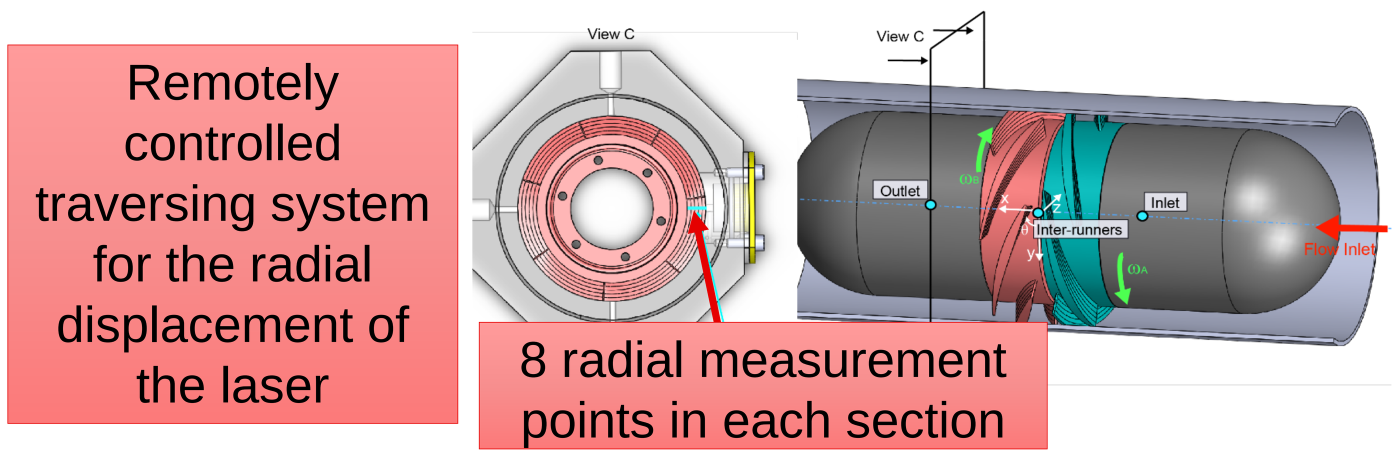
Experimental set-up



Velocity field investigation in the **meridional** and **tangential** component.

- ✓ 2D LDV system with 2 laser beams.
- ✓ Seeding particles: 10 μm diameter hollow glass spheres.





High reflection of the laser beams on the hub wall

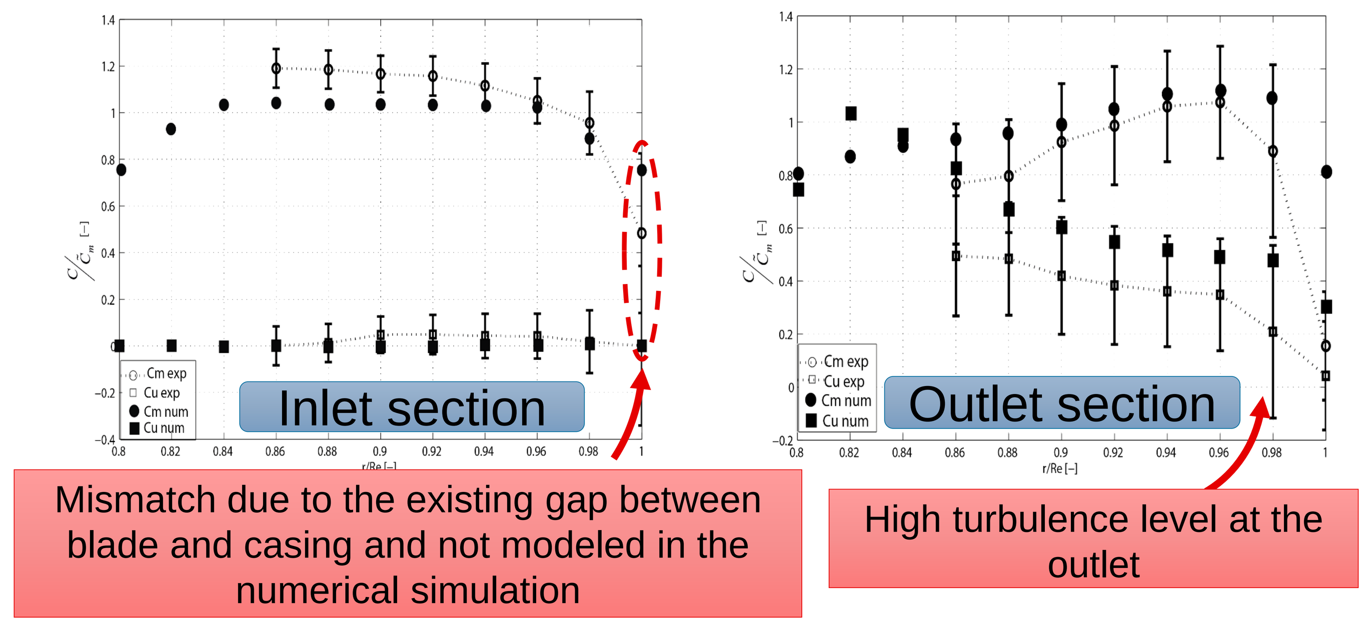
Obstruction of the LDV measurements close to the hub

Solution of the mass balance equation to fulfill the velocity profile

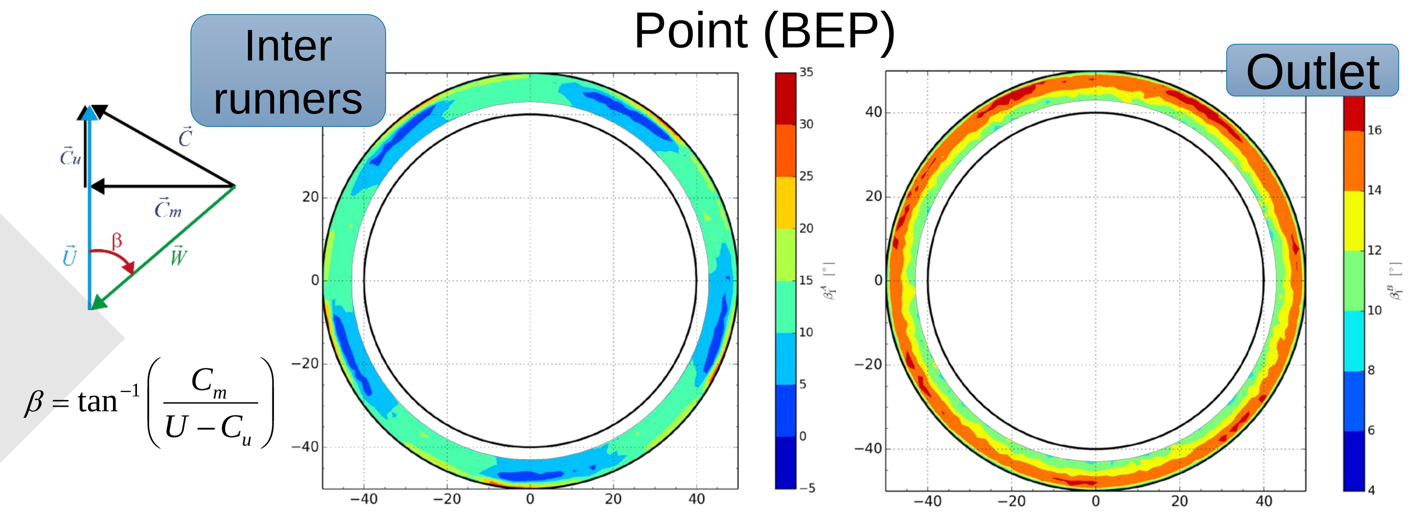
$$\tilde{Q} = \int_A \vec{C} \cdot \vec{n}\, dA = \int_{R_h}^{R_s} 2\pi C_m(r)\, r\, dr$$

