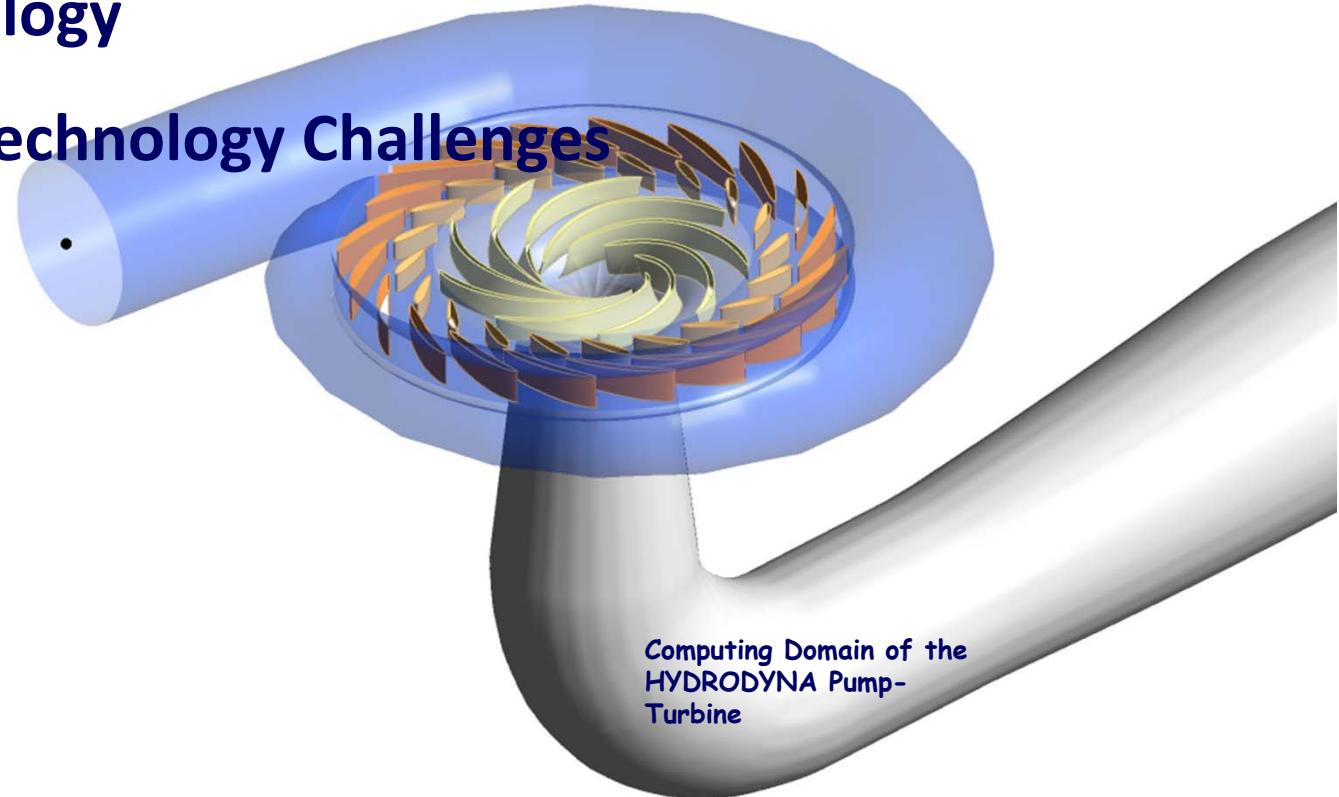




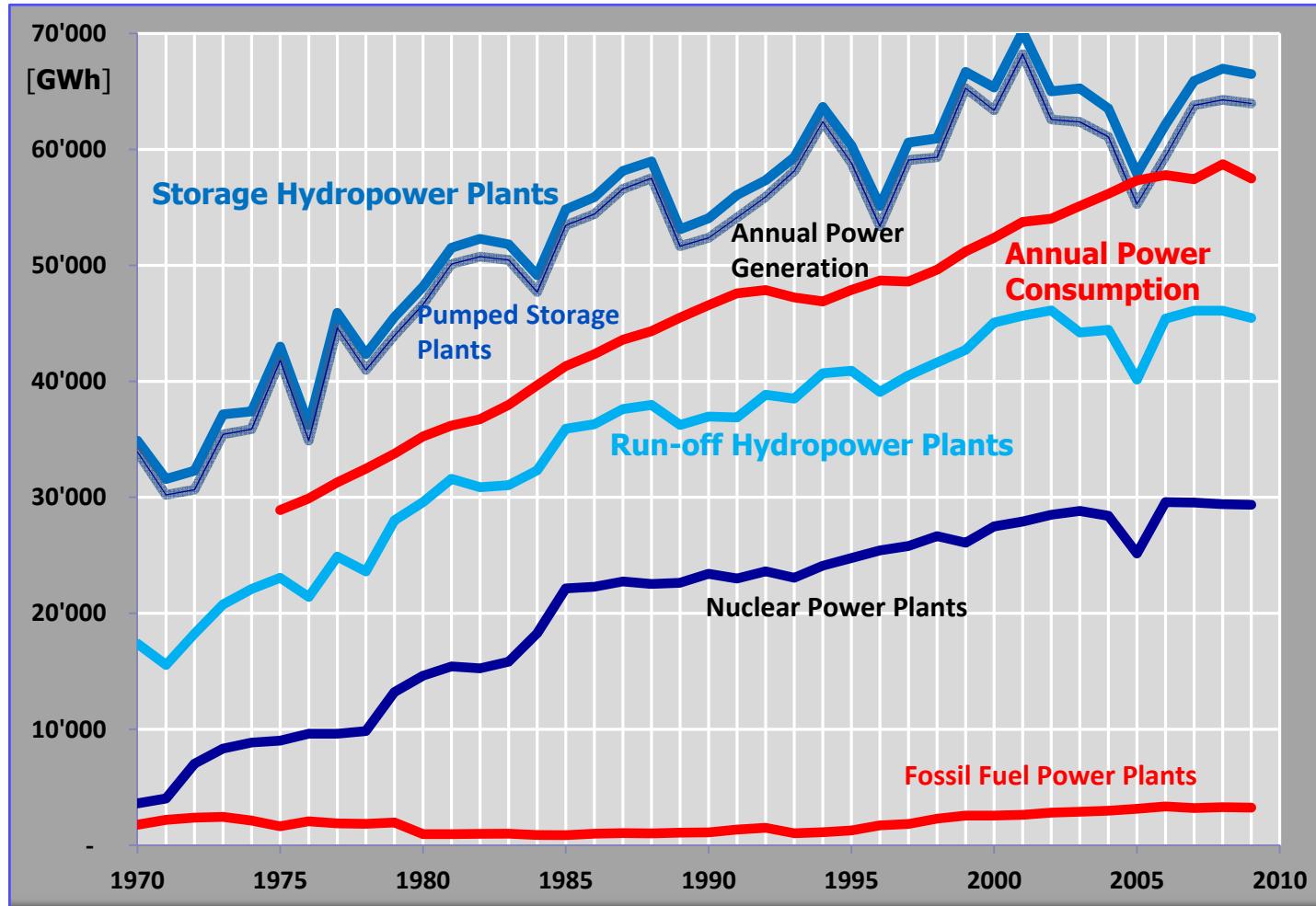
Scope

- **Pumped Storage Power Plants**
- **Today Technology**
- **Science and Technology Challenges**



