Printemps de la recherche 2009
Vers des opérateurs de stockage d'énergie ?

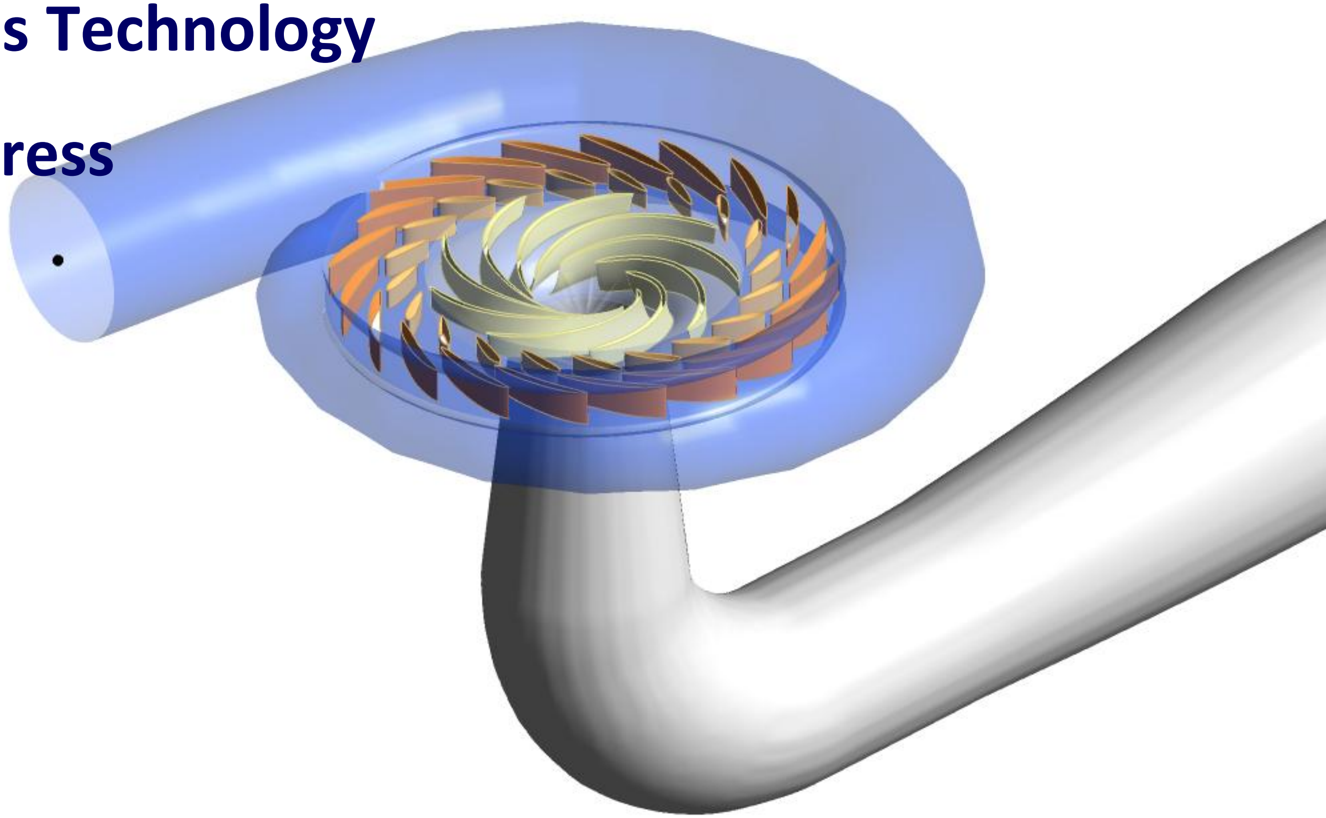
Scientific Challenges of Developing Advanced Pump-Turbine Technology for Storage Hydropower Plants

Prof. François Avellan, Dr. Eng.,
EPFL School of Engineering
Institute of Mechanical Engineering

Energy Center

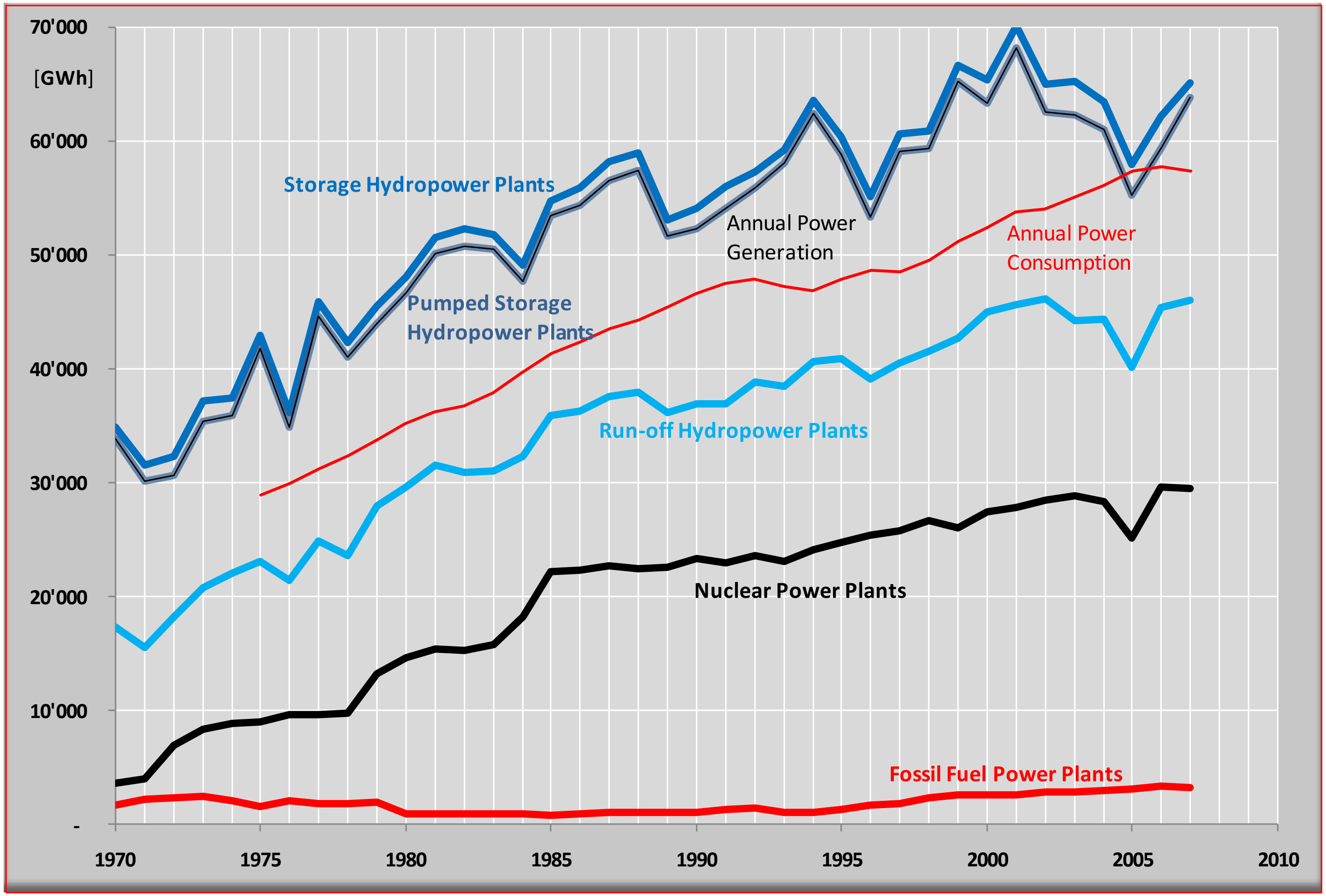
Scope

- Pumped Storage Power Plants
- Pump-Turbines Technology
- Research Progress



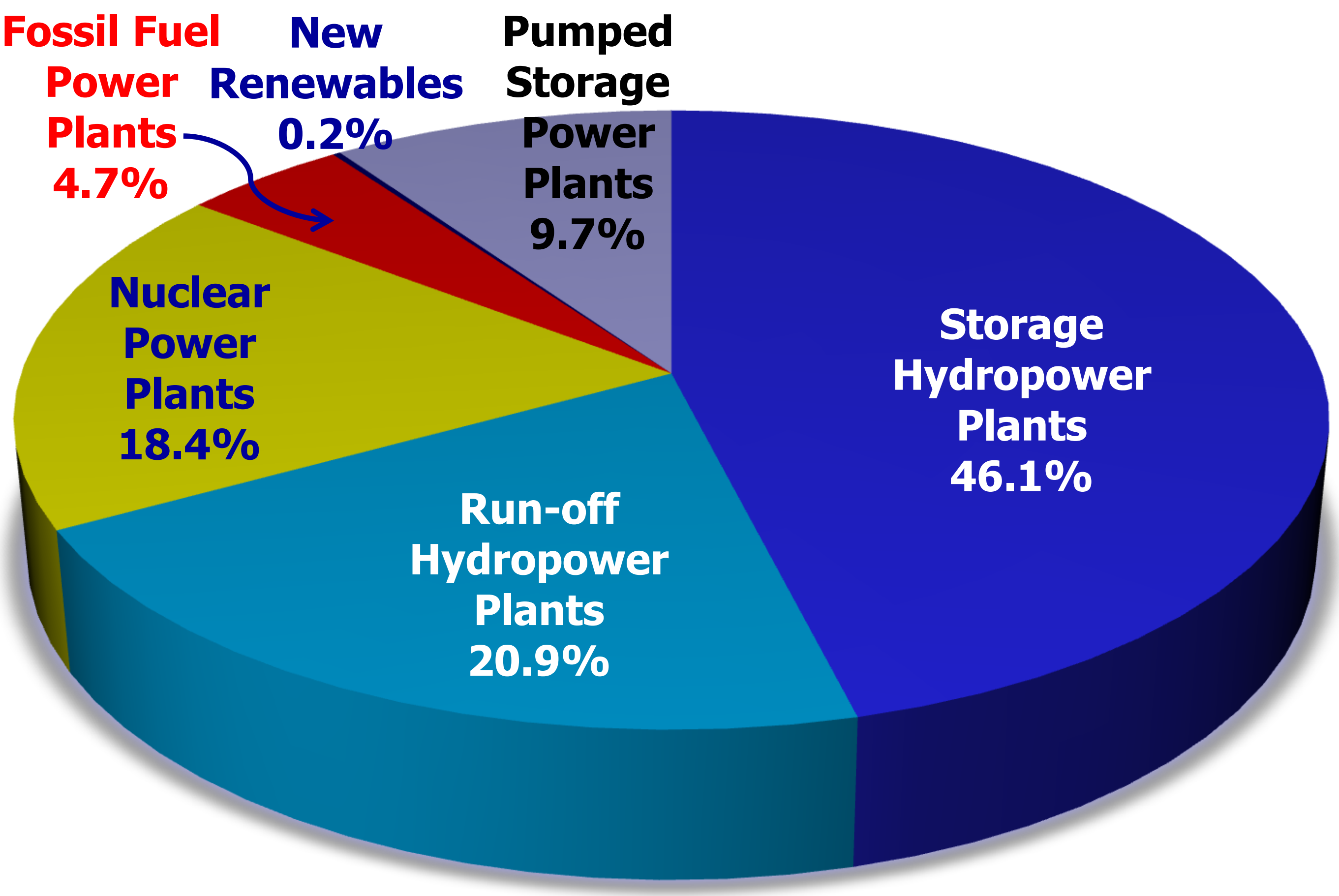
Swiss Power Generation

Swiss Electricity Data 2007 Survey



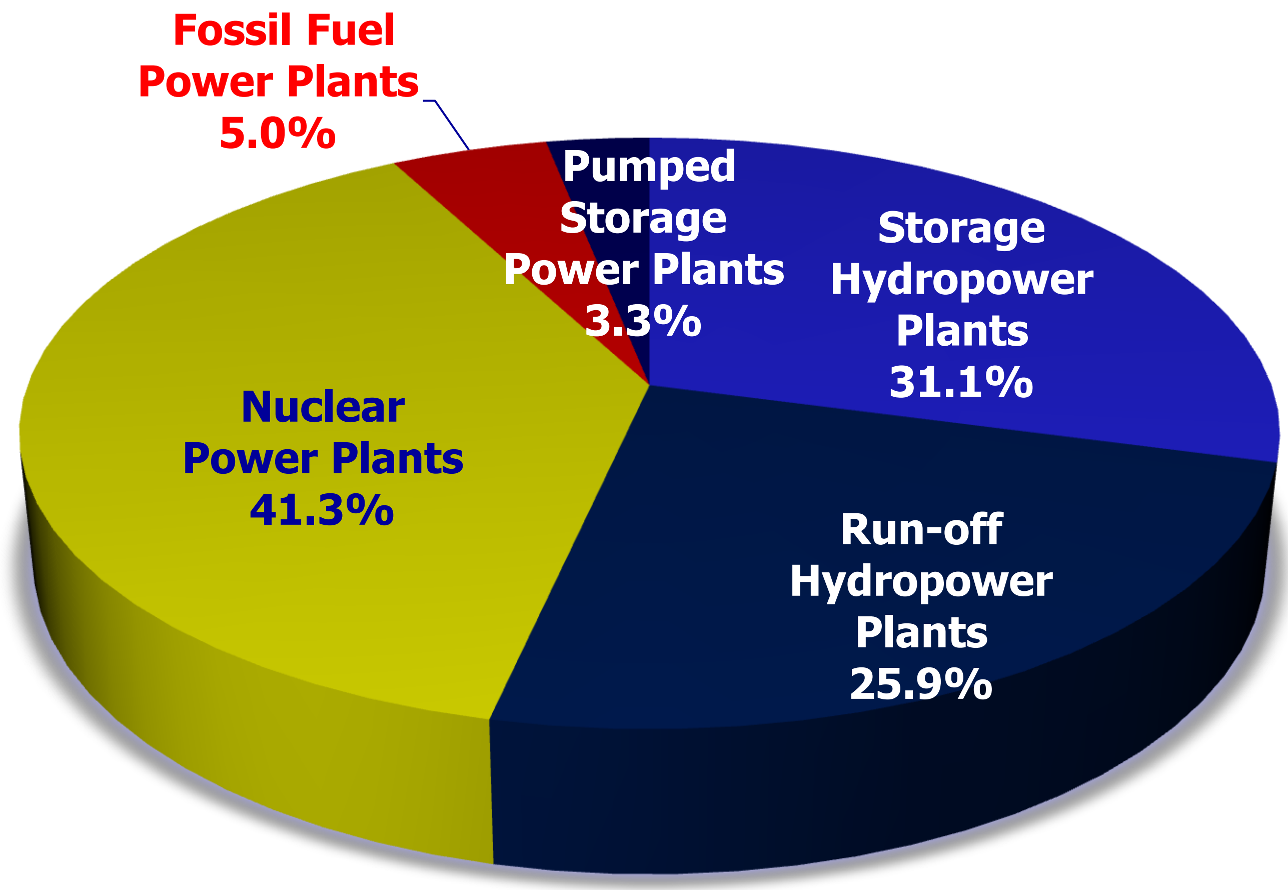
Switzerland to be Proud of a CO_2-Free Power Generation Mix