Results

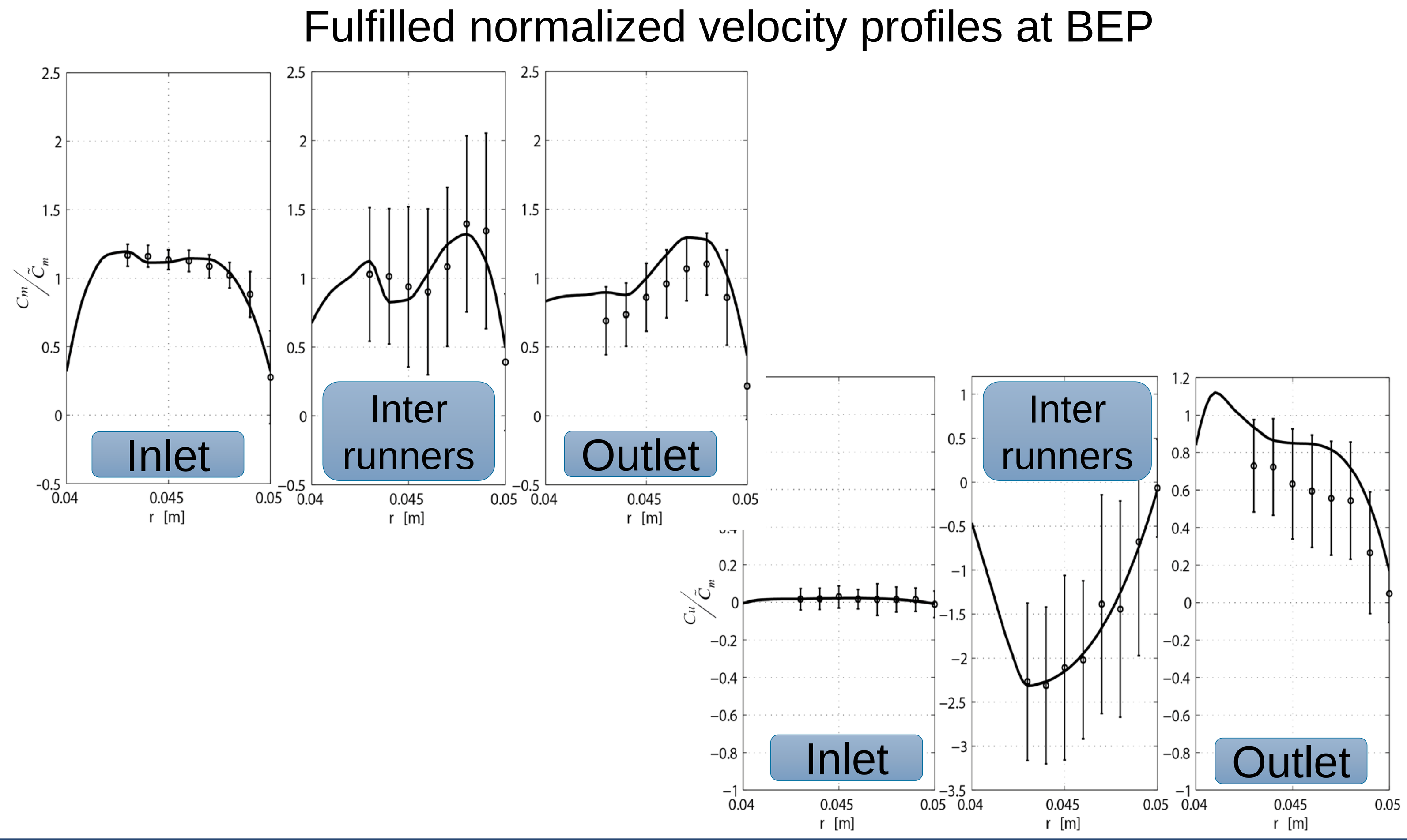
Comparison of meridional and tangential velocity profile with CFD study



Normalized average relative flow angle profile at Best Efficiency Point (BEP)



Fulfilled normalized velocity profiles at BEP



Conclusions

- ✓A **good agreement** with the numerical simulations is observed.
- ✓Almost axial outflow at the BEP and at similar operational conditions close to the tip ➔ **limitation** of the remaining unrecovered **rotational energy.**
- ✓The **fulfillment** of the velocity profile allows a further study on the **total specific rothalpy balance equation** for the computation of the **power** transmitted by the runners thus the computation of the **efficiency**.

➔Reliability on numerical simulation for further development
➔Physical understanding about what makes BEP better than other points
➔Further improvements of the blade shape
➔Computation of the micro-turbine performance

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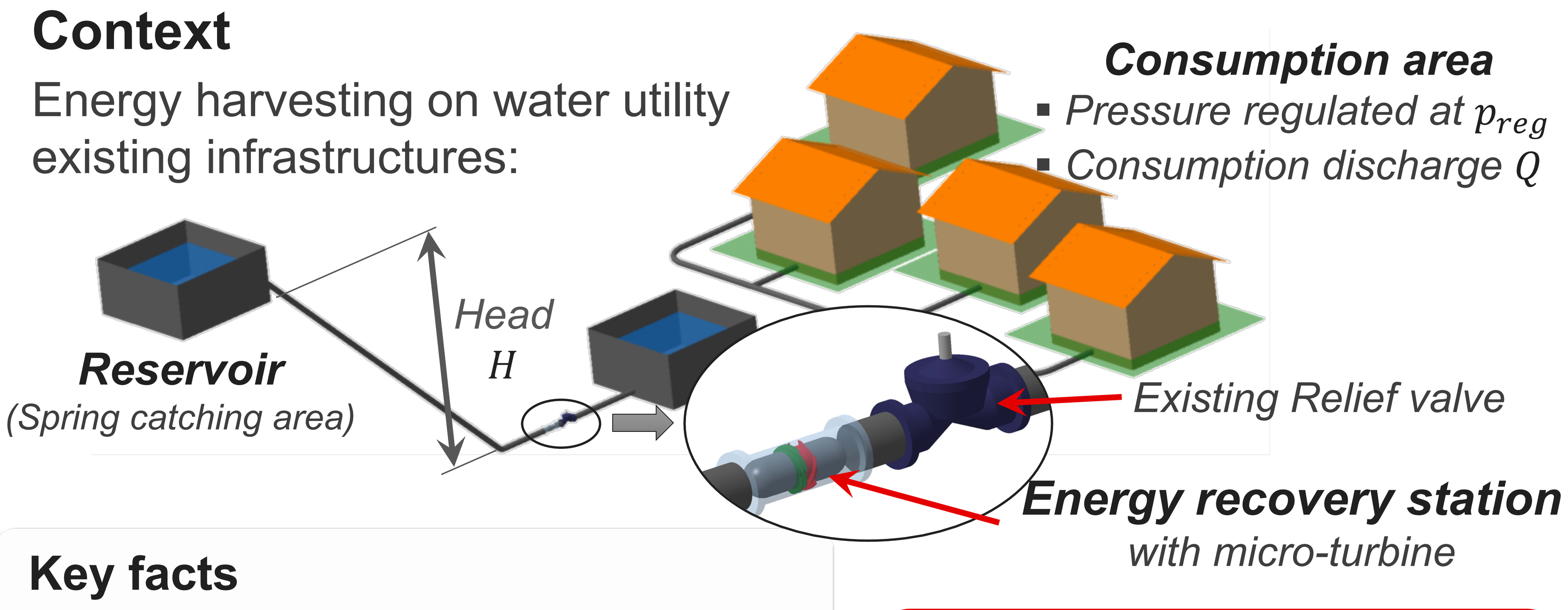
Exploitation scenarios towards the optimal control of an energy recovery station

Loïc Andolfatto, Cécile Münch-Alligné, François Avellan

Context

Energy harvesting on water utility existing infrastructures:



Key facts

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

Available hydraulic power:

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

Project

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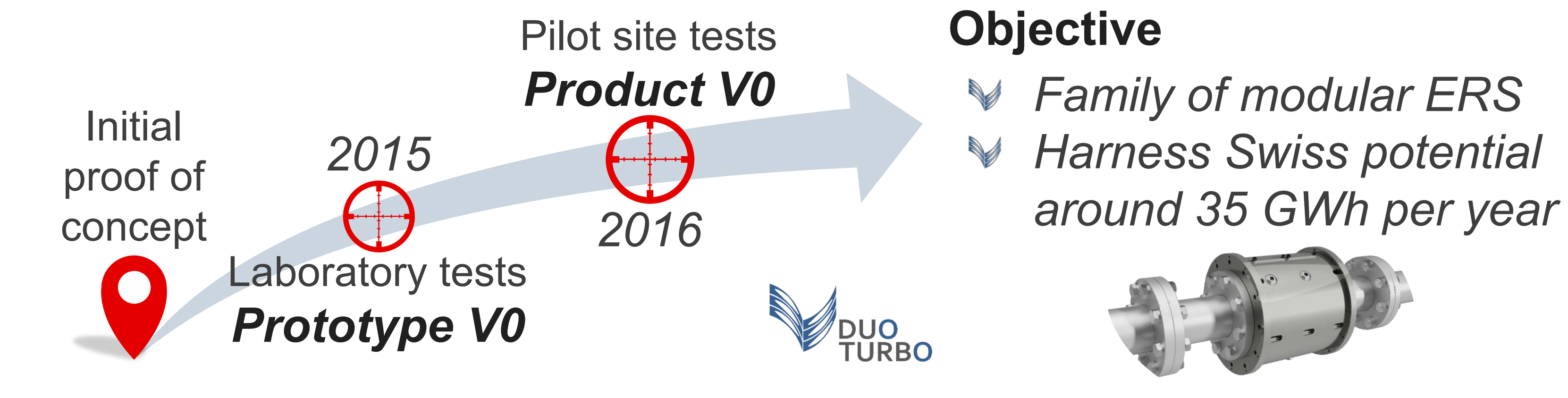


Objective

- *Family of modular ERS*
- *Harness Swiss potential around 35 GWh per year*

Research partners: Hes·so Valais Wallis, LMH Laboratory for Hydraulic Machines, EPFL

Implementation partners: Telsa Electrotechnique, Jacquier & Luisier SA Atelier mecanique, Valelectric Farner SA

Objectives

- Characterize variable **consumer-driven** flow discharge in water utility networks:
  - at *"several days horizon"* for architecture design
  - at *"several minutes horizon"* for control design
- Select appropriate **installation principle**
- Define adapted runner rotational speed **control strategy**

Input data

Instrumented pilot site with measurement of:

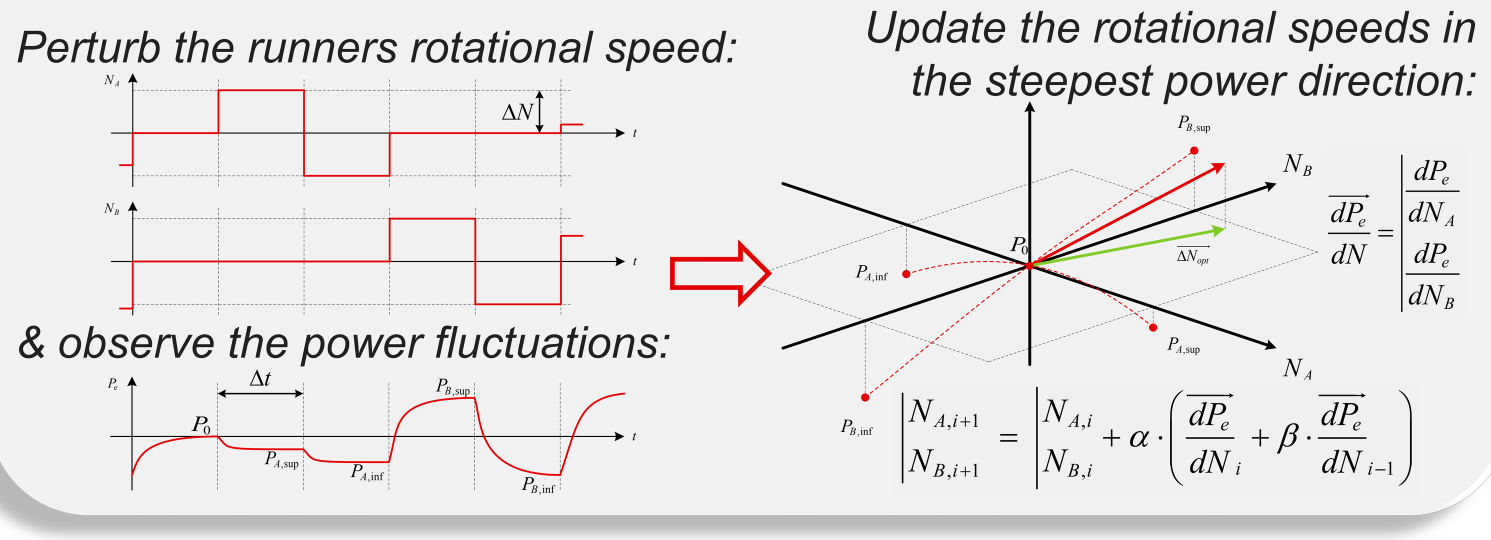
- Discharge
- Headwater pressure
- Tailwater pressure

Data sets:

- From July 2013 to June 2015 every 15 minutes
- During one day at 2 Hz

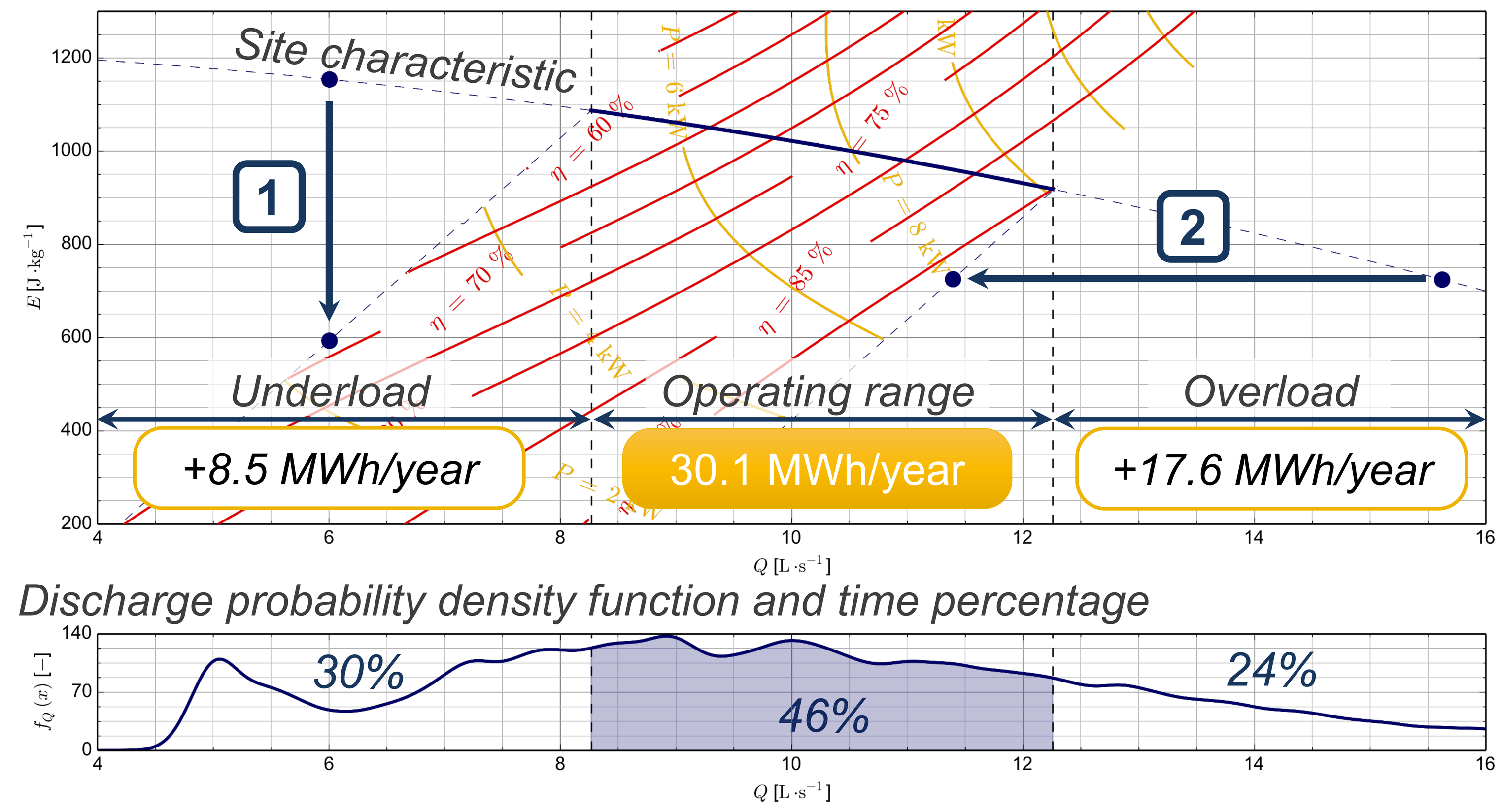
Instrumentation and data acquisition performed by hydraulic energy team of HES SO Valais