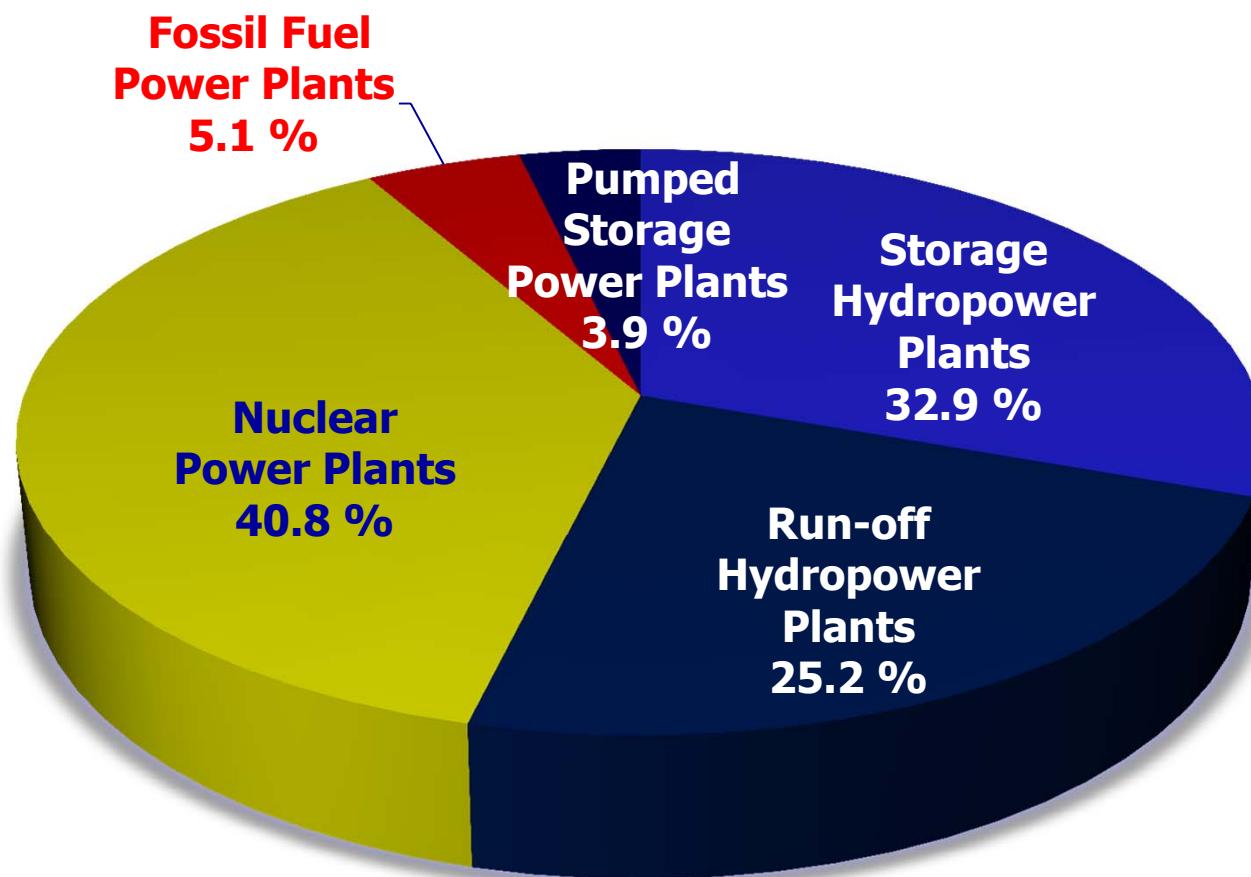
Swiss Power Generation

Swiss Electricity Data: 2009 Survey



Switzerland to be Proud of a Nearly CO₂-Free Power Generation Mix

Power Generation Mix in Switzerland



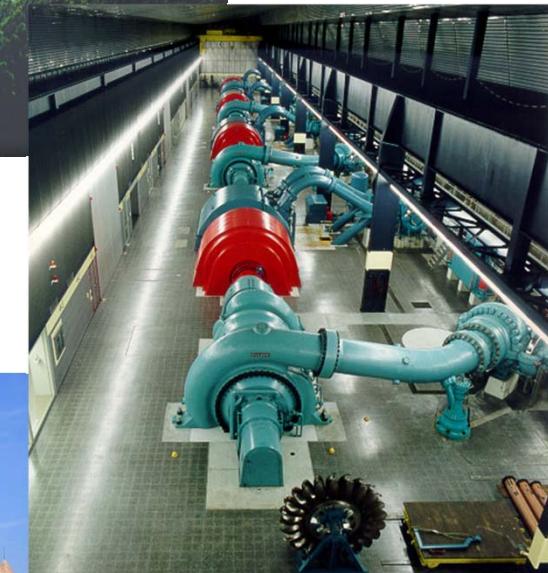
63'971 GWh Power Generation in 2009 :

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



Hongrin-Léman PSP

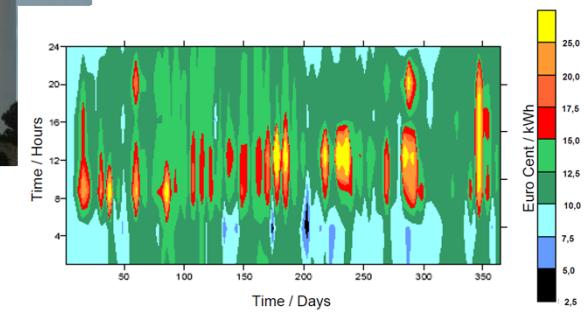
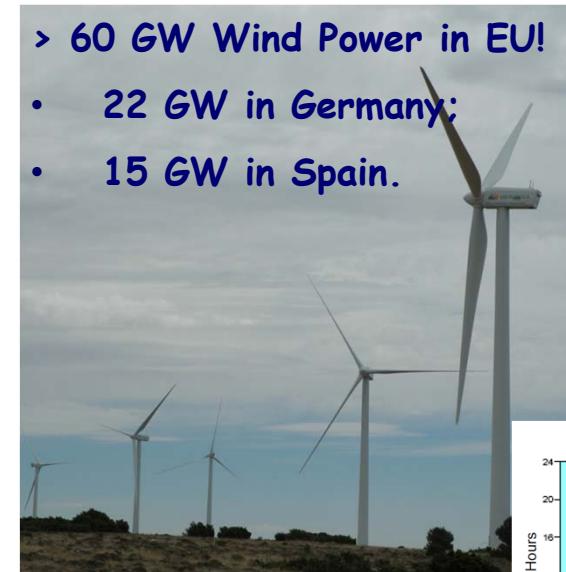
- **Hongrin Lake (1969) :**
52 millions m³ Capacity
- **Veytaux Power Station (1972)**
- **4 Horizontal Ternary Units**
 - ✓ **256 MW Pumping Power**
 - ✓ **240 MW Generating Power**
 - ✓ **850 mWC Head**
 - ✓ **600 min⁻¹**