Power Generation Capacity in Switzerland

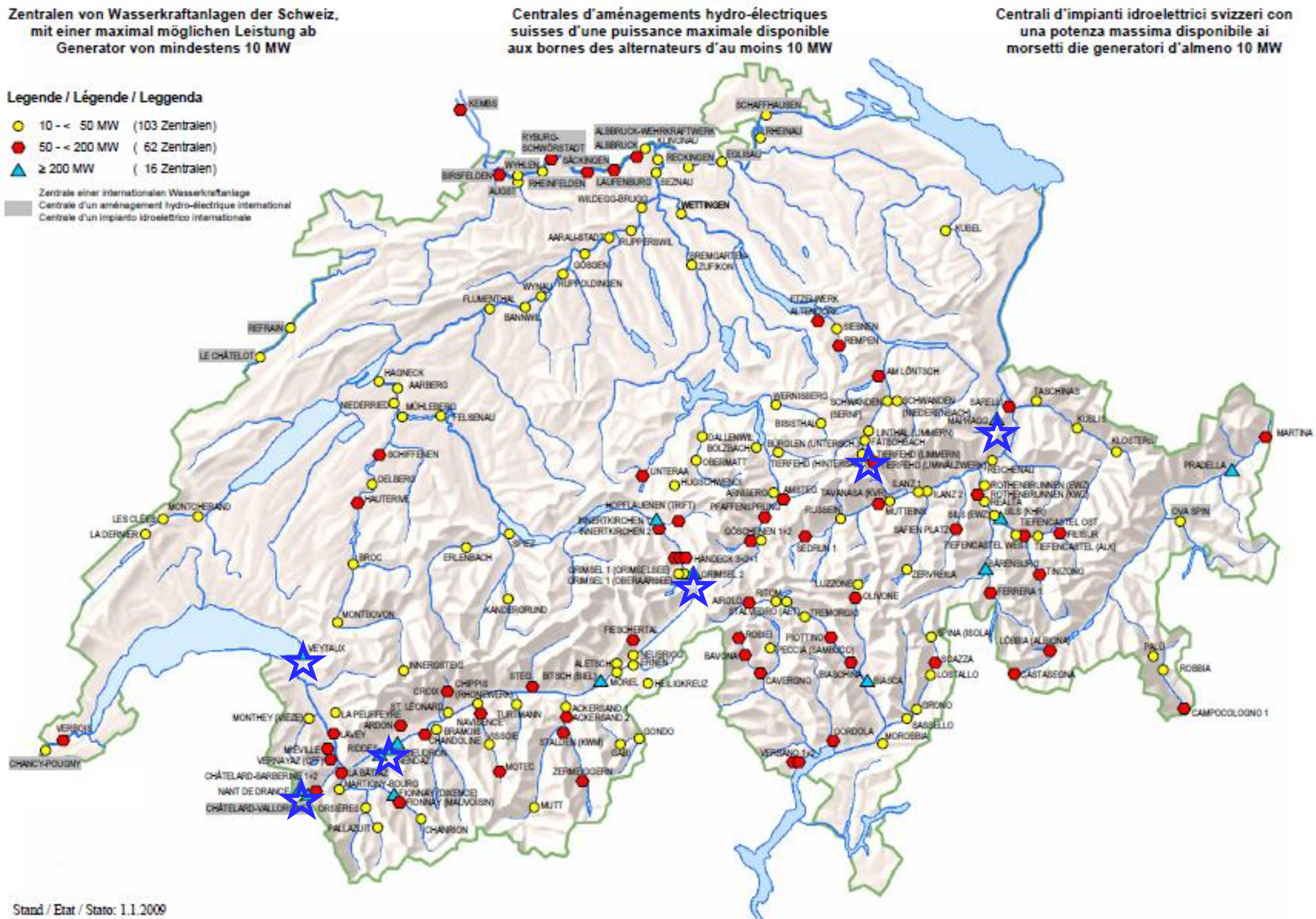


2009: 11’734 MW Hydropower Generating Capacity & 1’699 MW Pumping Power Capacity

Power Generation Mix in Switzerland



63’812 GWh Power Generation in 2009 :

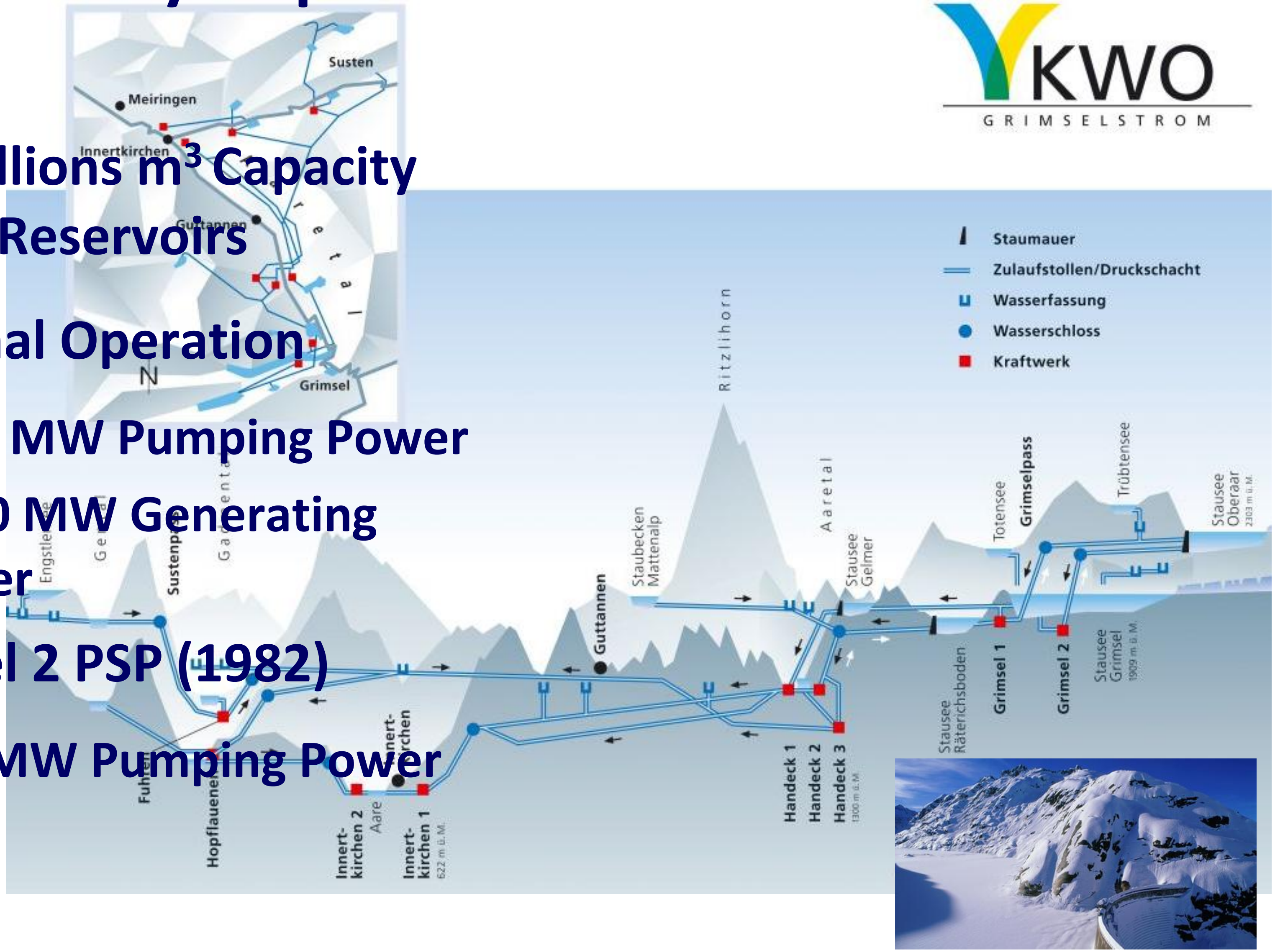


2009: 11'734 MW Hydropower Generating Capacity & 1'699 MW Pumping Power Capacity

Grimsel Hydropower Scheme

KWO GRIMSELSTROM

- 190 millions m^3 Capacity over 8 Reservoirs
- Seasonal Operation
  - ✓ ~400 MW Pumping Power
  - ✓ 1'250 MW Generating Power
- Grimsel 2 PSP (1982)
  - ✓ 350 MW Pumping Power



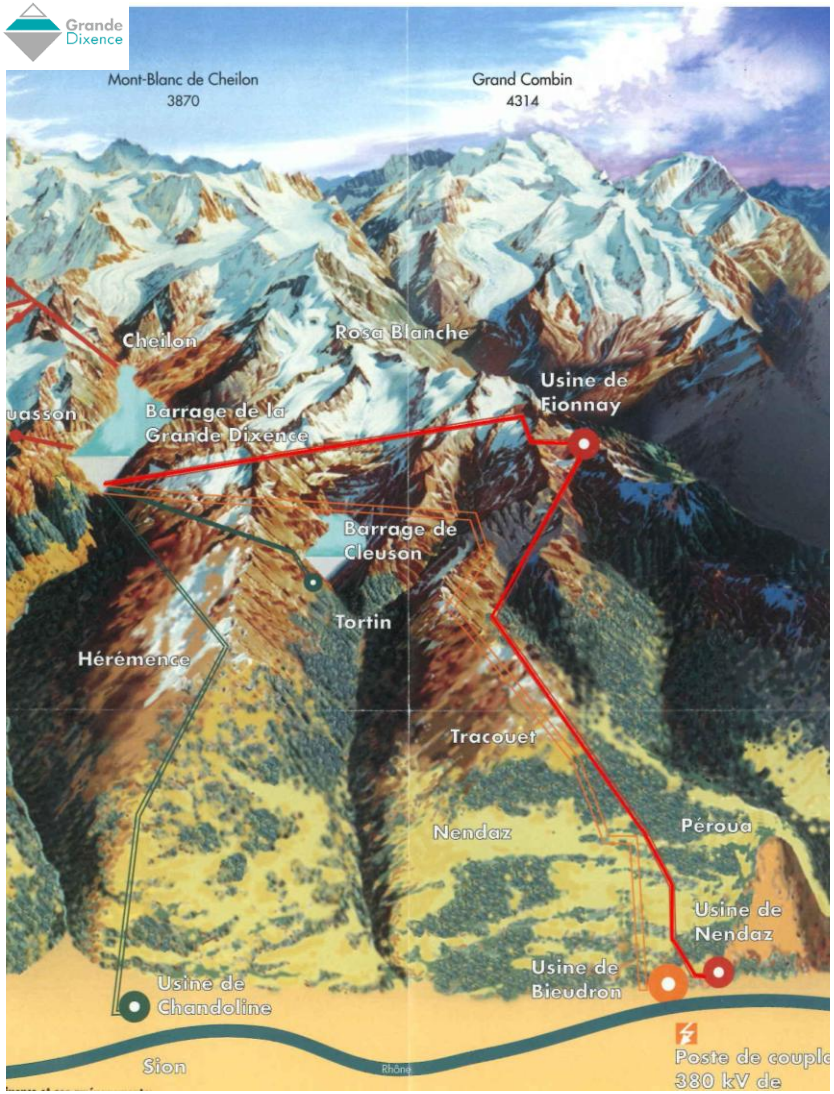
Grande Dixence Hydropower Scheme

Grande Dixence

- $400\ 10^6\ m^3$ Capacity
- Collecting Water from 35 glaciers
  - ✓ From Mattertal to Val d'Hérens
  - ✓ ~170 MW Pumping Power
- Seasonal Operation
  - ✓ 1'250 MW Generating Power