Perturb & Observe MPPT



Architecture design

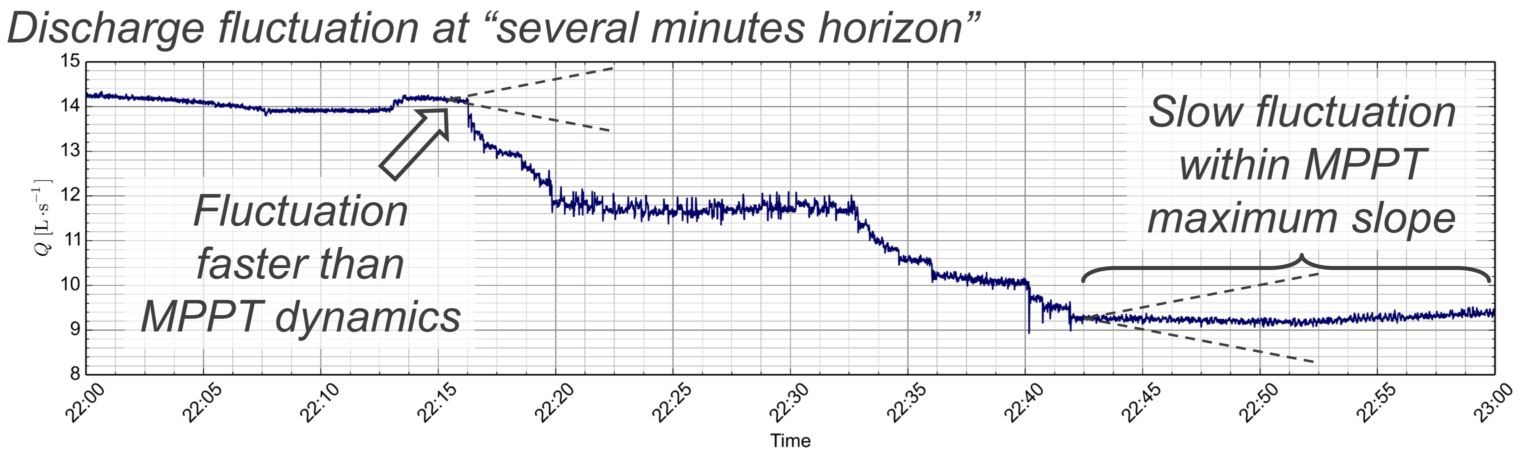
Micro-turbine hillchart and site characteristic



1. Tailwater relief valve allows to generate at underload
2. Discharge-controlled bypass allows to generate at overload

Control design

Discharge fluctuation at "several minutes horizon"



- Slow discharge fluctuations
  - ***Maximum Power Point Tracker*** (MPPT) with 2nd order 2 degree of freedom ***Perturb & Observe***
  - Fluctuation slope limited to 0.1 L.s^{-1}/min due to MPPT cycle time
- Quick discharge fluctuations
  - ***Power Step Detection*** to switch to reset control mode
  - Estimation of the operating condition and reset of the optimal rotational speed thanks to machine hillchart model

Conclusions

- Discharge within the **micro-turbine operating range** less than 50% of the time
- Discharge **fluctuation dynamics** faster than MPPT dynamics

⇒

- Discharge-controlled **bypass** and tailwater relief valve allows **full time production** (+87% of generated energy)
- Output power **step detection** and **hillchart-based** operating point estimation supplement MPPT during quick discharge fluctuation

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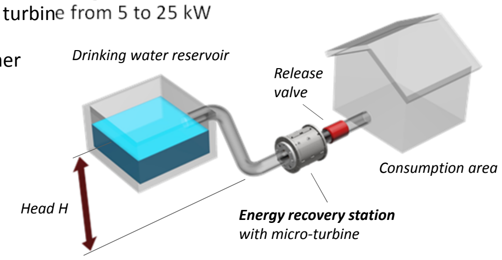
Design of a PM-Generator for a micro-hydro turbine

D. Violante, L. Farner, C. Münch-Alligné, S. Chevailler

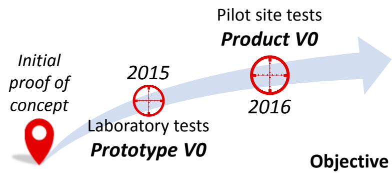
Context

- 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 for final customer



Project

DUO TURBO

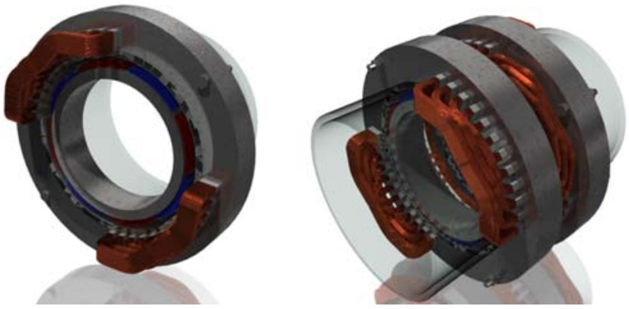


Objective

- *Family of modular ERS*
- *Harness Swiss potential around 35 GWh per year*

Concept

- Compact straflo-design with one synchronous PM generator per runner
- Stator windings of the two generators offset by 90°
- Multi-stage concept for covering wide ranges of hydraulic power

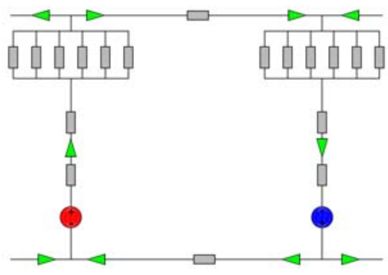


Requirements
(for 1 generator)

Rated torque	*10*	*Nm*
Rated voltage	*400*	*V*
Rated speed	*3500*	*rpm*
Rotor inner diameter	*100*	*mm*
Air gap	*2.9*	*mm*
No. of phases	*3*	-

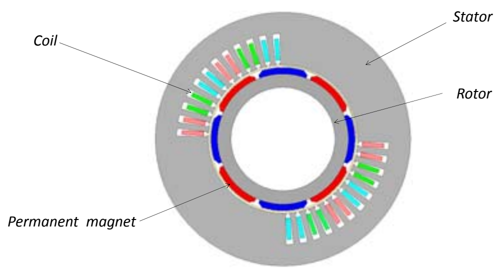
Design and Modelling

- Analytical pre-design to determine the generator main dimensions



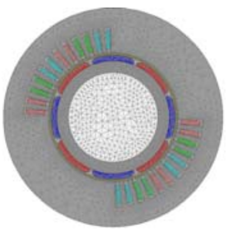
Reluctance model

- Modelling 2D using ANSYS Maxwell

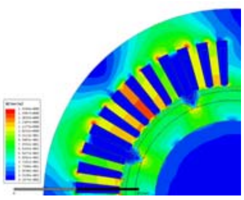


FEM Simulations

- Numerical electromagnetics simulations are used to validate and to optimize the performance of the generator, using ANSYS Maxwell