Pumped Storage Power Plants Services

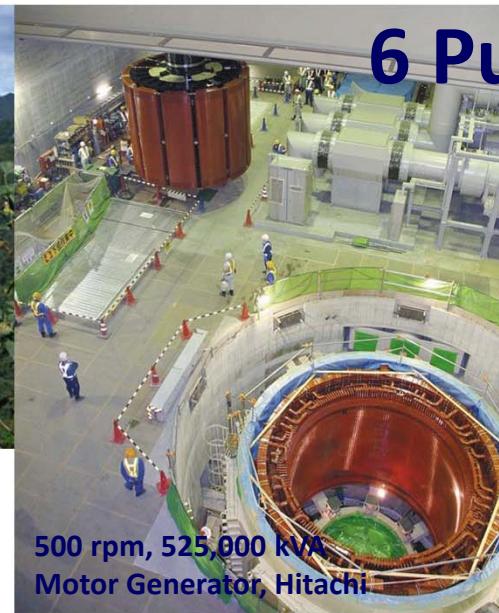
- Storage of Energy in Excess
 - ✓ Availability of HVAC Grid (220 kV & 380 kV in CH)
 - ✓ Reservoirs
- Grid Control
 - ✓ Generating Mode
 - ✓ Pumping Mode
- Mitigating the Flow Changes
 - ✓ Reservoirs



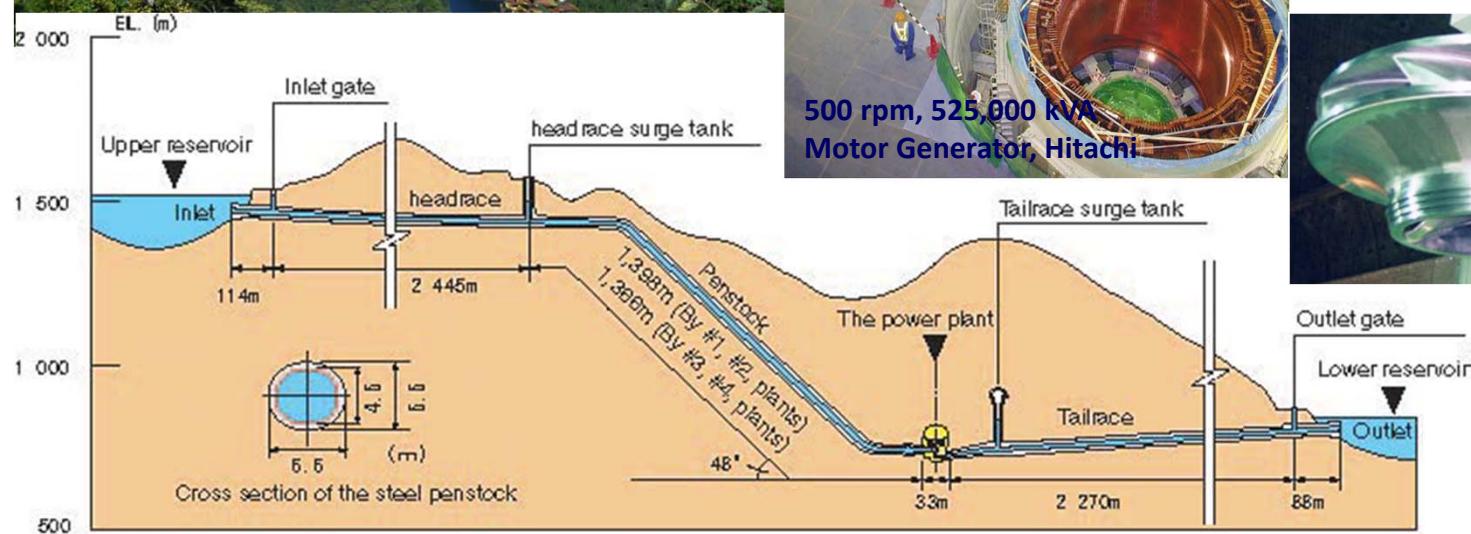


Last Outstanding Pumped Storage Plants Commissioned since 12 Years

Pumped Storage Power Plant	Capacity	Units	Unit Power	Owner	Country	Year
Yangyang	1'032 MW	4	258 MW	KOMIPO	South Korea	2006
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
Okutataragi	1'932 MW	6	322 MW	KEPCO	Japan	1998



6 Pump-Turbines @ 500 rpm



- ✓ **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

Vertical Ternary Units: Pelton-M/G-Pump

- Matching both Pumping and Generating Modes

- ✓ Length of the Rotating Train;
- ✓ Speed;
- ✓ Required Submergence.