Grande Dixence Hydropower Scheme

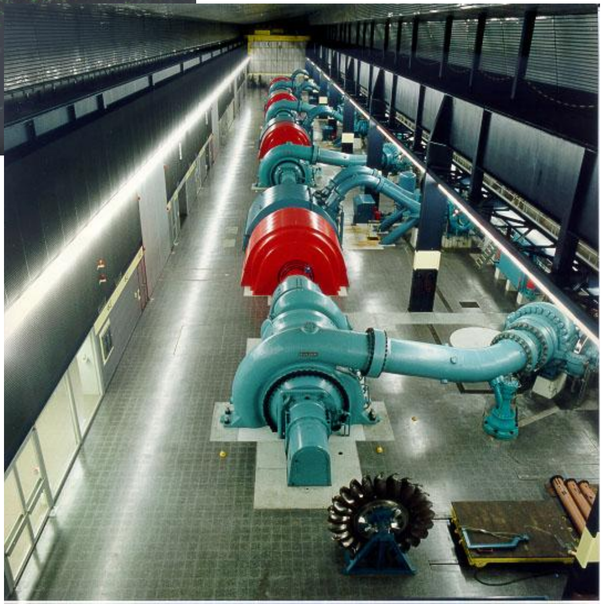
- **Collecting Water**
  - ✓ Z'Mutt 83 MW
  - ✓ Arolla 43 MW
  - ✓ Stafel 23 MW
  - ✓ Ferpecle 20 MW
- **Generating**
  - ✓ Bieudron 1'250 MW
  - ✓ Nendaz 385 MW
  - ✓ Fionnay 295 MW
  - ✓ Chandoline 100 MW



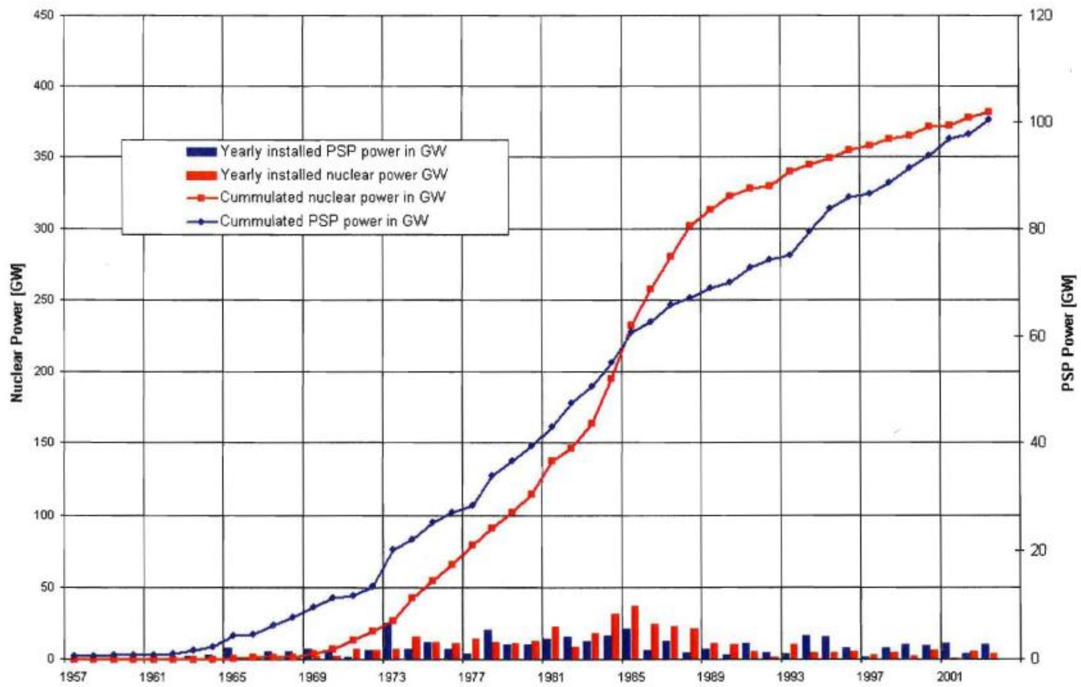
Reservoir Storage Capacity: Maximum Value

Hongrin-Léman Pumped Storage Plant

- 52 millions m³ Capacity
- Veytaux Power Station (1972)
  - ✓ 4 Tandem Units
  - ✓ 850 mWC Head
  - ✓ ~256 MW Pumping Power
  - ✓ 240 MW Generating Power



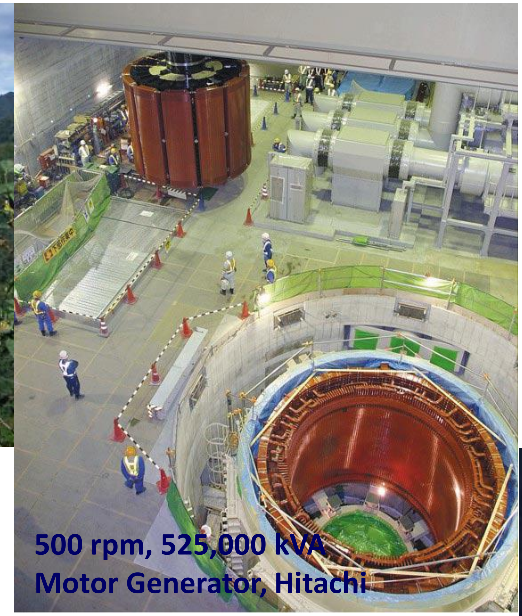
Electricity Storage: from Seasonal to Daily Operation and Grid Primary Control

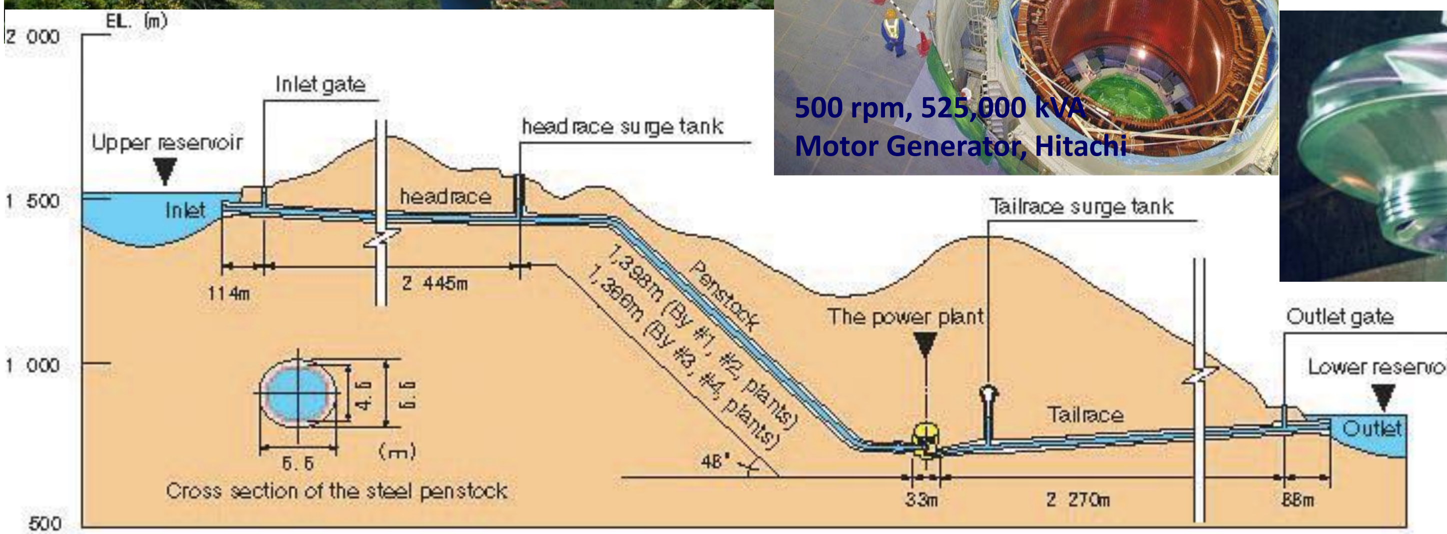


Worldwide Pumped Storage Plant Capacity Development vs. Nuclear Power Plant Capacity, *Source ALSTOM Power*

1 PSP Unit for 5 to 9 NPP Units According to UNIPEDE

Needs of Storage Capacity: Driven by the Development of Nuclear/Coal Power Plants



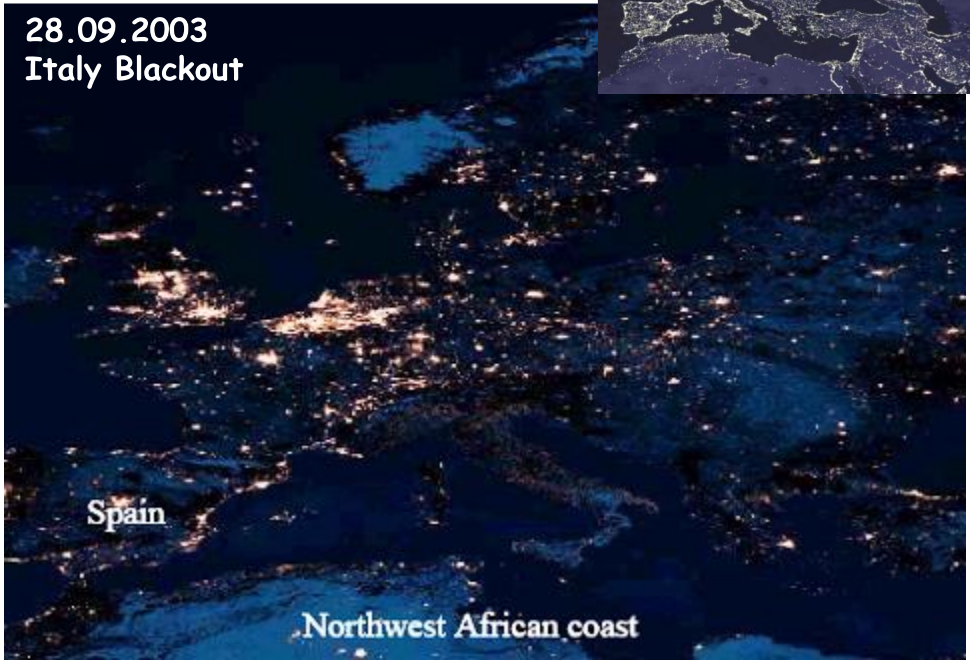


- 2’820 MW Capacity, 6 Pump-Turbines, 470 MW Pumping Power, 625 mWC Head
- TEPCO, Tokyo Electric Power Co.

Kannagawa PSP : Worldwide Largest Capacity Pumped Storage Power Plant

Development of New Renewable Energy Sources

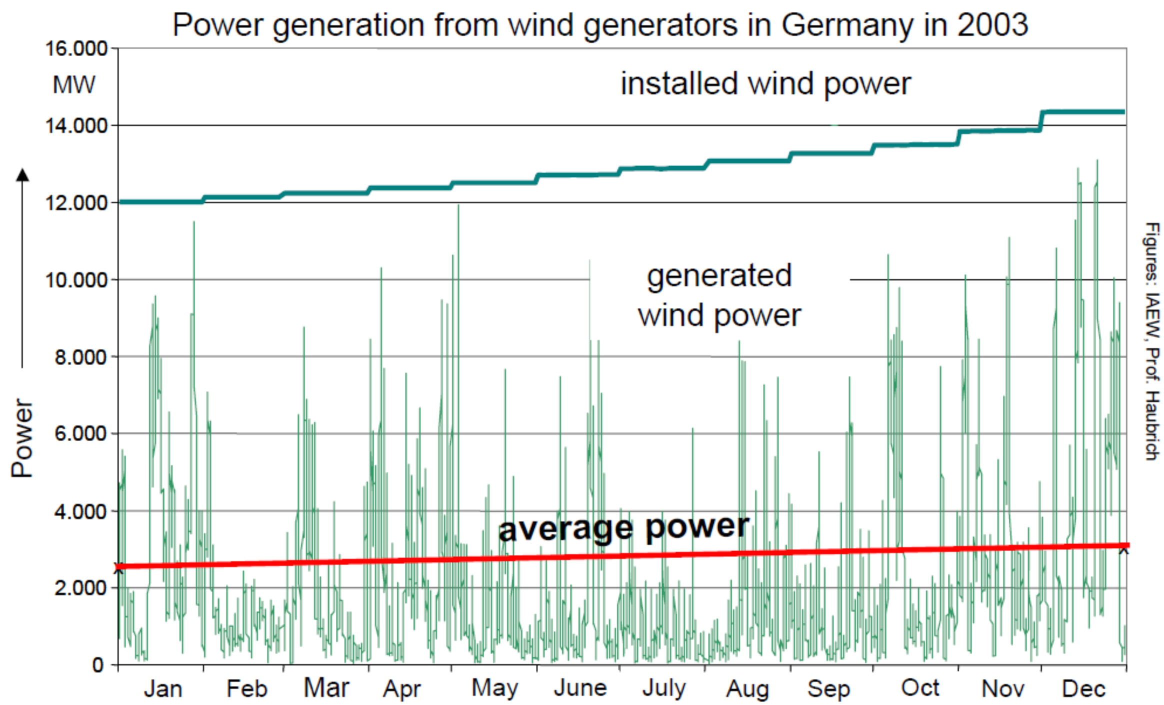
- Wind Power Tremendous Development
  - ✓ 55 GW in Europe;
  - ✓ 22 GW in Germany;
  - ✓ ~ 14 GW in Spain;
- Photo Voltaic ?
- Grid Stability ?
- Security of Supply?