Tetrahedral mesh



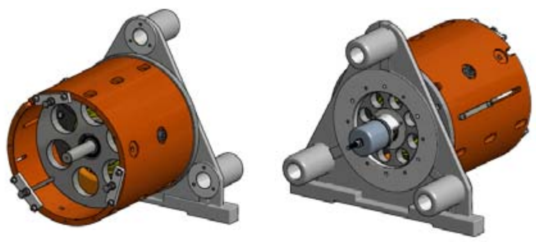
Magnetic flux density @rated current

Simulation results
(@rated speed, 3500 rpm)

Torque constant	*1.96*	*Nm/A*
EMF constant	*4.1*	*V/rev/s*
Rated current	*5.2*	*A*
Efficiency	*92*	*%*
Cogging torque	*153*	*mNm*

Perspectives

- Fabrication of the PM-generator until October 2015
- Experimental tests of the PM-generator until end of 2015



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

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EPFL LMH:

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Industrial partners:

Telsa SA, Jacquier-Luisier SA, Valelectric Farner SA,

Hes·so// Valais Wallis – Haute Ecole d'Ingénierie – Hochschule für Ingenieurwissenschaften
LMH Laboratory for Hydraulic Machines – EPFL École Polytechnique Fédérale de Lausanne
Valelectric Farner SA
Telsa Electrotechnique
Jacquier & Luisier SA Atelier mecanique

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New small-hydro testing infrastructure

Vlad Hasmatuchi, Francisco Botero, Shadya Gabathuler, Daniel Biner, Cécile Münch-Alligné

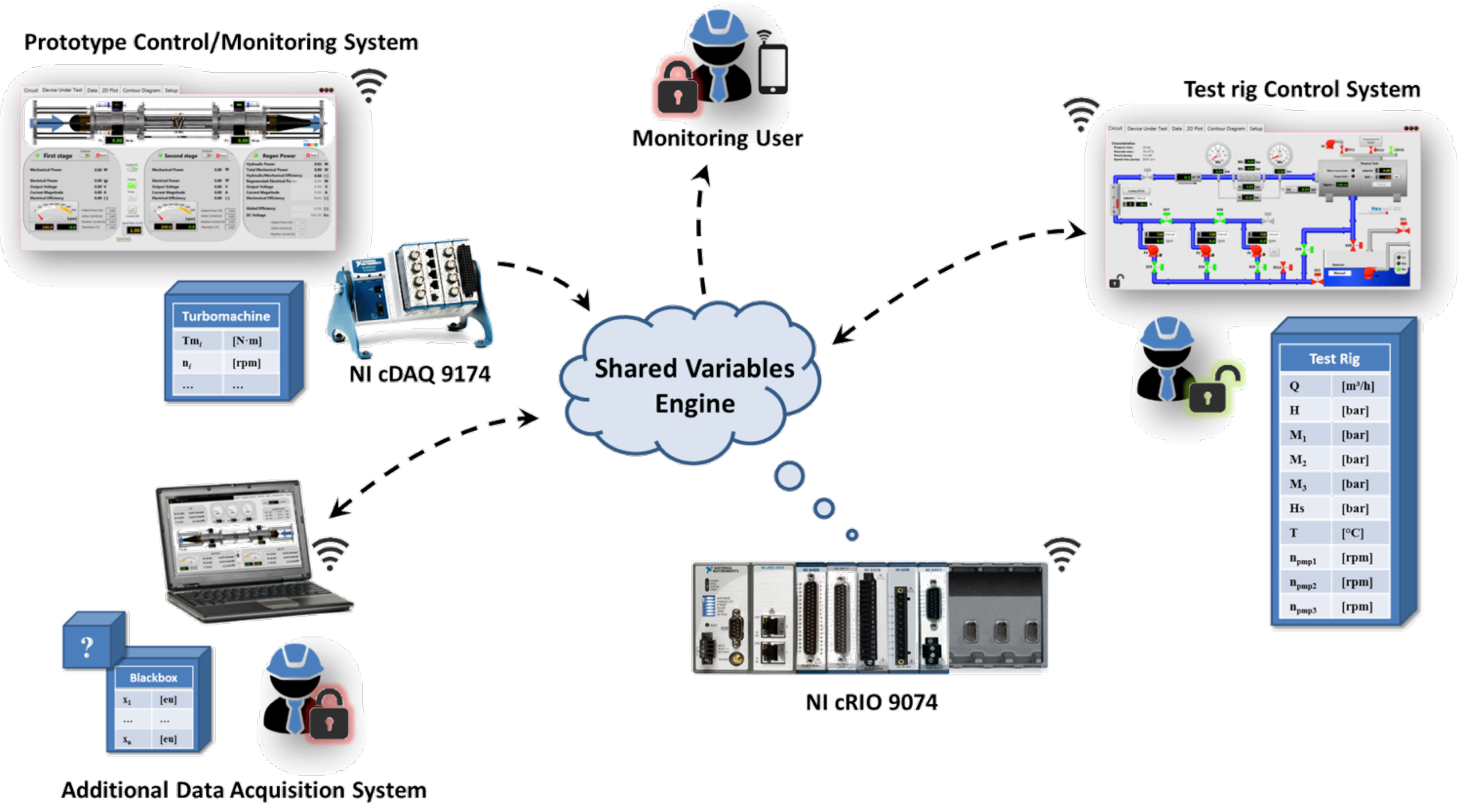
Objectives of model testing

- ✓ Validation of the hydraulic design
- ✓ Feedback for the optimisation of the design
- ✓ Productivity prediction for the final product
- ✓ Determination of the machine behaviour over the whole operating range:
  - ✓ Dynamic stability
  - ✓ Cavitation
  - ✓ Runaway
  - ✓ Structural loading

Capabilities of the new HES-SO VS hydraulic test rig

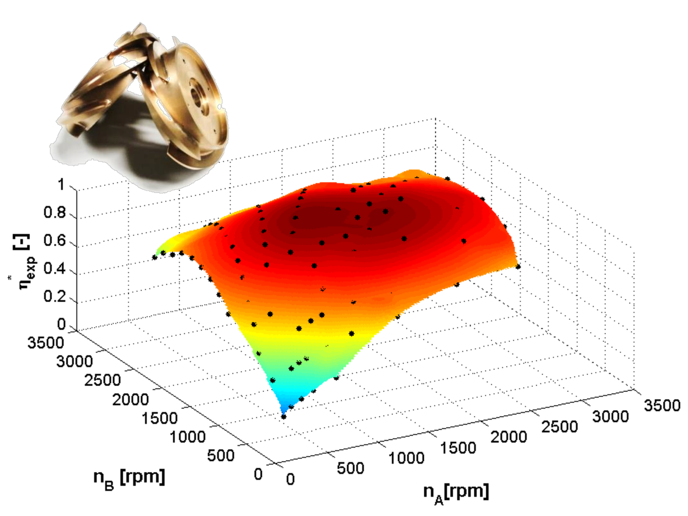
- ✓ High-precision measurements of hydraulic characteristics following the IEC 60193 standard recommendations
- ✓ Multi-user control system architecture (Wi-Fi communication)
- ✓ Automatic regulation of the recirculating pumps speed, discharge and head
- ✓ Allows for different positive and negative setup levels of the testing model and therefore to recover the cavitation performances as well