- High Grade Control

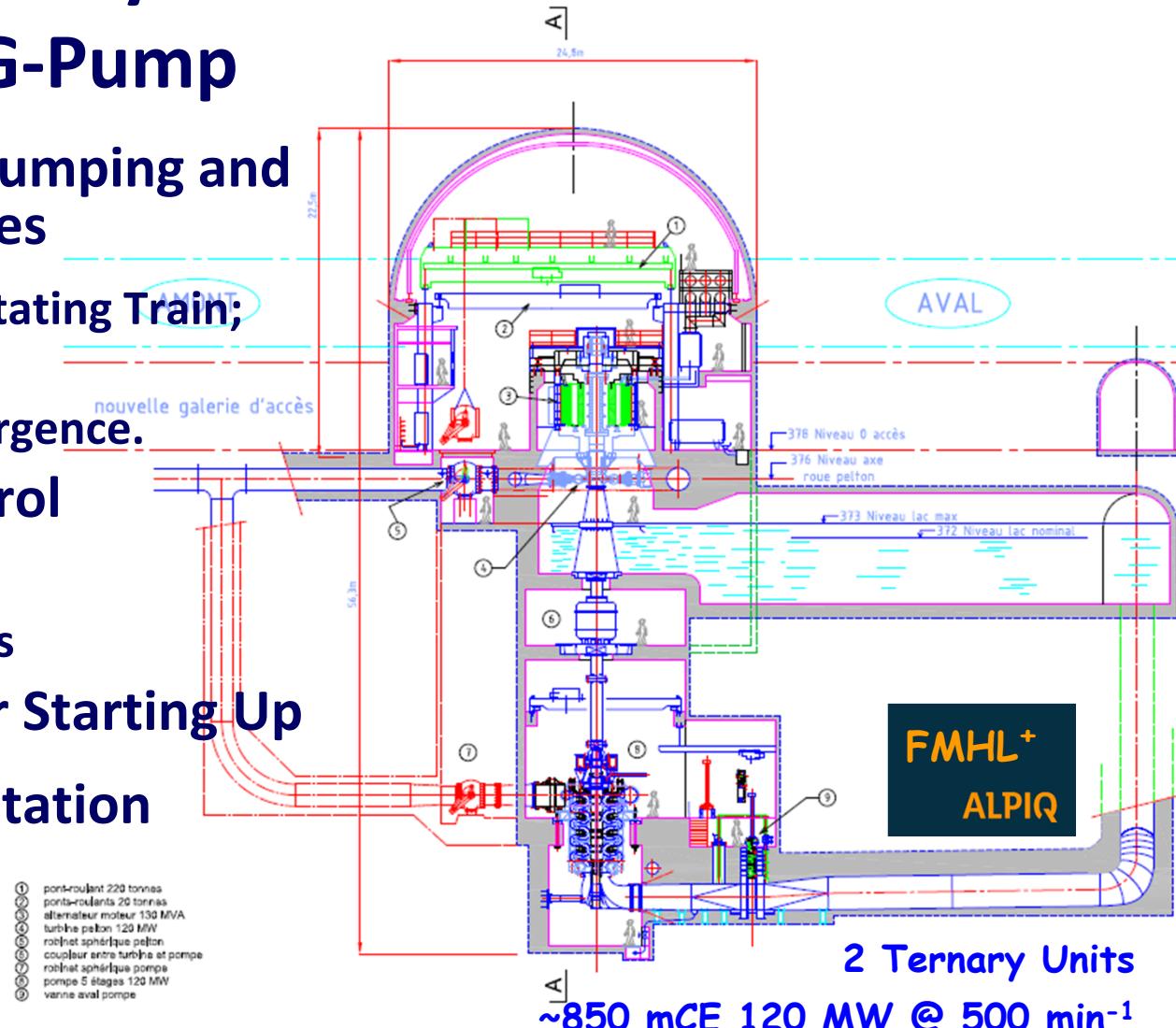
- ✓ Pelton Turbine
- ✓ Hydraulic By-Pass