Wind Power Generation 2003 Survey in Germany

RWTH AACHEN iSEA

On an annual basis the fluctuations remain high



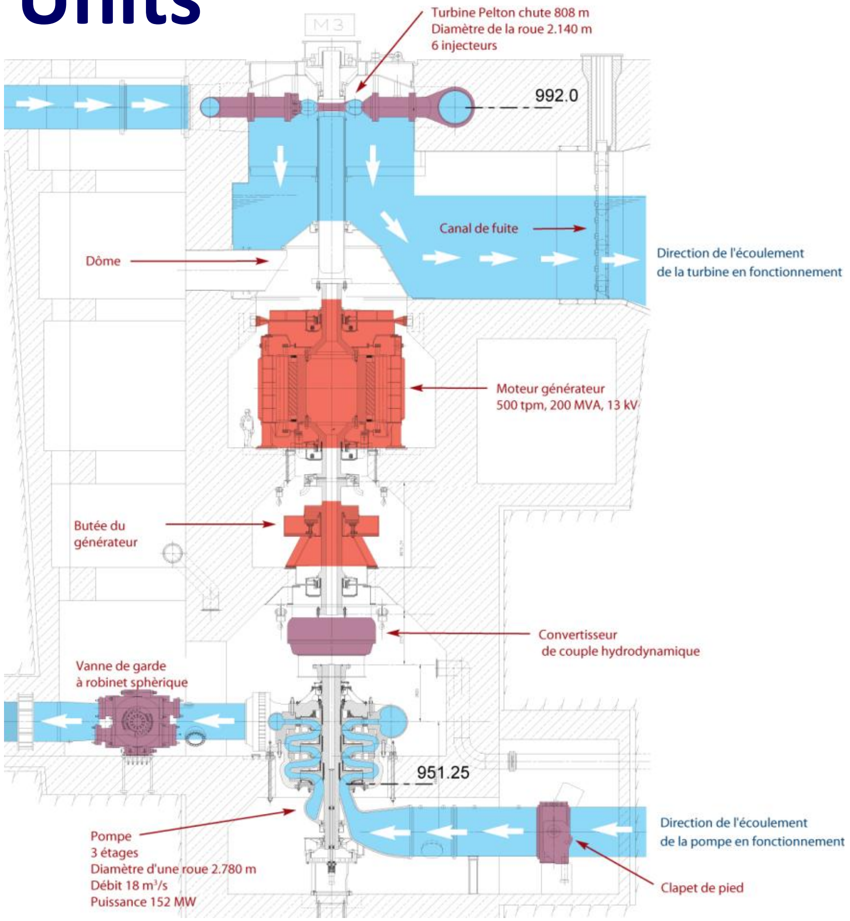
30.10.2006
Prof. Dr. Dirk Uwe Sauer
Demand for energy storage in regenerative energy systems
No 10

Last Outstanding Pumped Storage Plants Commissioned since 10 Years

Project	Installed Capacity	Number of Units	Unit Power	Owner	Year
Kannagawa	2'820 MW	6	470 MW	TEPCO Japan	2005
Goldisthal	1'060 MW	4	265 MW	Vattenfall Europe Germany	2002
Kazunogawa	1'648 MW	4	412 MW	TEPCO Japan	2001
Tianhuangping	1'800 MW			China	2001
Guangzhou	2'400 MW	8	300 MW	CLP, Guangdong China	2000
Matanoagawa	1'200 MW			Chugoku Electric Power Japan	1999
PAVEC Chaira	864 MW	4	216 MW	NEK Bulgaria	1998
Okutataragi	1'932 MW	6	322 MW	KEPCO Japan	1998

Tandem Pump-Turbine Units

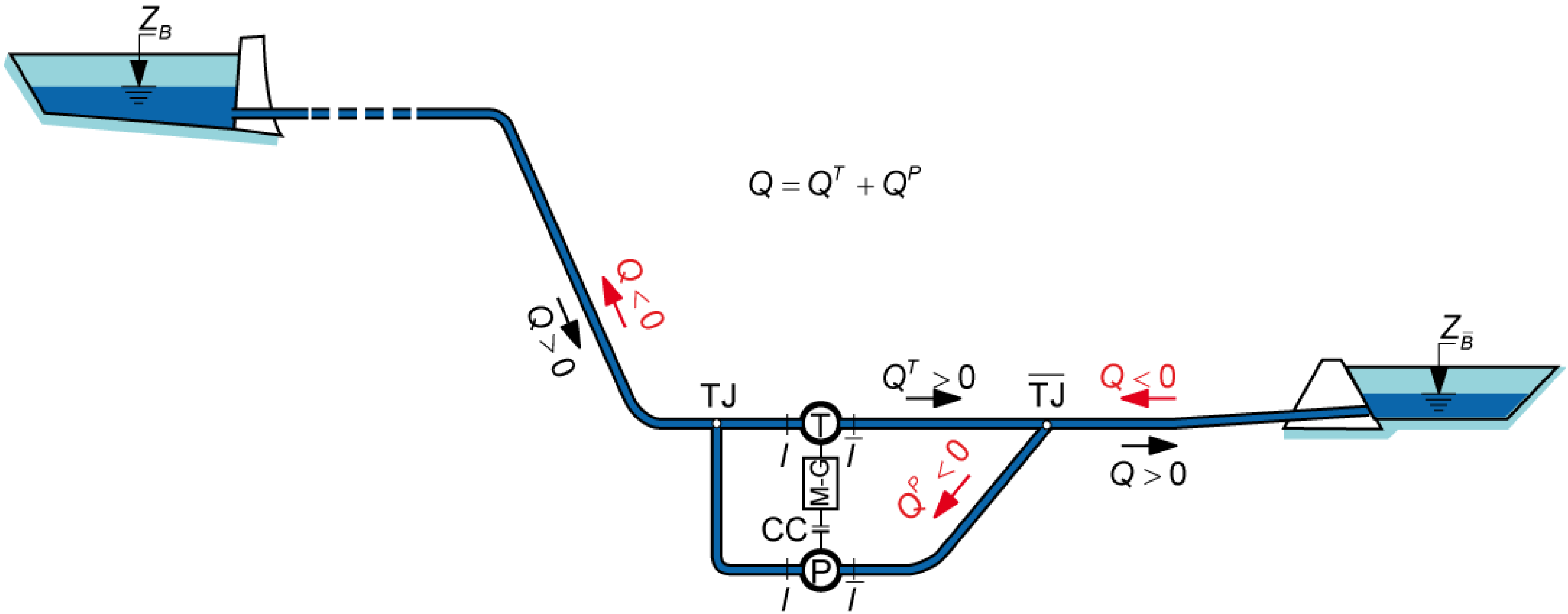
- Easy Start-Up Procedure
- Bidirectional Motor-Generator Speed
  - ✓ Air Cooling vs. Water Cooling
- Pumping & Generating Operating Ranges Matching
  - ✓ Shaft length
  - ✓ Speed & Cavitation
- Grid Primary Control
  - ✓ Pelton Turbine
  - ✓ Hydraulic Bypass



Kopswerk 2, Voralberger Kraftwerke AG

3 Tandem Units ~800 mWC, 150 MW @ 500 rpm

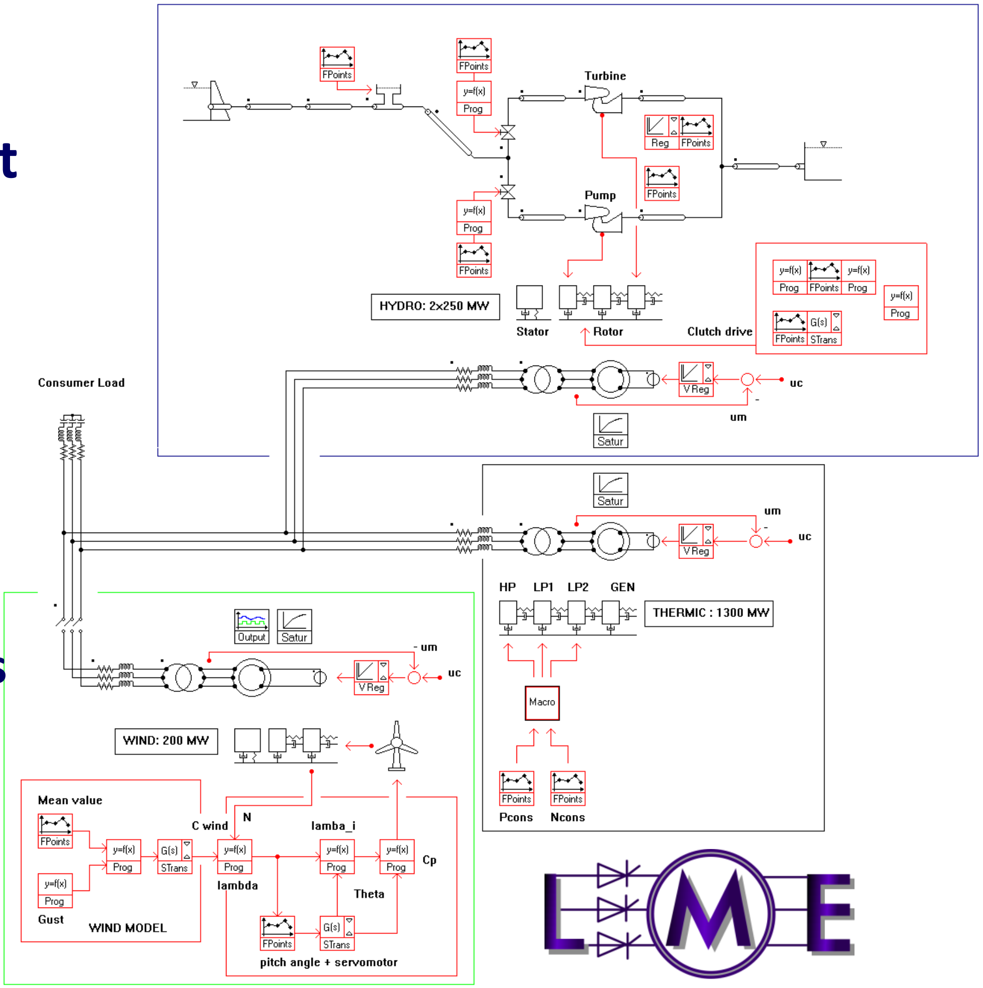
Hydraulic Bypass



$$P^{M-G} = P^T + P^P$$

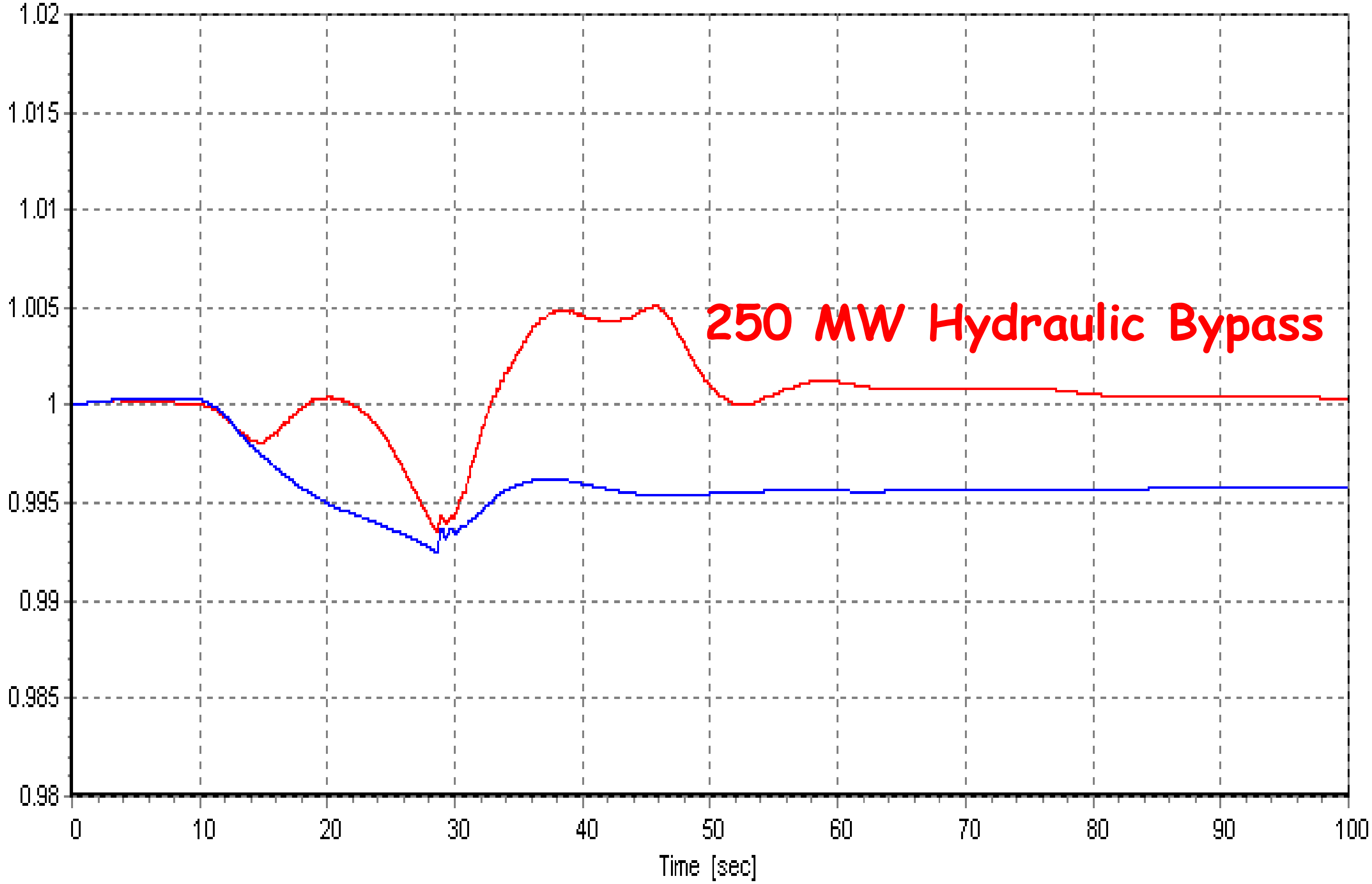
Mixed Islanded Network
Wind Farm Safety Tripp off

- 200 MW Wind Farm
- 1'200 MW Nuclear Power Plant
- 2x250 MW Pumped Storage Plant



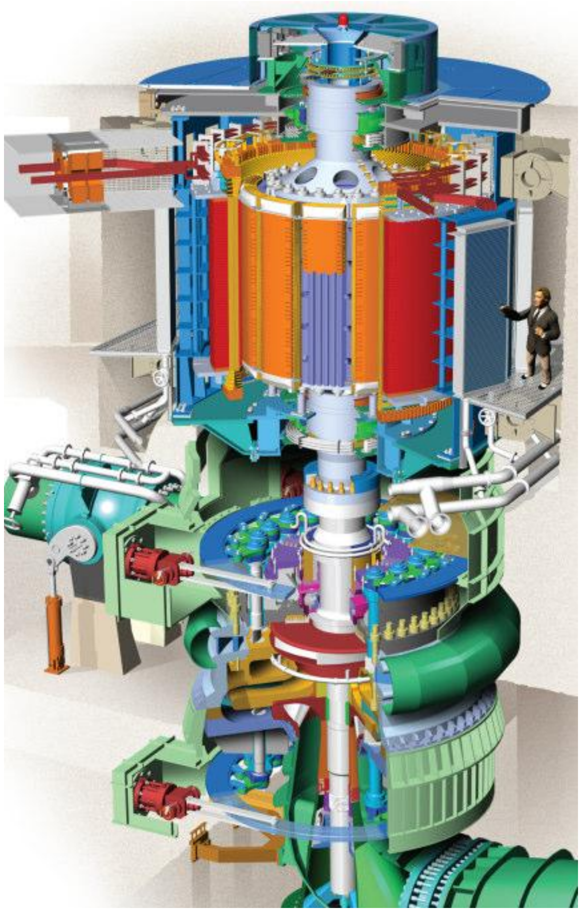
✓ C. Nicolet et al., "Storage Units to Stabilize Mixed Islanded Power Network: a Transient Analysis". HYDRO 2008, Ljubljana, Slovenia.