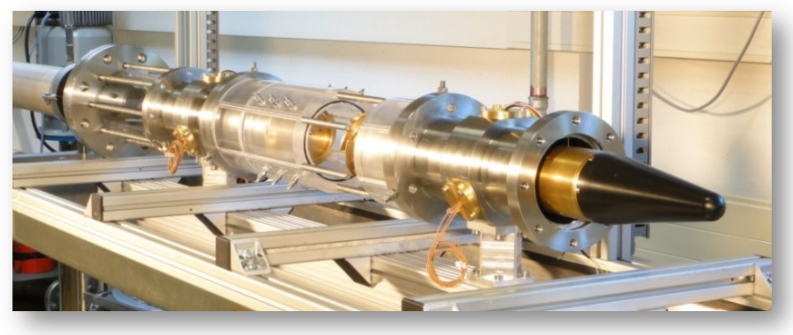
Multi-user control system architecture

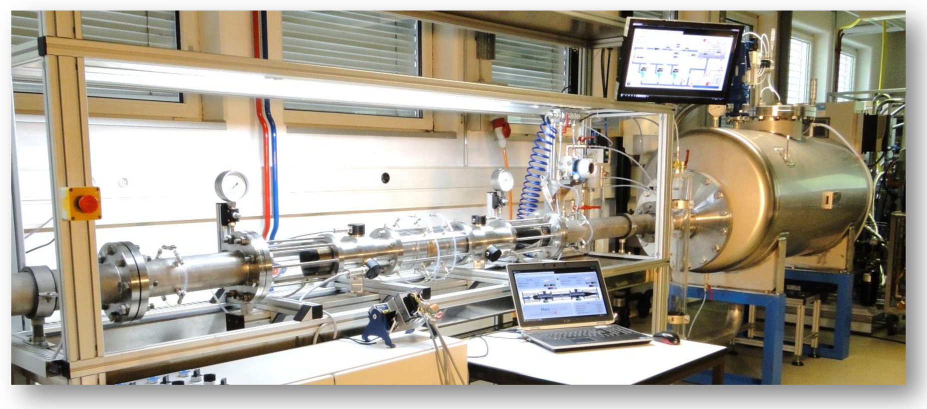


Performance testing projects

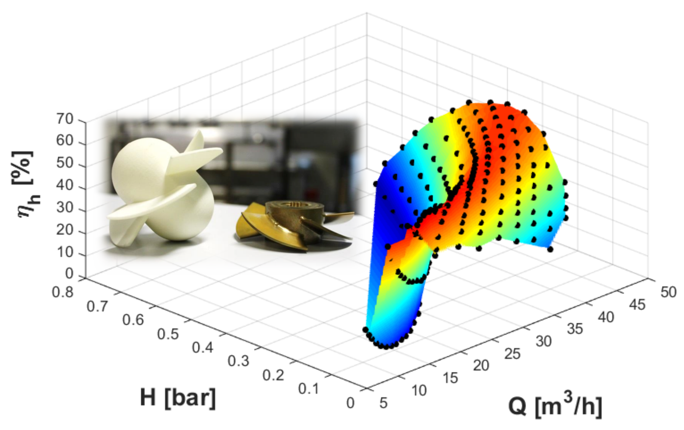
- ✓ **2 kW counter-rotating microturbine with independent variable speeds – "bulb" version**

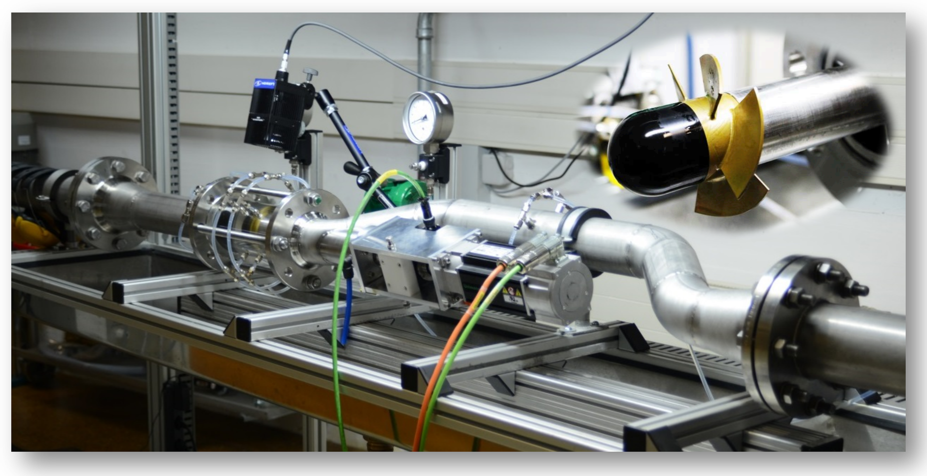




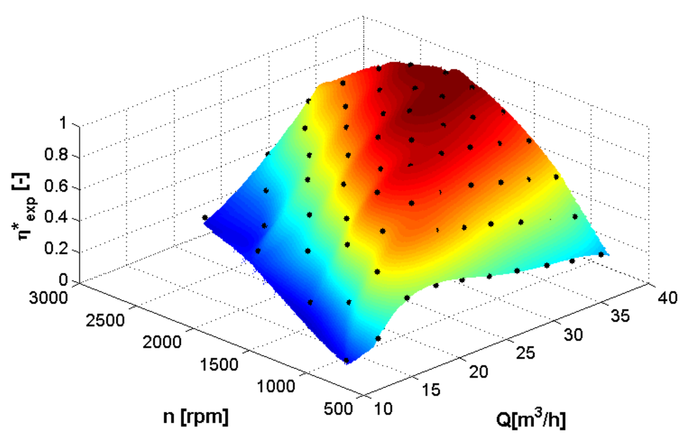


- ✓ **300 W reduced scale model of a tubular variable speed pico-turbine**





- ✓ **11 kW 5-stage reversed-pump with variable speed**



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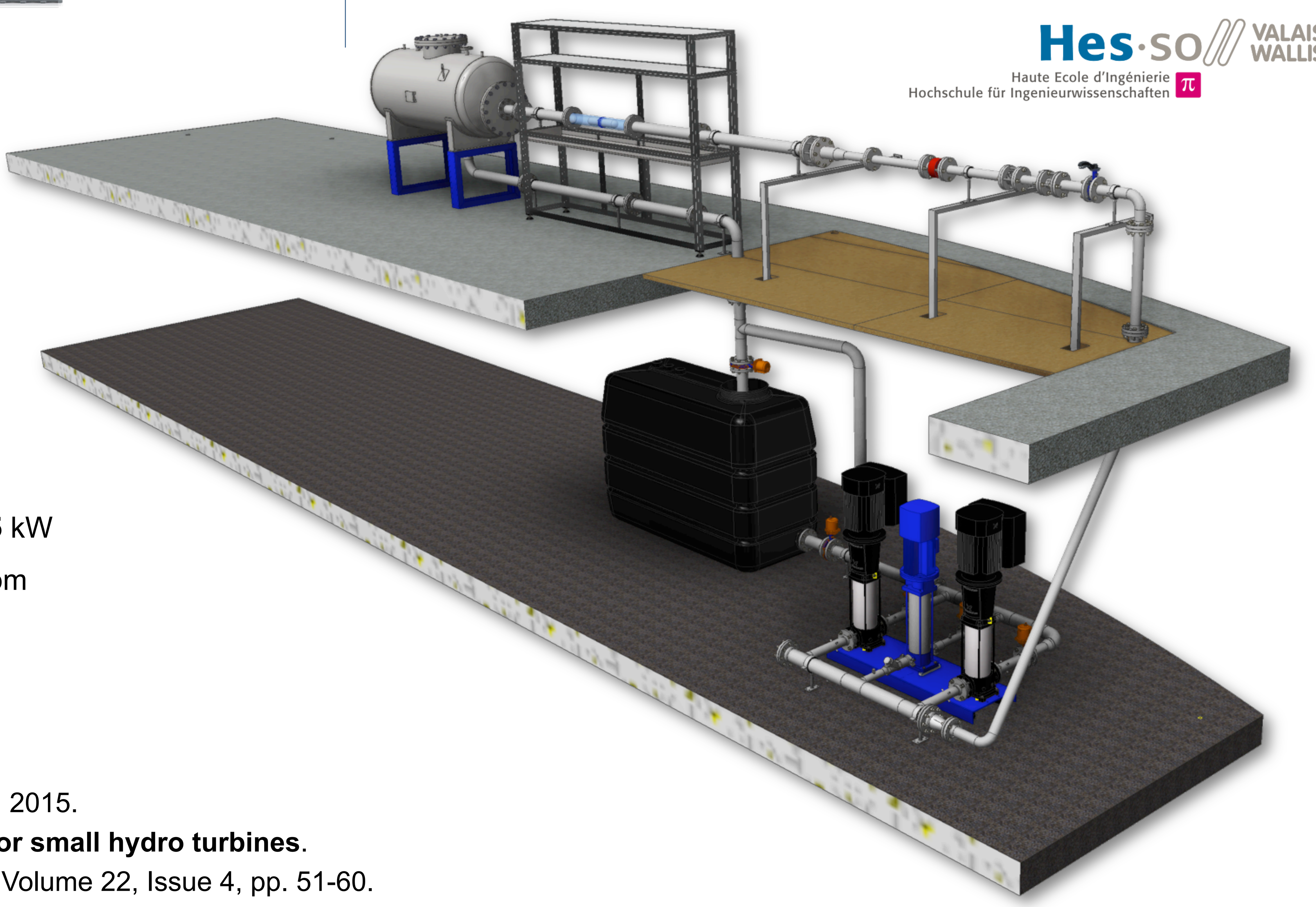