- Turbine Drive for Starting Up

- 1 Direction of Rotation

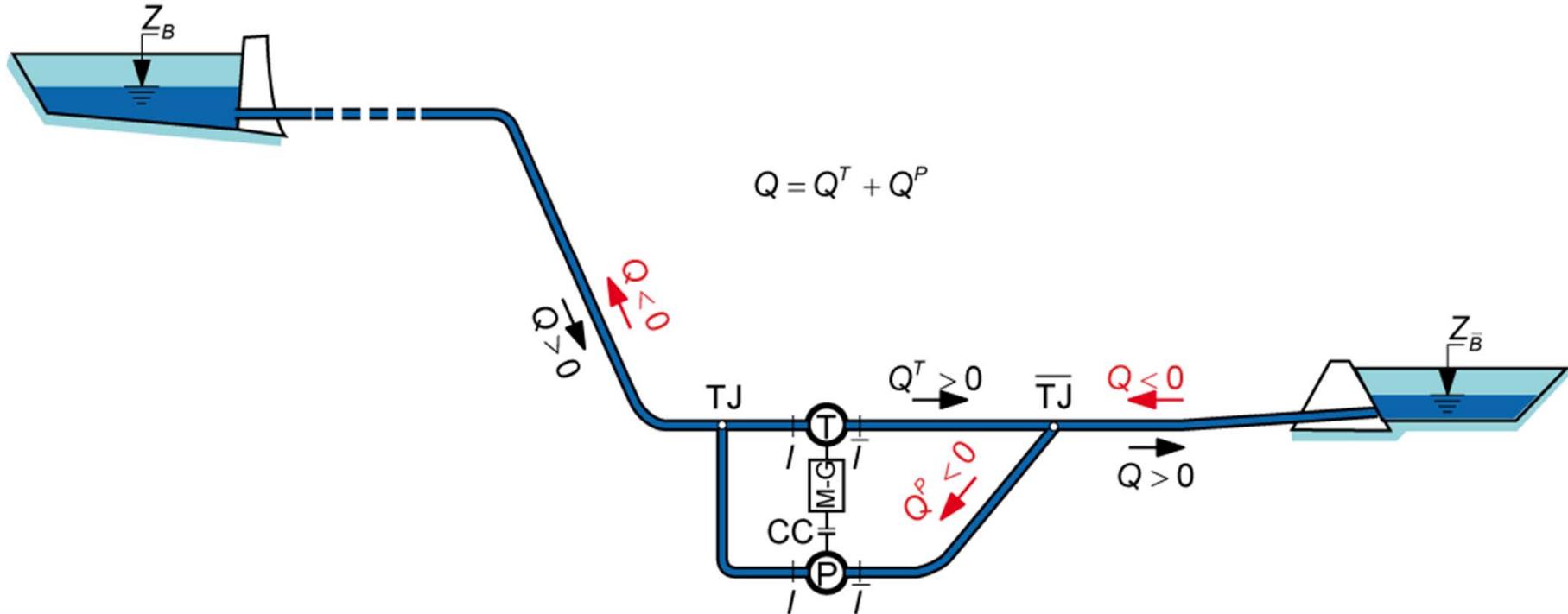
- ✓ Efficient Cooling

- Safe Transients





Hydraulic Bypass



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

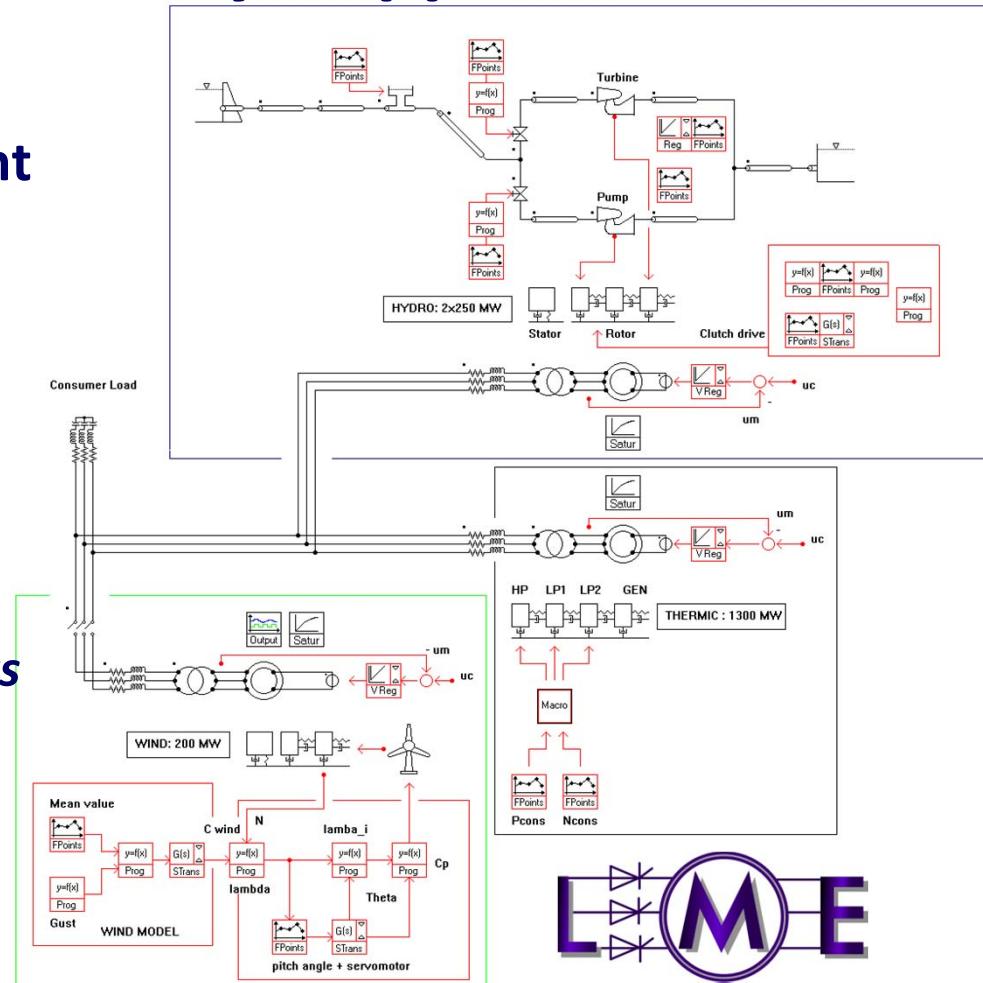


Mixed Islanded Network Wind Farm Safety Tripp off

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

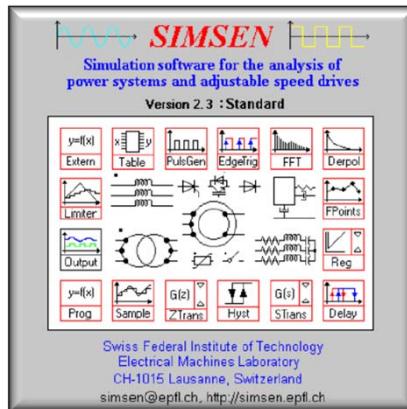
<http://simsen.epfl.ch/>

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

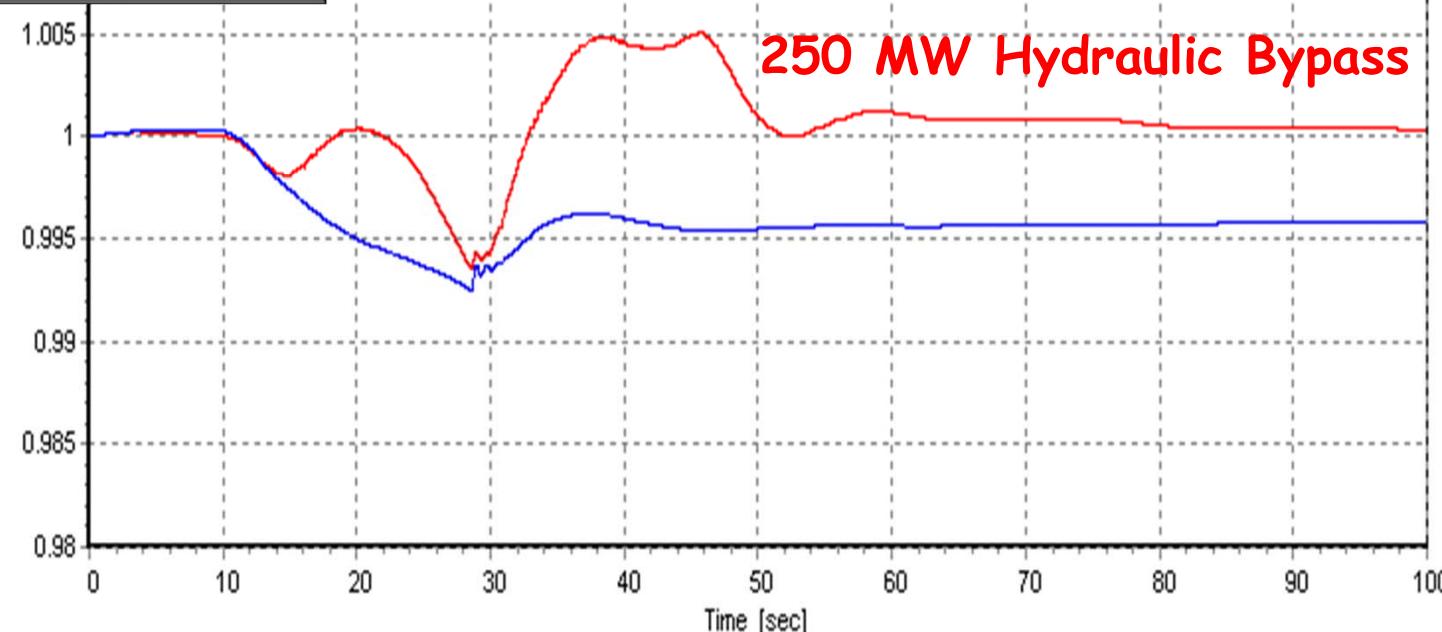




Grid Primary Control thru Hydraulic Bypass



200 MW Wind Farm Safety Tripp off
SIMSEN Numerical Simulation

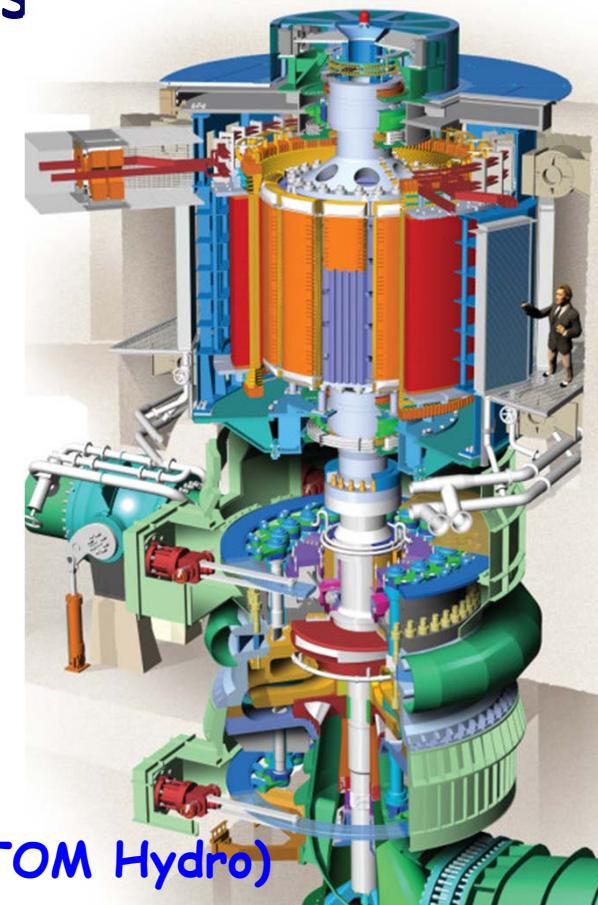


<http://simsen.epfl.ch/>



Reversible Pump-Turbine Units Technology Challenges

- Start-Up Procedures
 - ✓ Static Frequency Converter of Limited Power
 - ✓ Back to Back arrangement
 - ✓ Turbine or Pony Motor Drive
 - ✓ Dewatering/Watering Process
- Bidirectional Motor-Generator Speed
 - ✓ Air Cooling vs. Water Cooling
- Pumping & Generating Operating Ranges Matching