Grid Primary Control thru Hydraulic Bypass

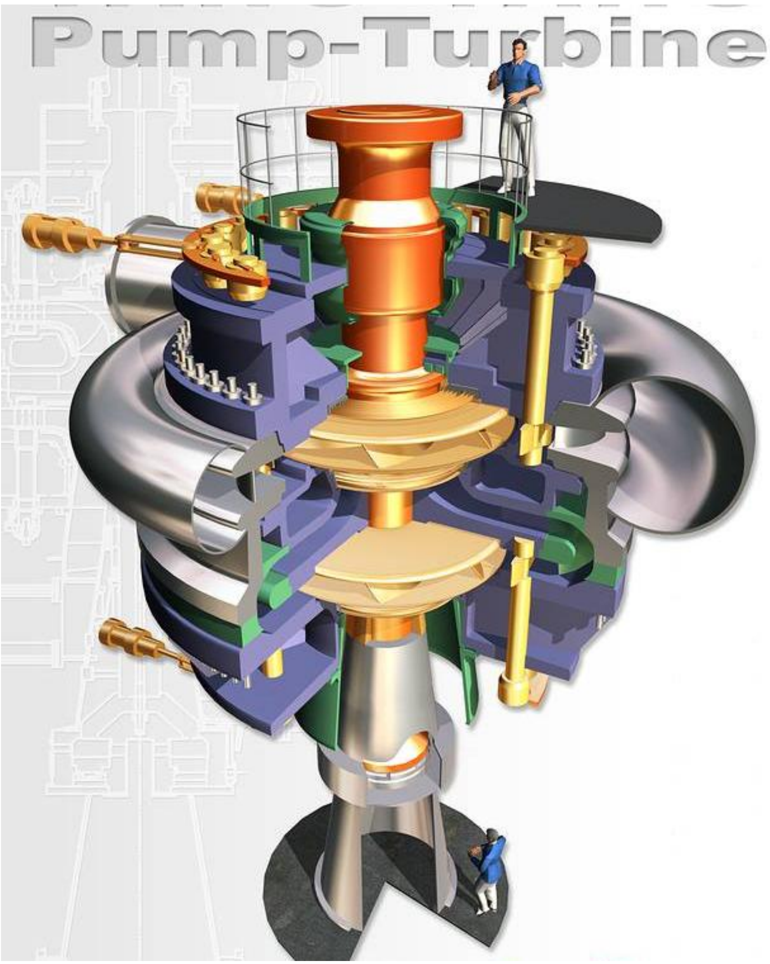


Reversible Pump-Turbine Units

- **Start-Up Procedures**
  - Static Frequency Converter Limited Power
  - Back to Back arrangement
  - Turbine Drive
- **Bidirectional Motor-Generator Speed**
  - Air Cooling vs. Water Cooling
- **Pumping & Generating Operating Ranges Matching**
  - Efficiency & Cavitation
- **Grid Primary Control**
  - Hydraulic Bypass
  - Variable speed
  - Double Regulated Stages

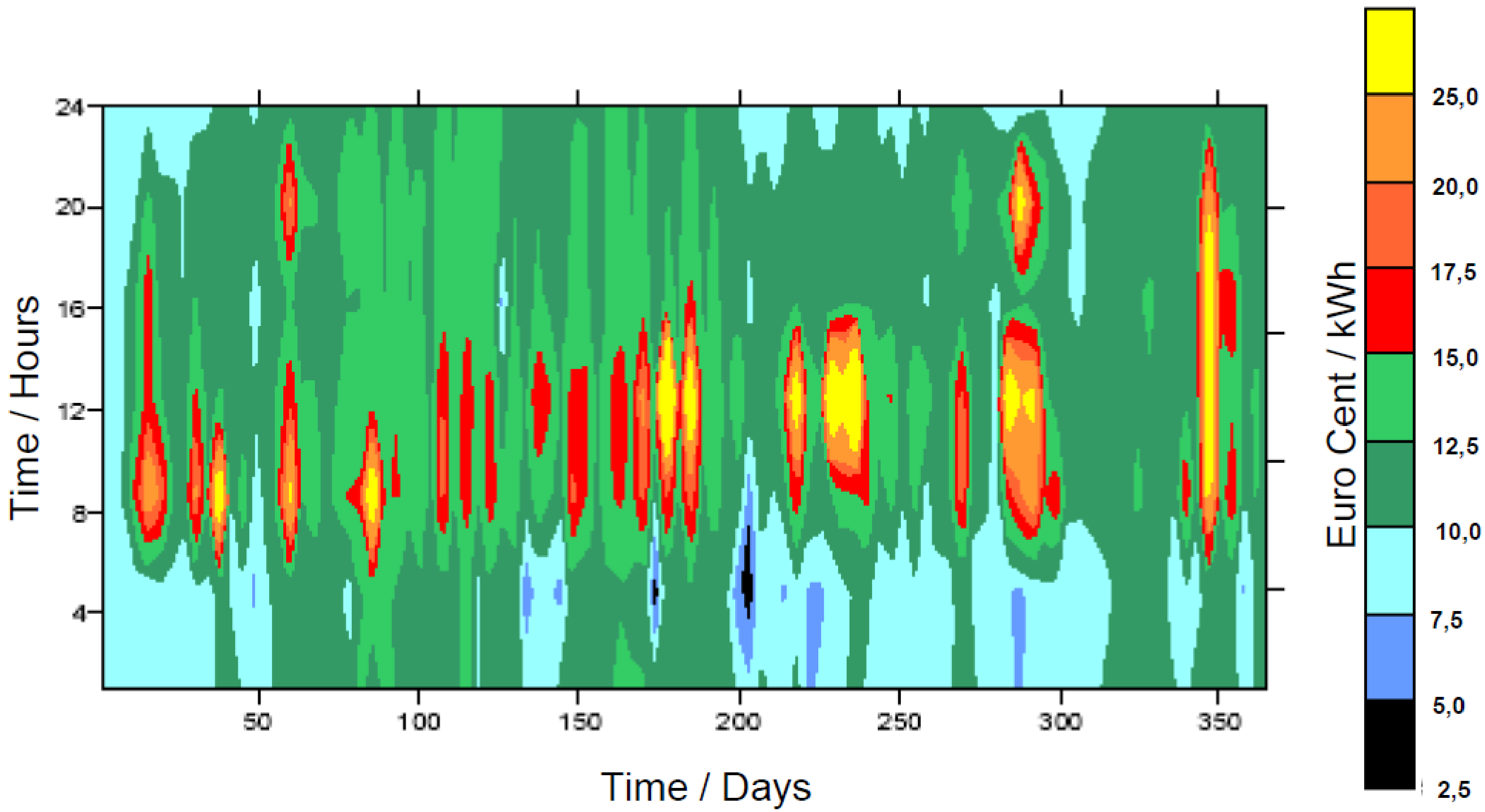


Reversible Pump-Turbine Units
Yangyang PSP, Korea



- ~800 mWC Head
- 4 units of 258 MW,
- Air Cooled 295 MVA Mot/Gen @ 600 min^{-1}
- Nq = 38 Stage Specific Speed
- Double Regulated Stages

Electricity Rate Spread 2001 Germany



Source: Fritz Crotogino, KBB Hannover

Toward a Sustainable CO_2-Free Domestic Power Generation System

- **Renewing Available Hydropower Schemes with Pumped Storage Power Plants for Maximizing Value of the Available Swiss Storage Capacities**
  - ✓ Minimizing Environmental Impacts;
  - ✓ Increasing Power Capacity and Efficiency;
  - ✓ Developing Power Control Capability;
  - ✓ Increasing Robustness, Availability, Maintainability & Safety.
- **Interconnected Electricity Networks Opportunities**
  - ✓ Enabling New Renewable Energy Development;
  - ✓ Peak Power Generation;
  - ✓ Grid Power Control Services.

620 MW Nant de Drance PSP Project Commissioning in 2015

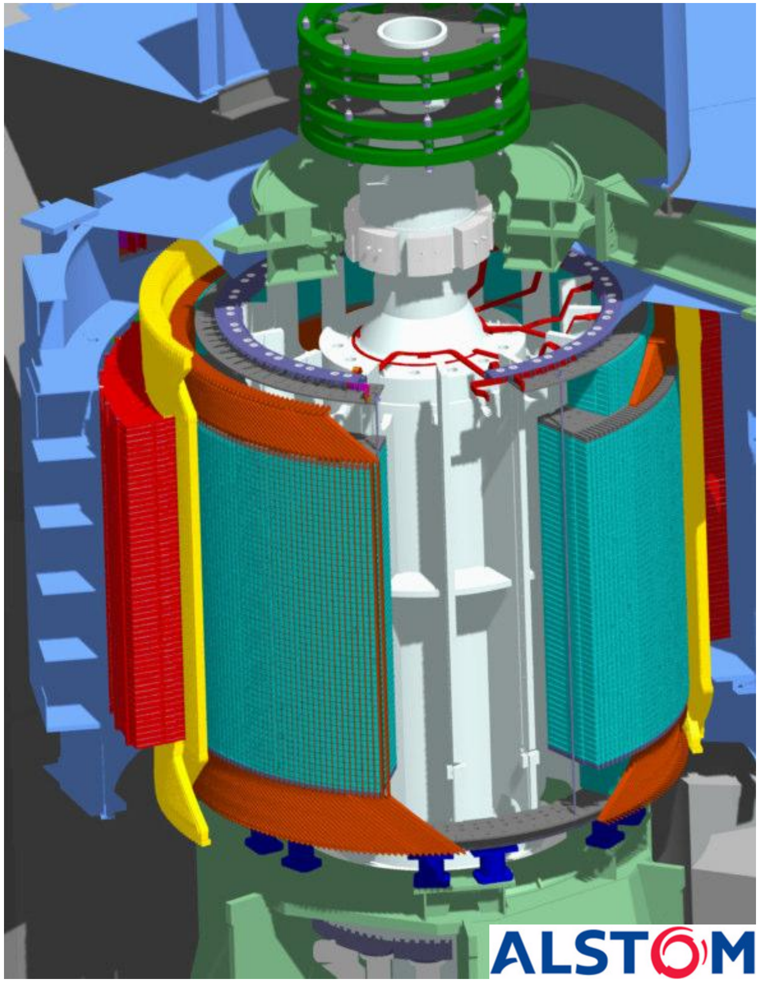
- Emosson Lake 210 10^6 m^3 Capacity
- Viel Emosson Lake 11 10^6 m^3 Capacity
- 250 to 390 mWC Head Range
- 4 x 155 MW Single Stage Pump-Turbines
- 428.6 ± 7 % rpm Variable Speed

1 GW Linthal PSP Project Commissioning in 2015

- Limmern 92 10^6 m^3 Capacity
- Mutt 25 10^6 m^3 Capacity
- 560 to 724 mWC Head Range
- 4 x 250 MW Single Stage Pump-Turbines
- 500 ± 6 % rpm Variable Speed

VARSPEED Technology

- Static Frequency Converter
  - ✓ Voltage Source Inverter
- Double Feed Asynchronous Machines
  - ✓ Cylindrical Rotor with Three Phases Winding
  - ✓ Slip Rings for Excitation
- Reversible Pump-Turbine

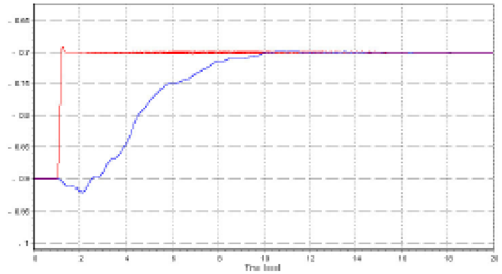


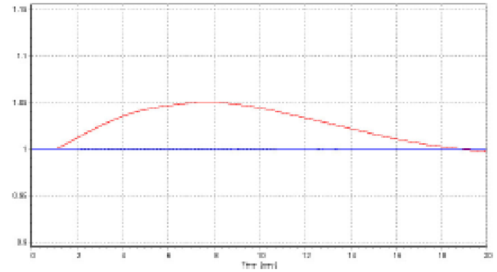
VARSPEED Technology

Varspeed ALSTOM

Improved dynamic behaviour

- Very fast change of the of the power set point





- Synchronous machine
  - Constant speed
  - Set point achieved in 10 sec
- Asynchronous machine
  - 5% speed variation
  - Set point achieved in 0.5 sec