Main characteristics

Maximum head: **160** mWC

Maximum discharge: **100** m3/h

Generating power: **20** kW

Pumping power: 2 x **18.5** kW & 1 x **5.5** kW

Maximum pumps speed: **3'500/3'000** rpm

Total circuit volume: **4.5** m³

Hasmatuchi V., Botero F., Gabathuler S., Münch C. 2015.
Design and control of a new hydraulic test rig for small hydro turbines.
The International Journal on Hydropower & Dams, Volume 22, Issue 4, pp. 51-60.

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Swiss Confederation
Commission for Technology and Innovation CTI

Micro-hydropower in water systems

Irene Samora[1, 2], Mário Franca[2], Anton J. Schleiss[2], Helena M. Ramos[1]

(1) Instituto Superior Técnico, University of Lisbon (2) Laboratoire de Constructions Hydrauliques, Ecole Polytechnique Fédérale de Lausanne

LCH LABORATOIRE DE CONSTRUCTIONS HYDRAULIQUES

TÉCNICO LISBOA

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

1. Introduction

A micro-hydropower scheme can consist of generating energy in small rivers and water supply, irrigation, wastewater or drainage systems. In the context of the Energy Strategy 2050, micro-hydropower can be a way of improving the energetic efficiency of existent systems. Nevertheless, conventional turbines are not cost-effective for micro-hydro and the potential for energy production at such a small scale is not yet fully studied.

In this research project, in the scope of the Ph.D. Thesis by Irene Samora under the joint IST-EPFL doctoral initiative, focus is given to the water supply systems. A new turbine is proposed along with an integrated simulation and optimization tool to support the design of micro-hydro in water systems.

2. The five blades tubular propeller turbine (5BTP)

The five blades tubular propeller turbine (Fig. 1) was developed during the EU-Project HYLOW at IST, Lisbon, and its design was optimized by means of numerical simulation. A new prototype with a diameter of 85 mm was tested in cooperation with HES SO Valais and with financial support from the Swiss Federal Office of Energy (Fig. 2 and Fig 3). The maximal output power obtained was of 300 W.

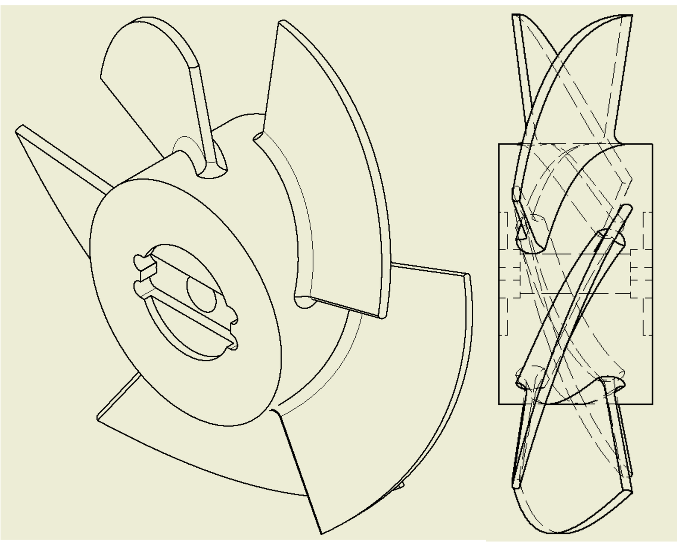

Fig. 1 – Sketch of the 5BTP

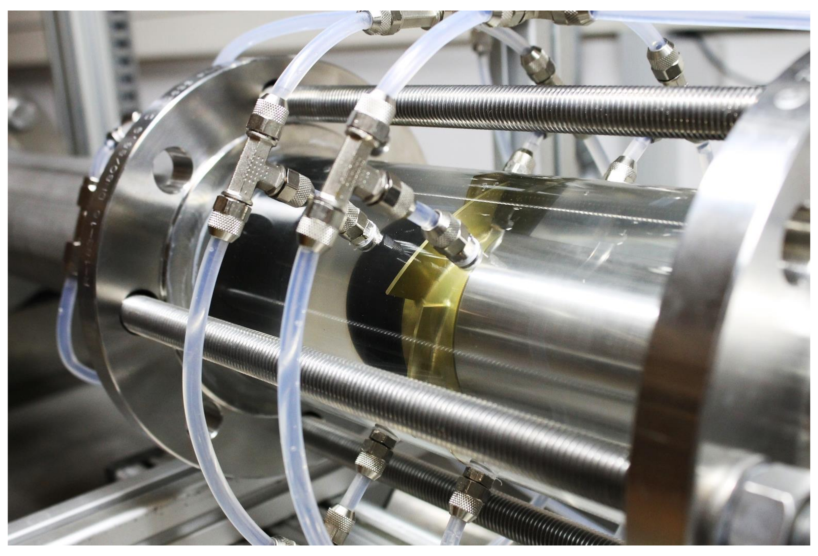

Fig. 2 – 5BTP in the laboratory

The turbine was submitted to different flow conditions and connected to an external generator with a rotation speed controller. For each pair of flow and rotation speed, the head and electric power were measured and hence, the efficiency of the turbine was deduced. The results are presented in Fig. 4.