 - ✓ Efficiency
 - ✓ Cavitation
 - ✓ Transients: Start-up & Load Rejection
- Grid Primary Control
 - ✓ Variable speed
 - ✓ Double Regulated Stages



Yang Yang (ALSTOM Hydro)

- 800 mWC
- $4 \times 258 \text{ MW à } 600 \text{ min}^{-1}$
- Double Regulated Stages (n_q 38)



620 MW Nant de Drance PSP Project (VS)



Commissioning in 2015

- Emosson Lake **$210 \ 10^6 \ m^3$ Capacity**
- Vieil Emosson Lake **$11 \ 10^6 \ m^3$ Capacity**
- 250 to 390 mWC Head Range
- 4 x 155 MW Single Stage Pump-Turbines
- $428.6 \ min^{-1} \pm 7 \%$ Variable Speed Drive



1 GW Linthal PSP Project (GL)

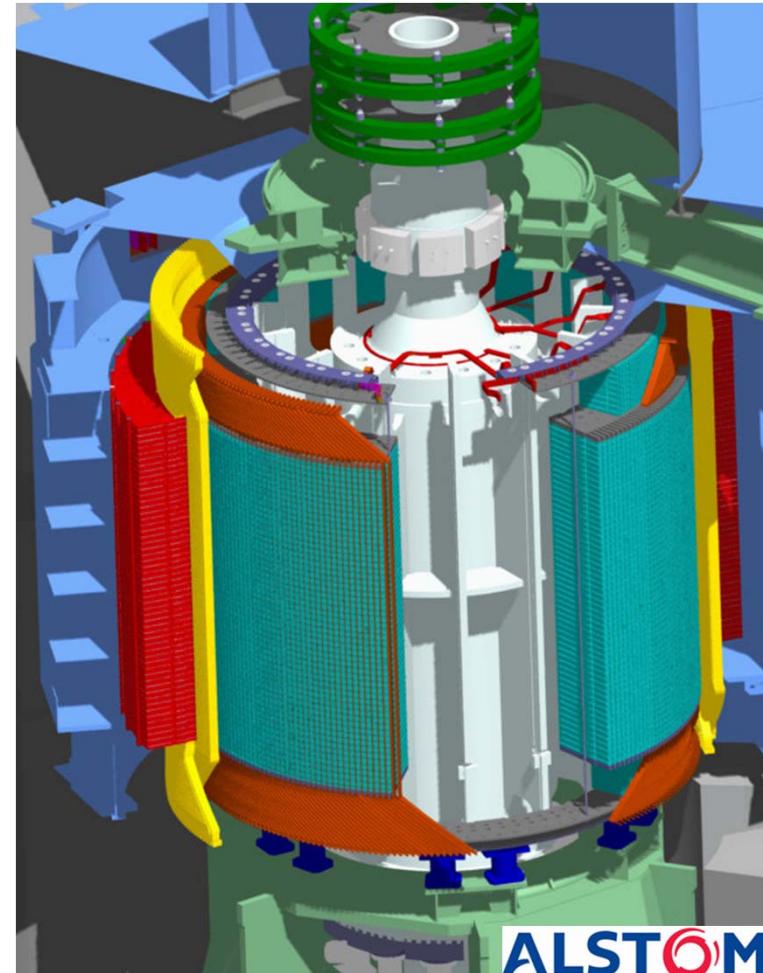


- Limmern **$92 \ 10^6 \text{ m}^3$ Capacity**
- Mutt **$25 \ 10^6 \text{ m}^3$ Capacity**
- **560 mWC to 724 mWC Head Range**
- **4 x 250 MW Single Stage Pump-Turbines**
- **$500 \text{ rpm} \pm 6\%$ Variable Speed Drive**



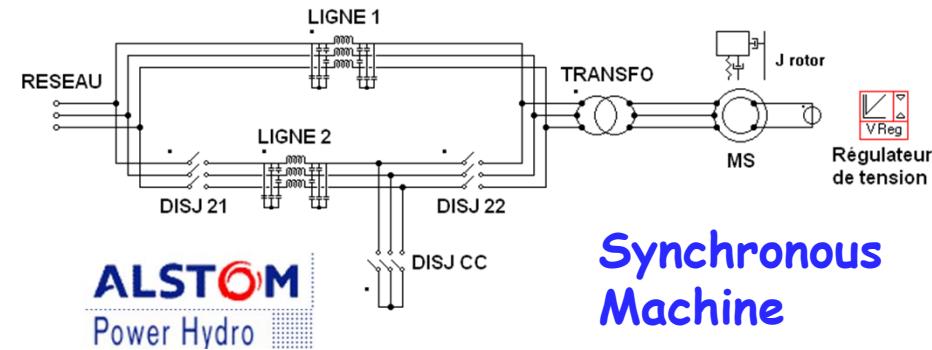
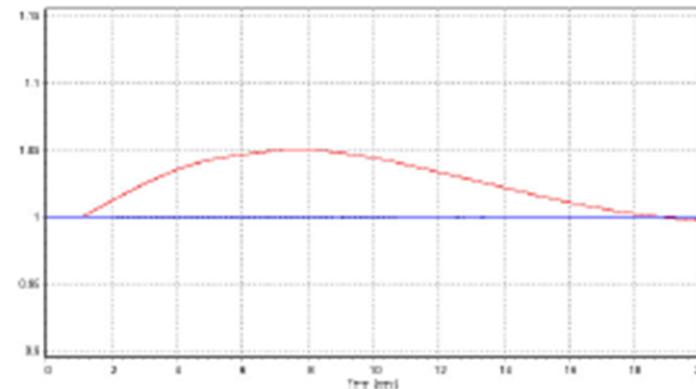
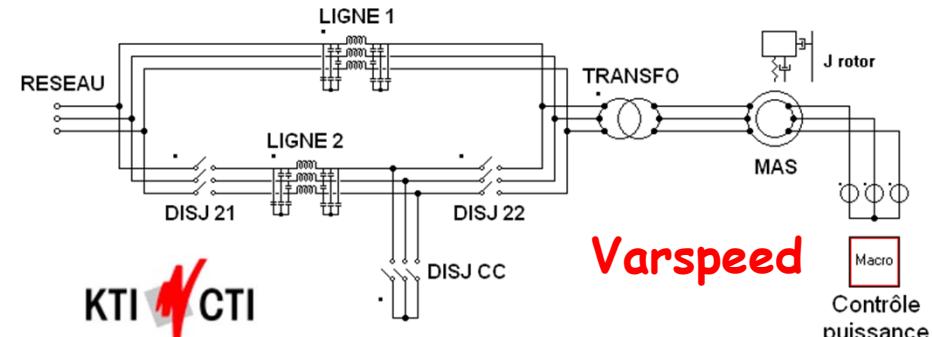
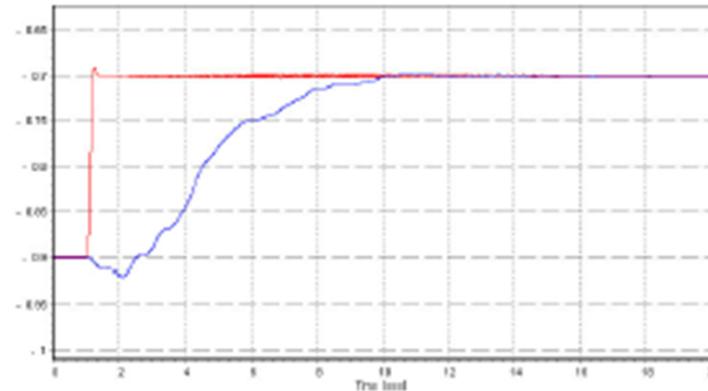
VARSPEED Technology