PSP - 25.03.2009 - P 28

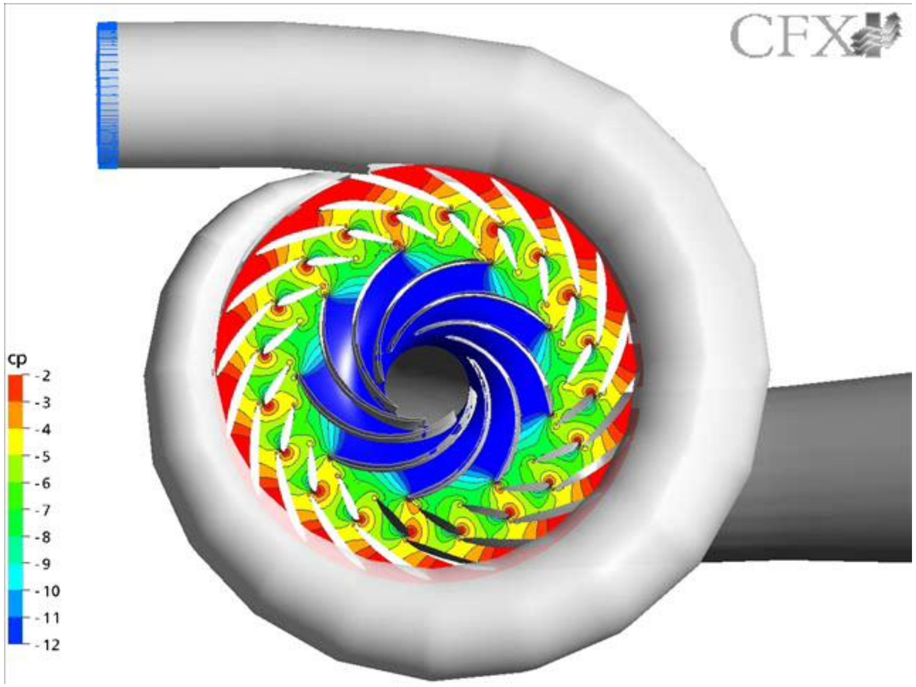
New Technology Challenges

- Meeting Demand of Peaking Power
- Frequent Starts & Stops
- Short Time Response
- Extending Operating Ranges
- Improving Reliability and Availability
- Reducing Unexpected Outage
- Enhancing Safety

Knowledge Enhancement in Hydrodynamics of Pump-Turbines

- Identification and Control of Flow Unsteadiness;
- Development of Basic Knowledge of Fluid Structure Coupling;
- Prediction Methodology for the Machine Conditions.

- Rotor-Stator Interactions in Generating Mode



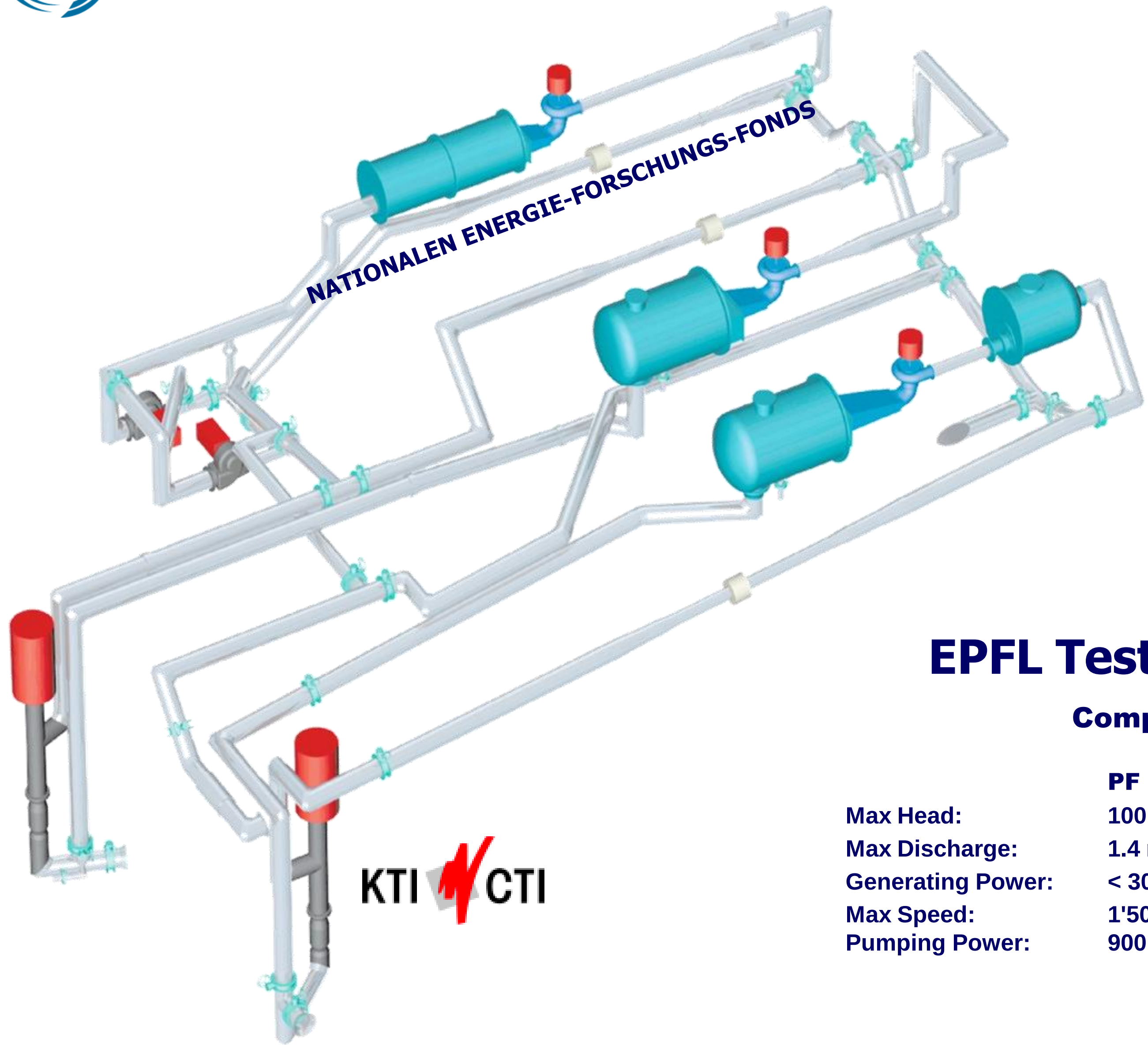
Approach to the Problem: Identification of Sources of Unsteadiness

- Hydrodynamics
  - ✓ Flow Instabilities: Turbulence, Wakes, Flow Separation Blade to Blade Vortices, Cone Swirl etc.
  - ✓ Non Uniform Incoming Flows: Stator-Rotor, Rotor-Stator
  - ✓ Cavitation: Cavity fluctuations, Compliance
- System-Machine Interactions
  - ✓ Mechanical: Unbalanced rotor, Misalignment
  - ✓ Hydraulic: Power Plant Layout
  - ✓ Electro-Magnetic: UMP, Grid Load Variation, Varspeed
  - ✓ Governing Control System
- Transients
  - ✓ Starts & Stops

General Approach

- Discovery Experiments & Modeling
- Numerical Simulation
- Experimental Validation
  - ✓ Basic Physics
  - ✓ Scaled Model
  - ✓ Prototype Machine

Experimental Infrastructure



- Research
- Education
- Experimental Validation

EPFL Testing Facilities

Complying IEC 60193 Standards
Efficiency Uncertainty <2 ‰

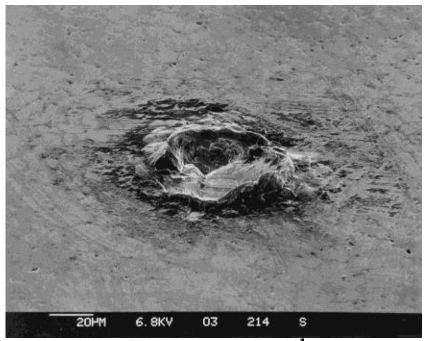
	PF 1	PF 2	PF 3
Max Head:	100 mCE	120 mCE	100 mCE
Max Discharge:	1.4 m^3/s	1.4 m^3/s	1.4 m^3/s
Generating Power:	< 300 kW	< 300 kW	< 300 kW
Max Speed:	1'500 rpm	2'500 rpm	2'500 rpm
Pumping Power:	900 kW	1000 kW	2 x 400 kW

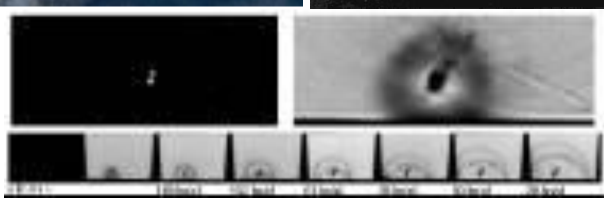
Largest Hydropower Plants in the World

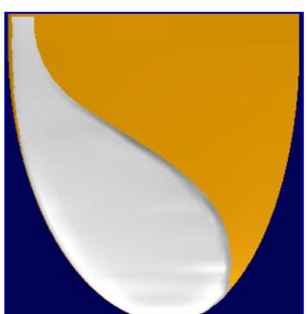
Hydropower Plant	Country	Capacity	EPFL
3 Gorges	China (2009)	18'200 MW	
Itaipú	Brazil / Paraguay	12'600 MW	✓
Guri (Raúl Leoni)	Venezuela	10'000 MW	✓
Grand Coulee	USA	6'494 MW	✓
Sayano – Shushensk	Russia	6'400 MW	
Krasnoyarsk	Russia	6'000 MW	
Churchill Falls	Canada	5'428 MW	
La Grande 2	Canada	5'328 MW	✓
Bratsk	Russia	4'500 MW	
Ust-Ilim	Russia	4'320 MW	
Tucurui	Brazil	4'245 MW	✓

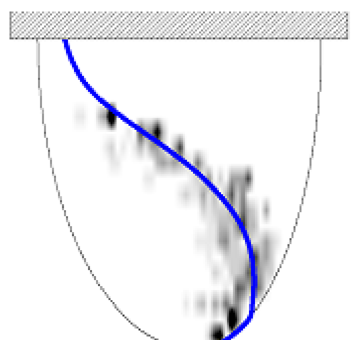
Cavitation Physics

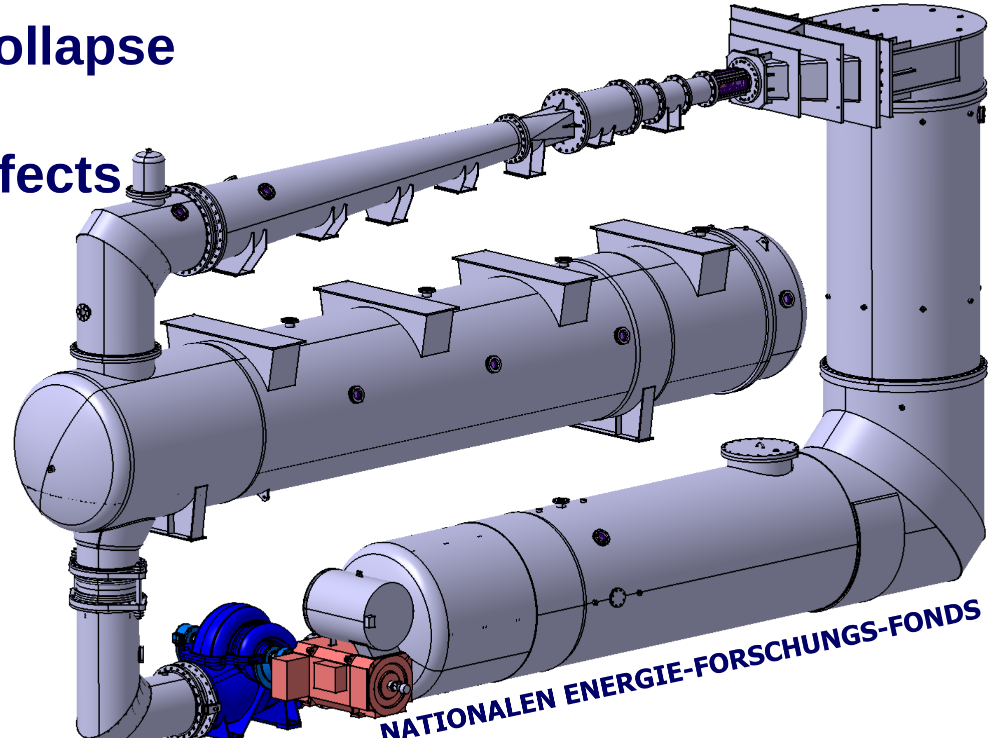
- Onset, Development & Collapse
- Modeling & Control
- Materials Erosion, Bio Effects