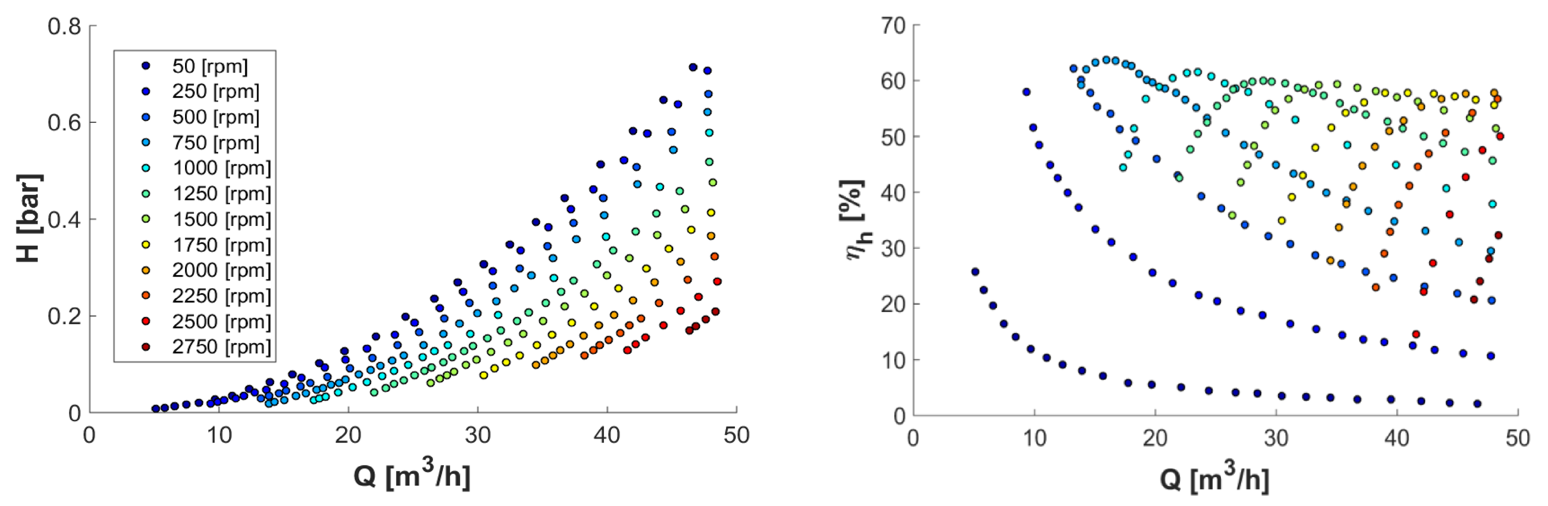

Fig. 4 – Results of the experimental campaign

Acknowledgments

Research 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. Acknowledgments are also due to eauservice (Lausanne).

3. Optimal location of micro-turbines in a water supply network

In parallel, an analysis to evaluate the hydropower production in urban drinking systems is being conducted. In the particular case of these systems, areas of the network often have more pressure than needed due to the connection to other areas at higher altitudes. Pressure reducing valves are commonly used as a mean for dissipation of this excess energy. The installation of micro-turbines is an alternative to these valves, and allows the recovering of a part of this surplus. Nevertheless, the flow in water supply systems is highly variable and most water-supply networks are meshed. Hence, the optimal location of the turbines is not a straightforward problem.

Objective: to develop an optimization tool to maximize the energy production in a sub-grid for a given number of turbines to install, while pressure restrictions must be respected.

Methodology:

- use of characteristic and efficiency curves of a turbine
- use of a database of flow demand given every hour
- EPANET 2.0 simulations combined with the simulated annealing optimization algorithm

Case study: sub-grid of the water supply system of the city of Lausanne, Switzerland (Fig. 5). The sub-grid consists of a closed network of 335 links and 312 nodes for which there was a complete series of hourly flows between 2009 and 2013. The curves obtained from numerical simulation of the 5BTP turbine were used, even though they may overestimate the energy production.

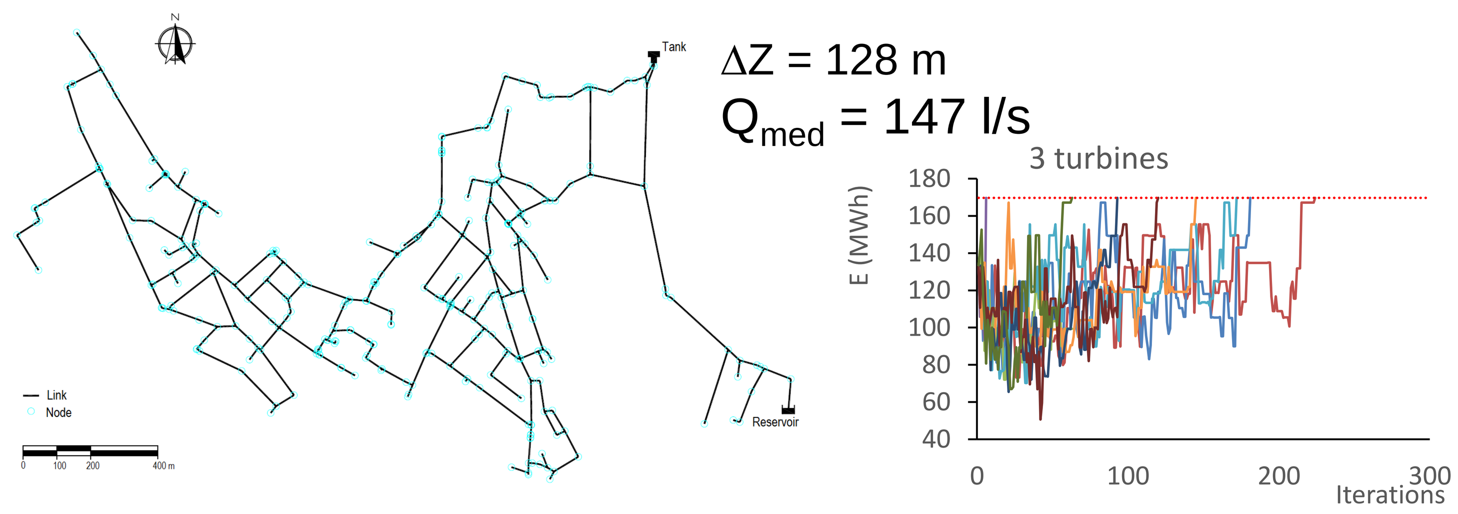

Fig. 5 – Case study network (data provided by eauservice, Lausanne), and results of the optimization algorithm for 3 turbines

Tests to evaluate the convergence of the algorithm were carried out for the installation of two and three turbines and considering also constraints in some links (Fig. 5).

4. Conclusions

So far it was verified that the micro-turbine has an encouraging performance, with efficiencies of around 60%. The application of the optimizations algorithm to the case study was also successful.

In future work, the real experimental curves of the 5BTP will be applied to case studies and a method is searched to analyze sub-grids of existing water supply networks and select the ones with higher potential for micro-hydropower.

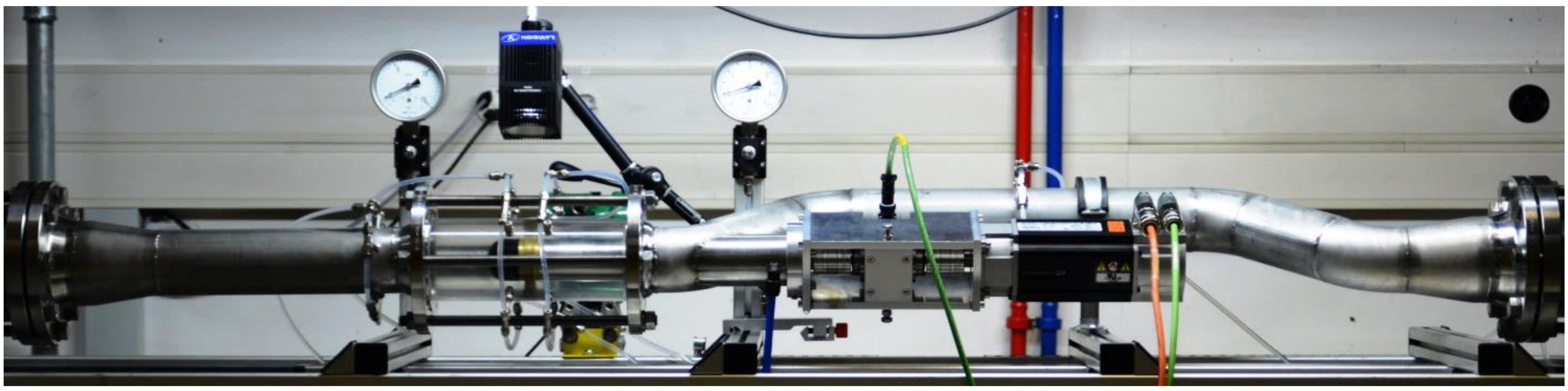

Fig. 3 – Laboratory installation

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