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



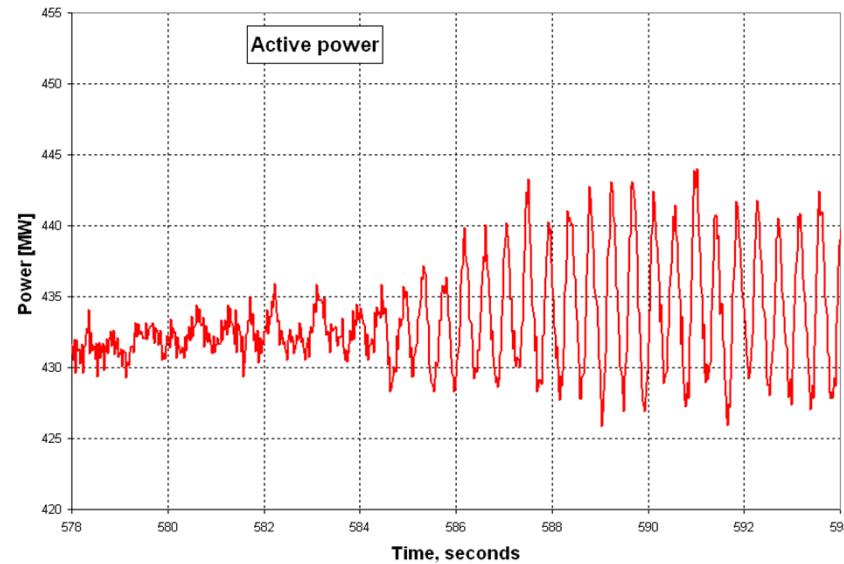


Numerical Simulation of the Very Fast Change of the Power Set Point



<http://simsen.epfl.ch/>

Yves Pannatier : "Optimisation des stratégies de réglage d'une installation de pompage-turbinage à vitesse variable", Thèse EPFL N° 4789, 2010.



Sciences and Technology Challenges

○ Safety, Reliability and Flexibility

- ✓ Meeting Demand of Peaking Power
- ✓ Grid Primary Control
 - Short Time Response
- ✓ Frequent Starts & Stops
- ✓ Extending Operating Ranges





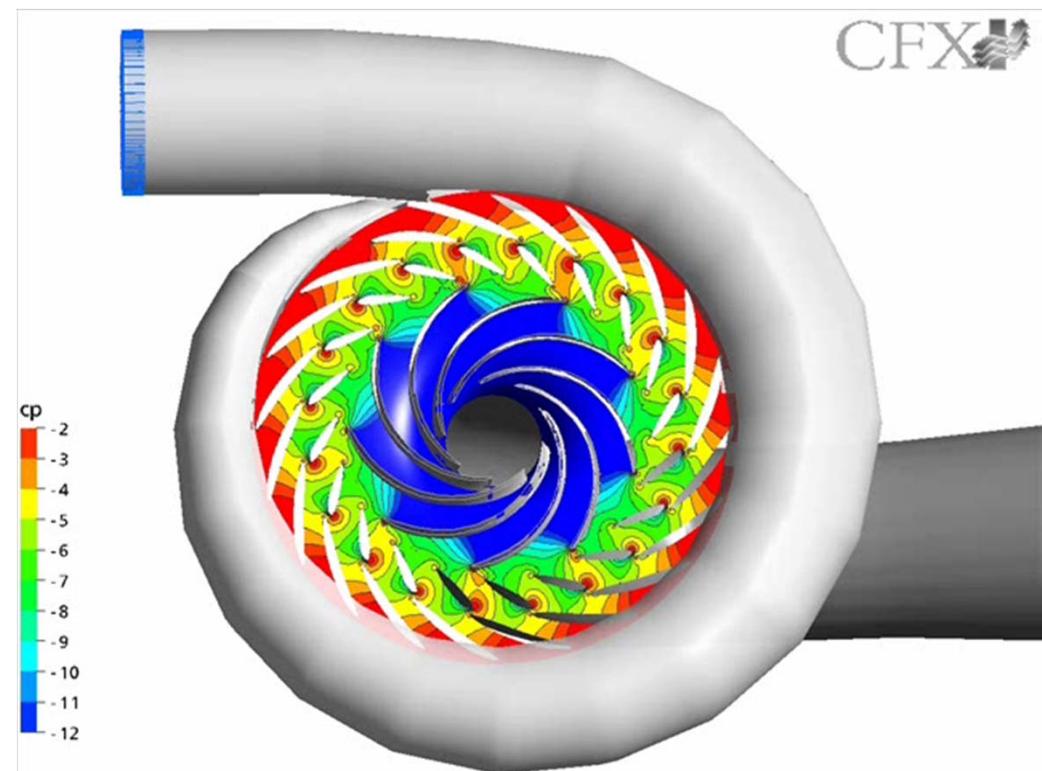
Rotor-Stator Interactions in Generating Mode