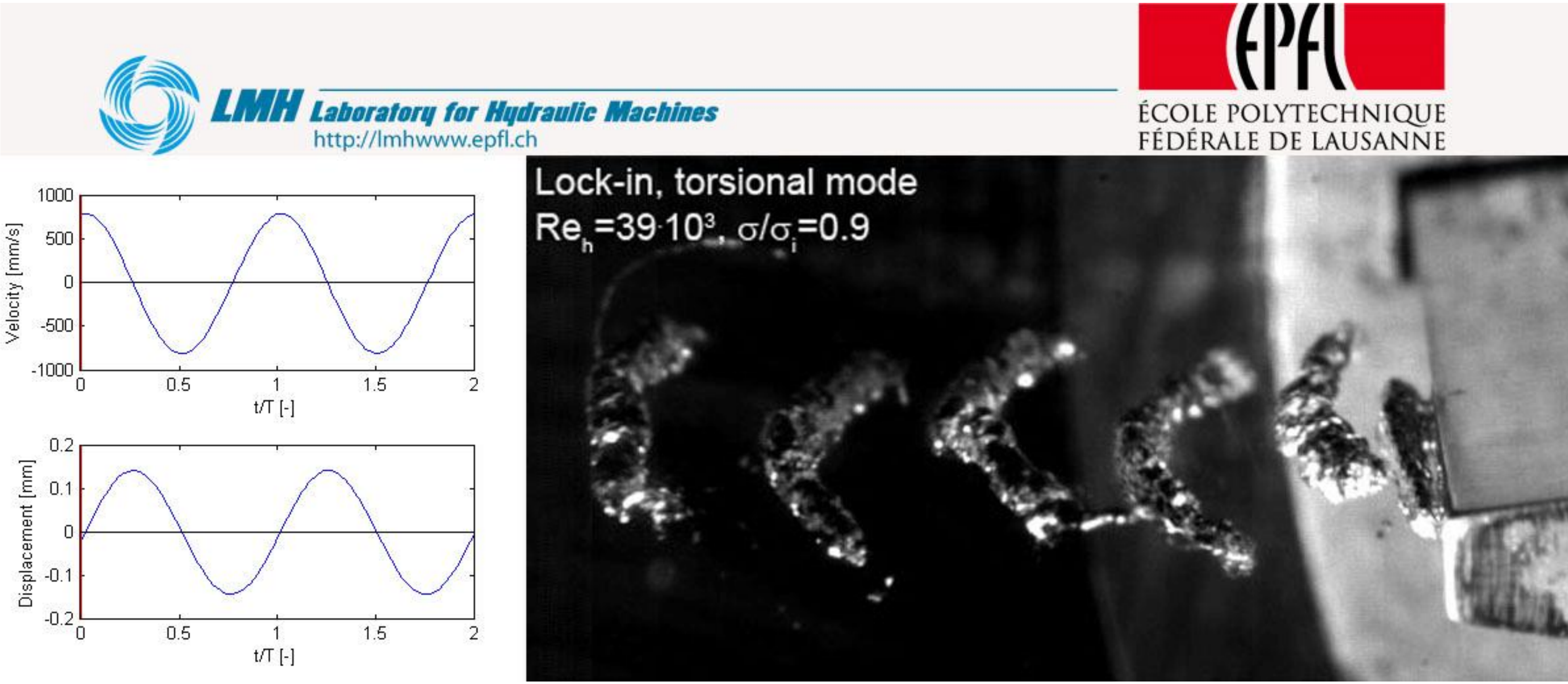
Max Flow Velocity : 50 m/s
Max Pressure : 20 bar
Optical Instrumentation
p-transducers

FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

KTI CTI

Unique Research Facility: **EPFL High Speed Cavitation Tunnel**

Vortex Induced Vibrations



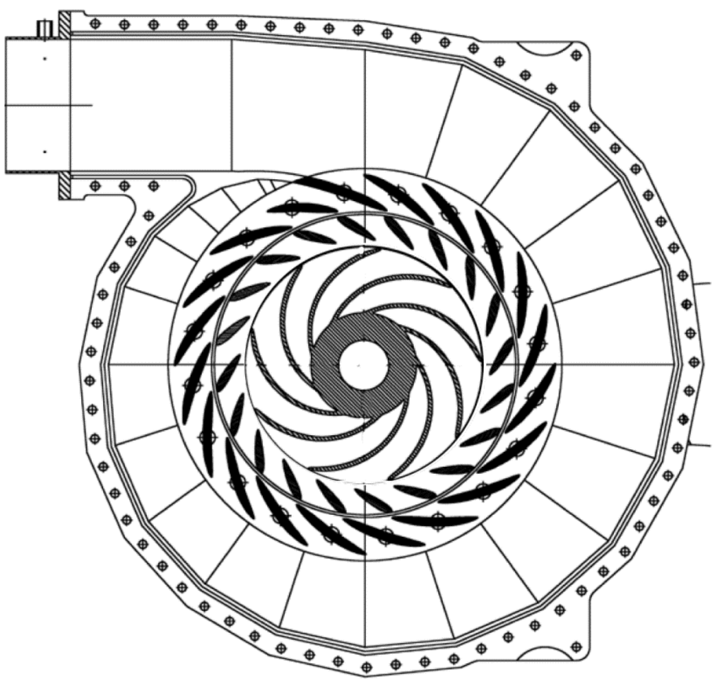
AUSONI, P.; FARHAT, M., ESCALER, X., EGUSQUIZA, E., AVELLAN, F. (2007): "Cavitation Influence on Kármán Vortex Shedding and Induced Hydrofoil Vibrations", Jo Fluids Engineering, June 2007

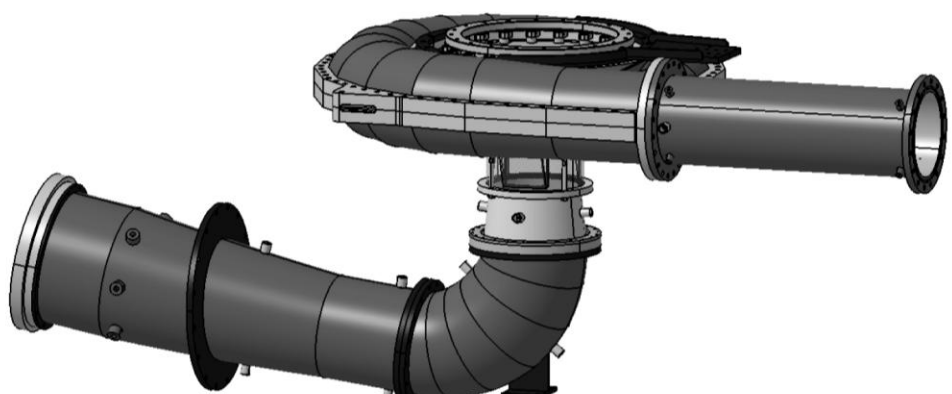
20YEARS EUREKA

EUREKA N° 3246

HYDRODYNA

- Rotor-Stator Interactions
  - ✓ Experimental Investigations
  - ✓ Validation of Unsteady Numerical Simulations





HYDRODYNA Case Study $z_o = 20$, $z_b = 9$

CDIF UPC | EDF Electricité de France | ALSTOM Power Hydro | VATECH VA TECH HYDRO | Power Systems GE Hydro | VOITH SIEMENS HYDRO POWER GENERATION

LMH Laboratory for Hydraulic Machines

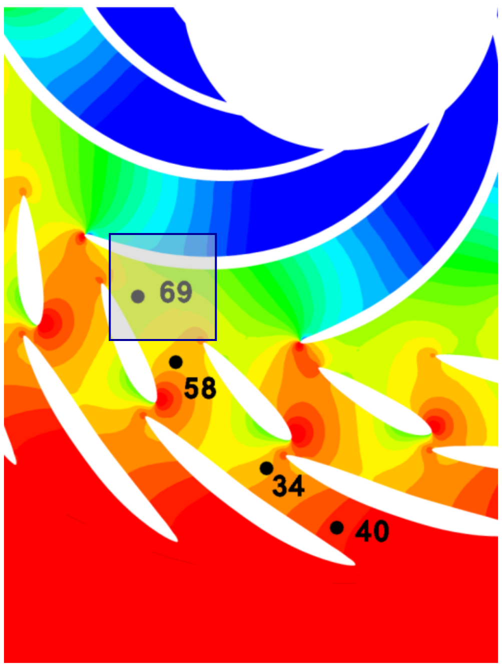
20YEARS

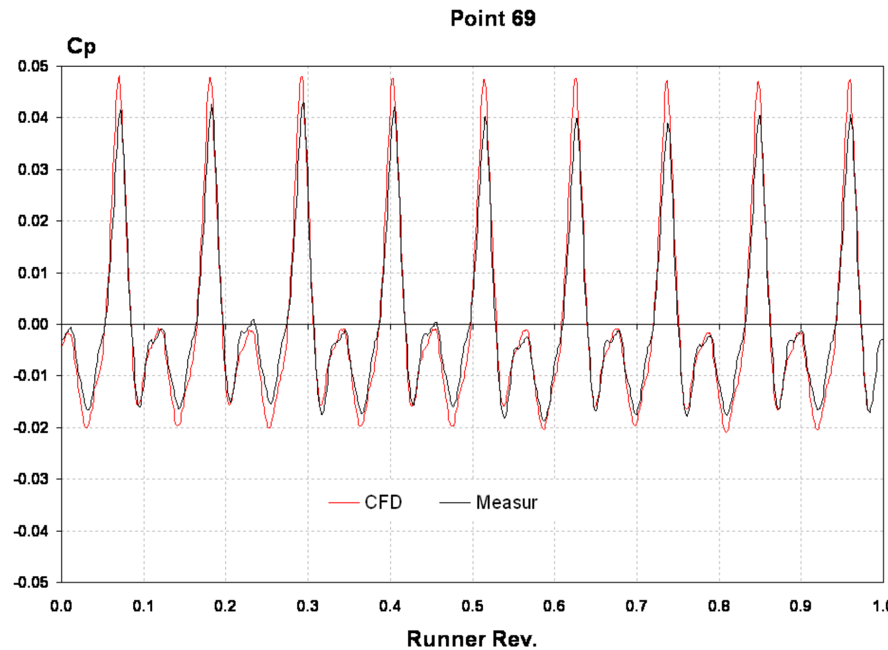
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

EUREKA

EUREKA
N° 3246

HYDRODYNA





KTI CTI

CDIF UPC

EDF Electricité de France

ALSTOM Power Hydro

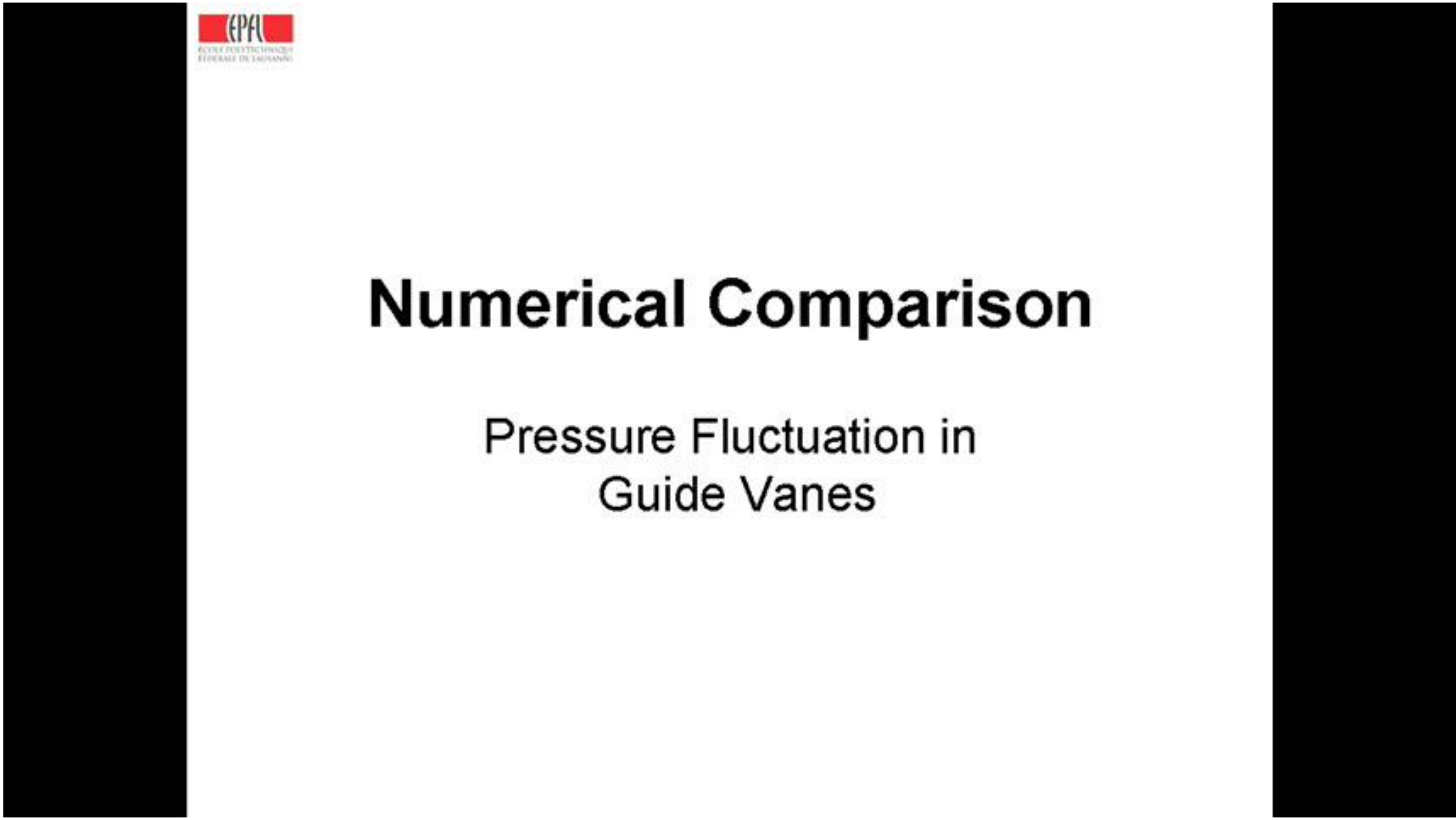
VATECH VA TECH HYDRO

GE Power Systems GE Hydro

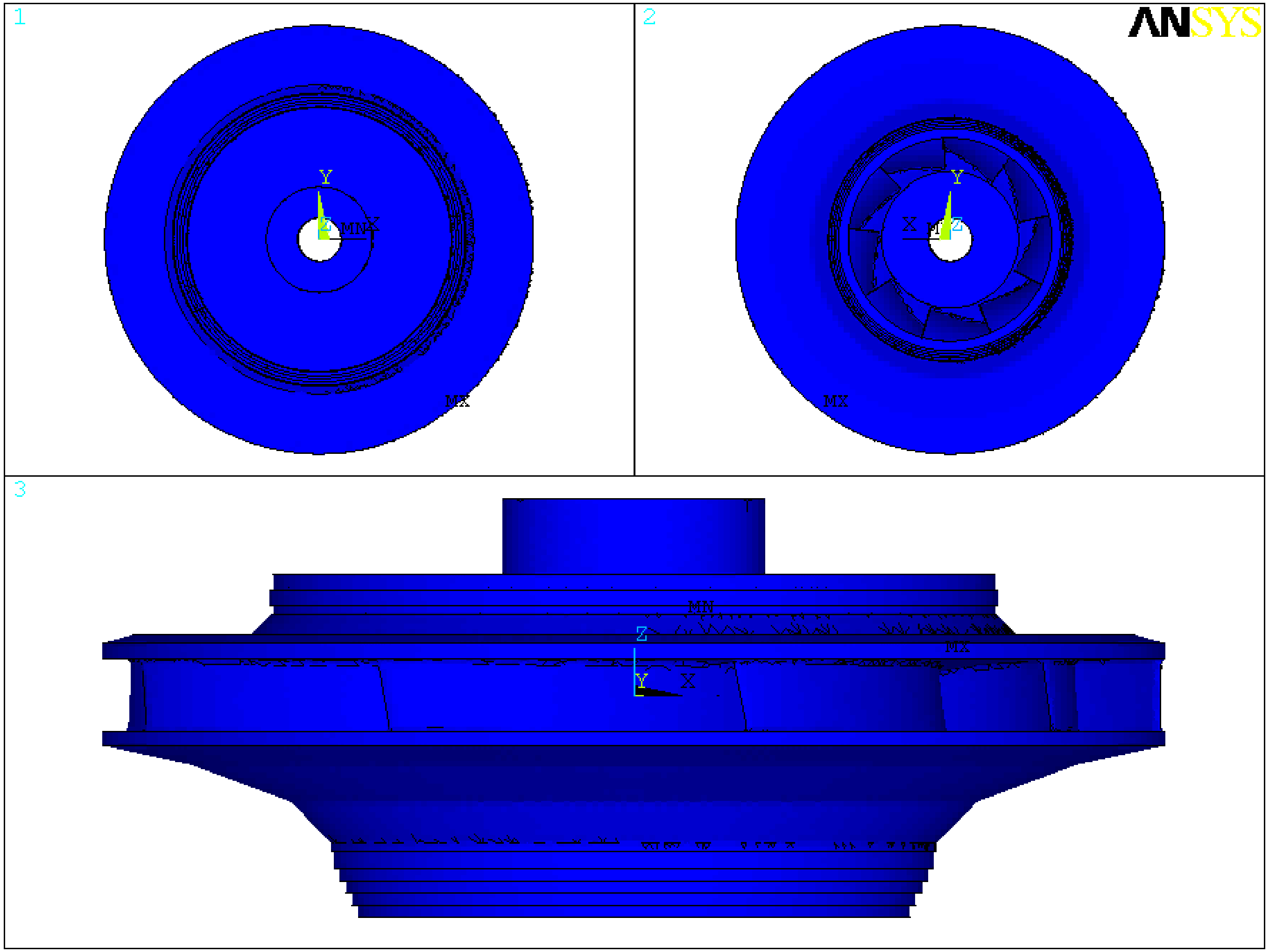
VOITH SIEMENS HYDRO POWER GENERATION

Experimental Validation of RSI Numerical Simulations

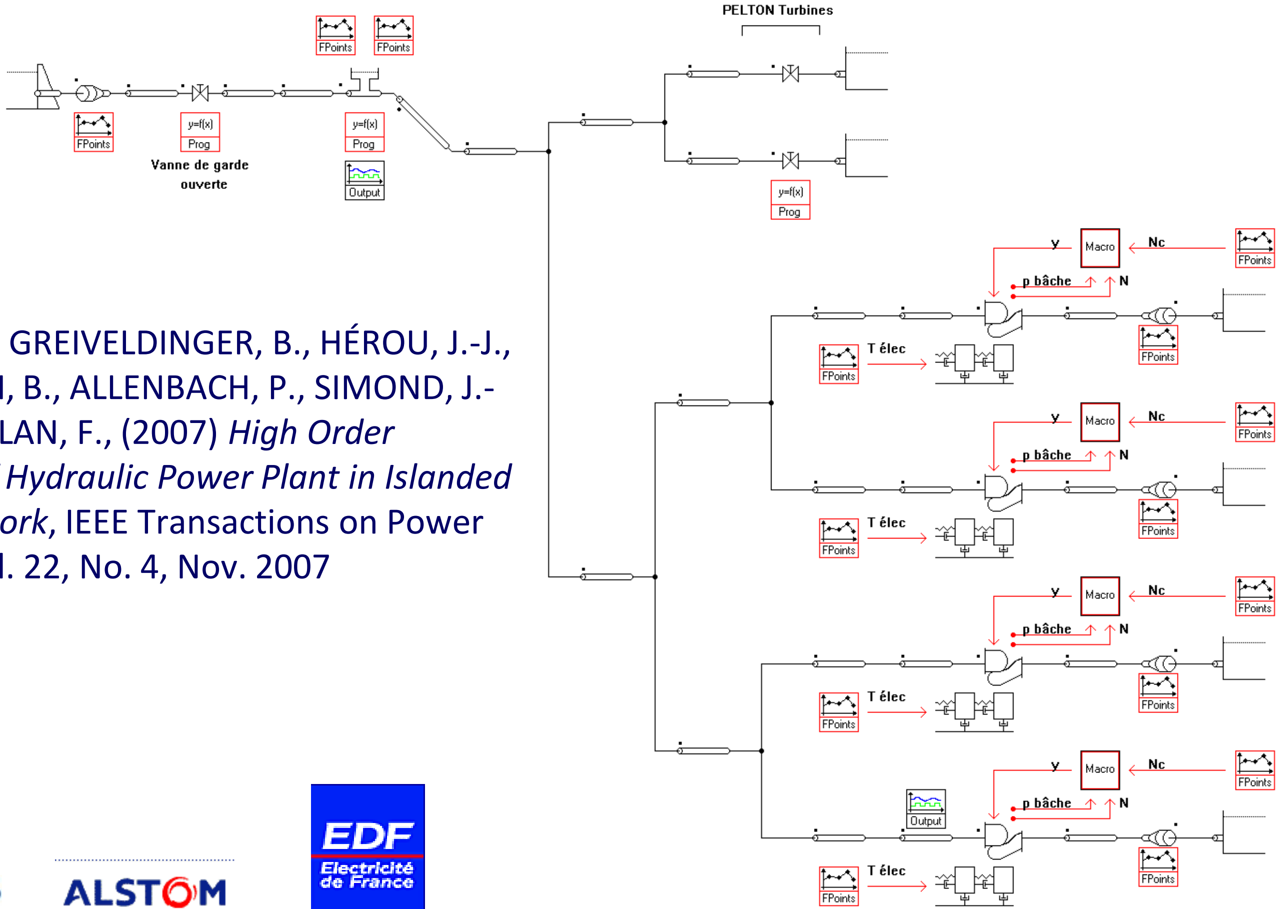
K = -2 Mode of Interactions
9 Impeller Blades by 20 Guide Vanes



Impeller Modal Analysis



Hydro-Acoustic Modeling of Hydroelectric Systems



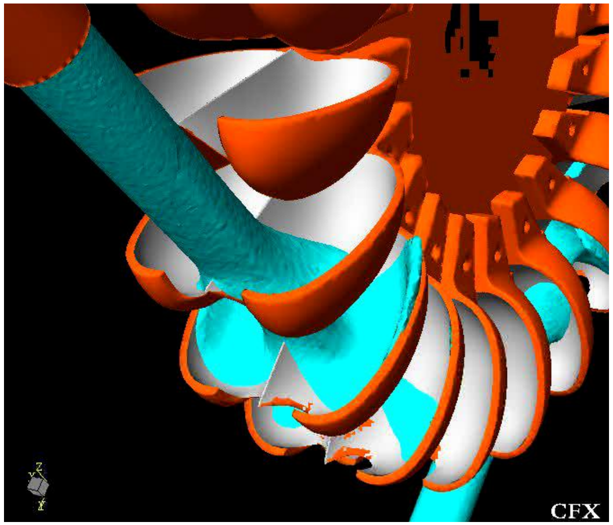
- ✓ NICOLET, C., GREIVELDINGER, B., HÉROU, J.-J., KAWKABANI, B., ALLENBACH, P., SIMOND, J.-J. AND AVELLAN, F., (2007) *High Order Modeling of Hydraulic Power Plant in Islanded Power Network*, IEEE Transactions on Power Systems, Vol. 22, No. 4, Nov. 2007

LMH *Laboratory for Hydraulic Machines*

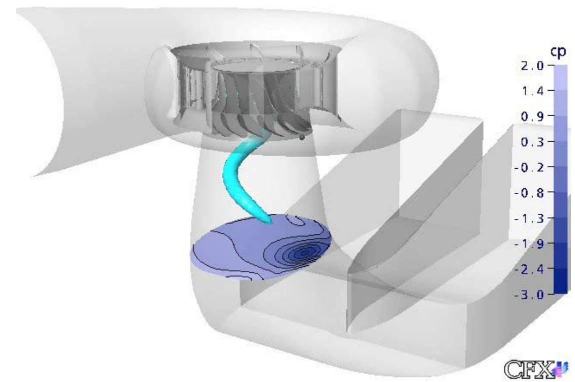
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Hydrodynamics of Turbomachines

Free Surface Flow

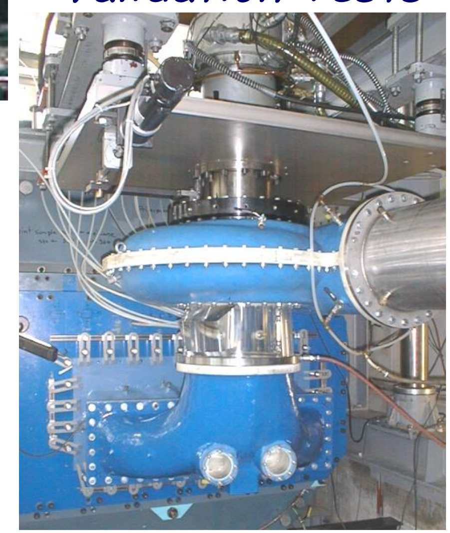


Flow Analysis

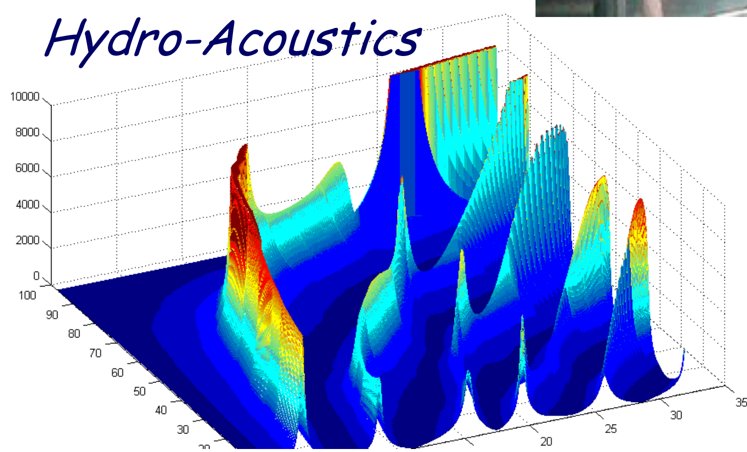


Cavitation

Validation Tests



Hydro-Acoustics



Ongoing Projects: HYDRODYNA Phase II, HYDRONET, CTI ALSTOM Hydro Acoustics, SNF Cavitation Physics

Education Program

- EPFL Mechanical and Electrical Engineering Master Study
- EPFL Doctoral Study
- Professional development, yearly short course in hydraulic machinery
- Special training and class on demand.

Hydrodynamics of Turbines, Pumps and Pump-Turbines

The EPFL Laboratory for Hydraulic Machines...

Contributes to the Educational Objectives, Research Goals and Public Service Outreach of EPFL.

Performs Basic, Applied Research and Exploratory Development in Support of Hydro-Technology Suppliers.

Promotes the Transfer of Advanced Knowledge, in Partnership with Technology Centres of both Industries and Public Utilities.

Many Thanks for your Kind Attention

Doctoral Works in Progress

- Ruchonnet N. (~2009). RANS and Hydroacoustic Concurrent Flow Simulations in a Turbine;
- Berten S. (~2009). Vibratory Characteristic of a Centrifugal Pump;
- Zobeiri A. (~2010). Dynamics of Fluid Structure Coupling;
- Alligné S. (~2010). Hydroacoustic Stability of a Francis Turbine;
- Hasmatuchi V. (~2011). Off Design Hydrodynamics of a Pump Turbine;
- Roth S. (~2011) Fluid Structure Coupling in Hydraulic Machines
- Calmon M. (~2011) Hydrofoil Dynamics;

EPFL Doctoral Thesis

- **Ausoni Philippe:** " Turbulent Vortex Shedding from a Blunt Trailing Edge Hydrofoil", EPFL Doctoral Thesis to be presented in July 2009.
- **Braun Olivier:** "Part load flow in radial centrifugal pumps", EPFL Doctoral Thesis N°4422, 2009.
- **Zobeiri Alireza:** "Investigations of time dependent flow phenomena in a turbine and a pump-turbine of Francis type : rotor-stator interactions and precessing vortex rope", EPFL Doctoral Thesis N°4272, 2009.

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