○ HYDRODYNA

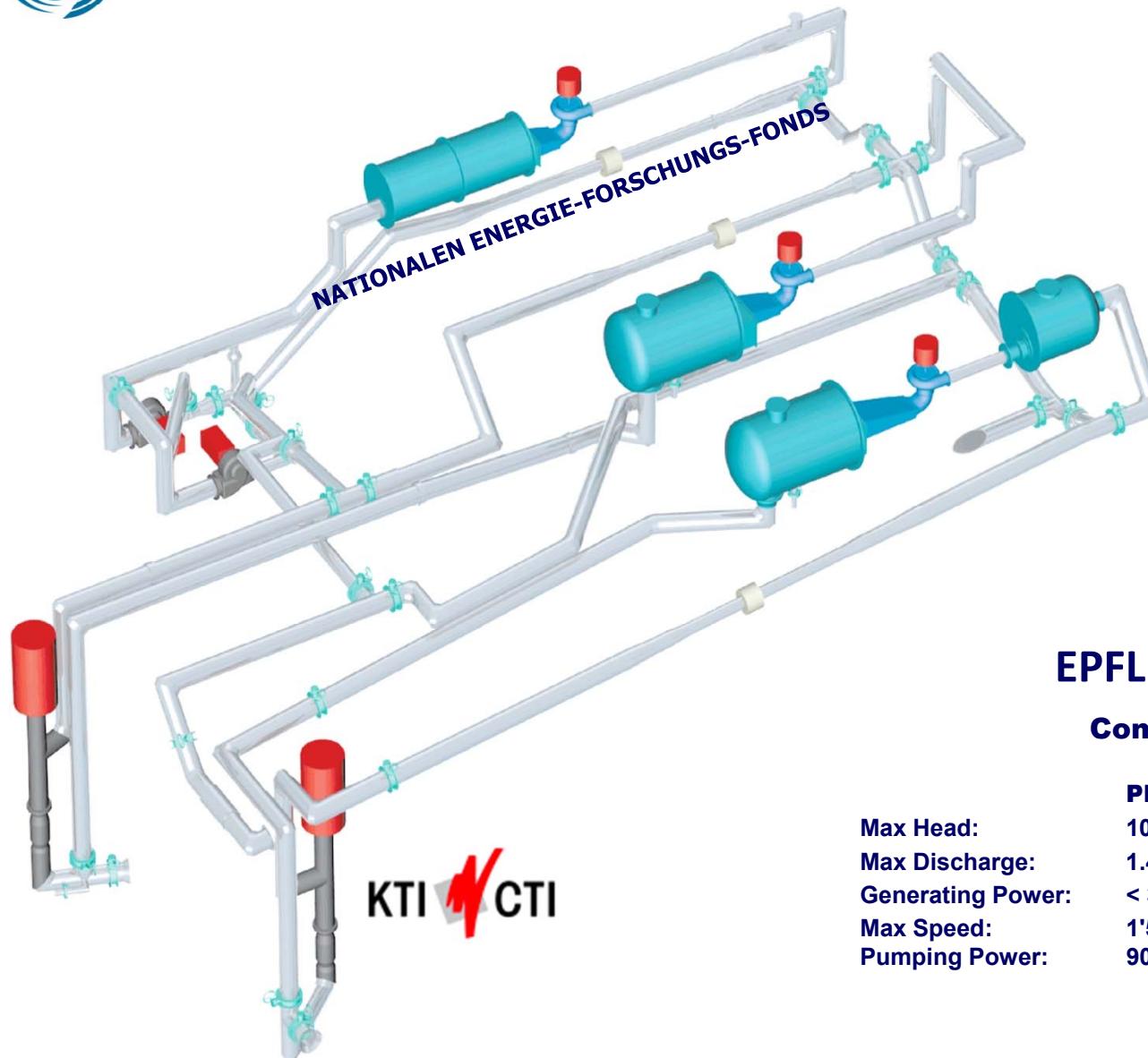
Case Study

$$z_o = 20, z_b = 9$$

- ✓ Experimental Investigations
- ✓ Validation of Unsteady Numerical Simulations



Unsteady Pressure Field
in Generating Mode
Max Discharge



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

World Class Research Facilities: 3 Test Rigs for Hydraulic Turbines, Pumps and Pump-Turbines



IEC 60193 Pump-Turbine Model Testing

Pumped Storage Power Plant	Country	Owner/Manufacturer	Capacity	Year
Ludington	MI, USA	Consumers Energy	6 x 312 MW	2010
XIANYOU	China	DONGFANG Electrical Machinery Ltd	1'200 MW	2009
XIAN SHUI JAN	China	HARBIN Electrical Machinery Ltd.	4 x 370 MW	2009
Very High Head	-	R&D/ALSTOM Hydro	-	2007-8
ROCKY MOUNTAIN	GA, USA	Oglethorpe Power/American Hydro	3 x 370 MW	2005-6
BLENHEIM GILBOA	NY, USA	Rev. Eng. & Impeller Model NYPA	4 x 260 MW	2003
CHEONSONG	South Korea	Korea Western Power Co /GE Hydro	2 x 350 MW	2003
Nq 45	-	R&D/ALSTOM Hydro	-	2002
VENDA NOVE II	Portugal	EDP/VOITH Hydro	2 x 98 MW	2001
ALQUEVA	Portugal	EDIA operated by EDP/ALSTOM Hydro	2 x 130 MW	1999
TAUM SAUK*	MO, USA	Union Electric Company/American Hydro	2 x 220 MW	1997

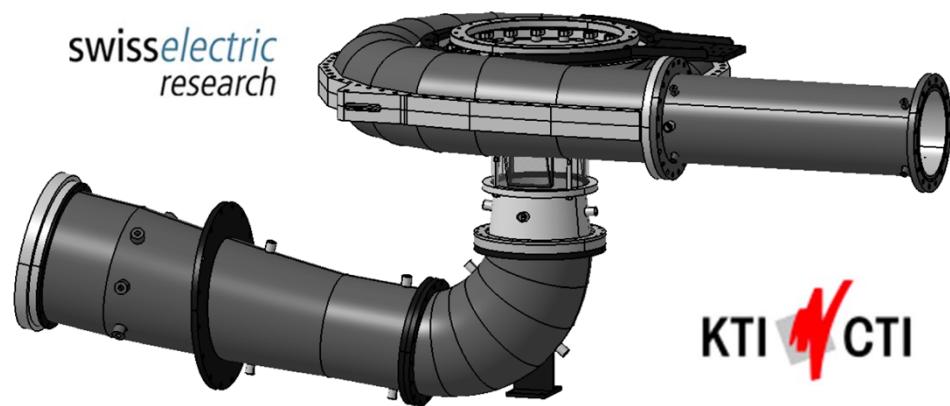


HYDRODYNA Research Project

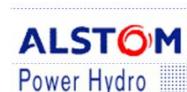
Pump-Turbine Hydrodynamics

- **Investigating, Modeling and Harnessing Unsteady Flows;**
- **Fluid Structure Coupling;**
- **Rotor-Stator Interactions;**
- **Cavitation;**
- **Performance Curve Stability**

swiss**electric**
research



Pompe-turbine HYDRODYNA $z_o = 20$, $z_b = 9$

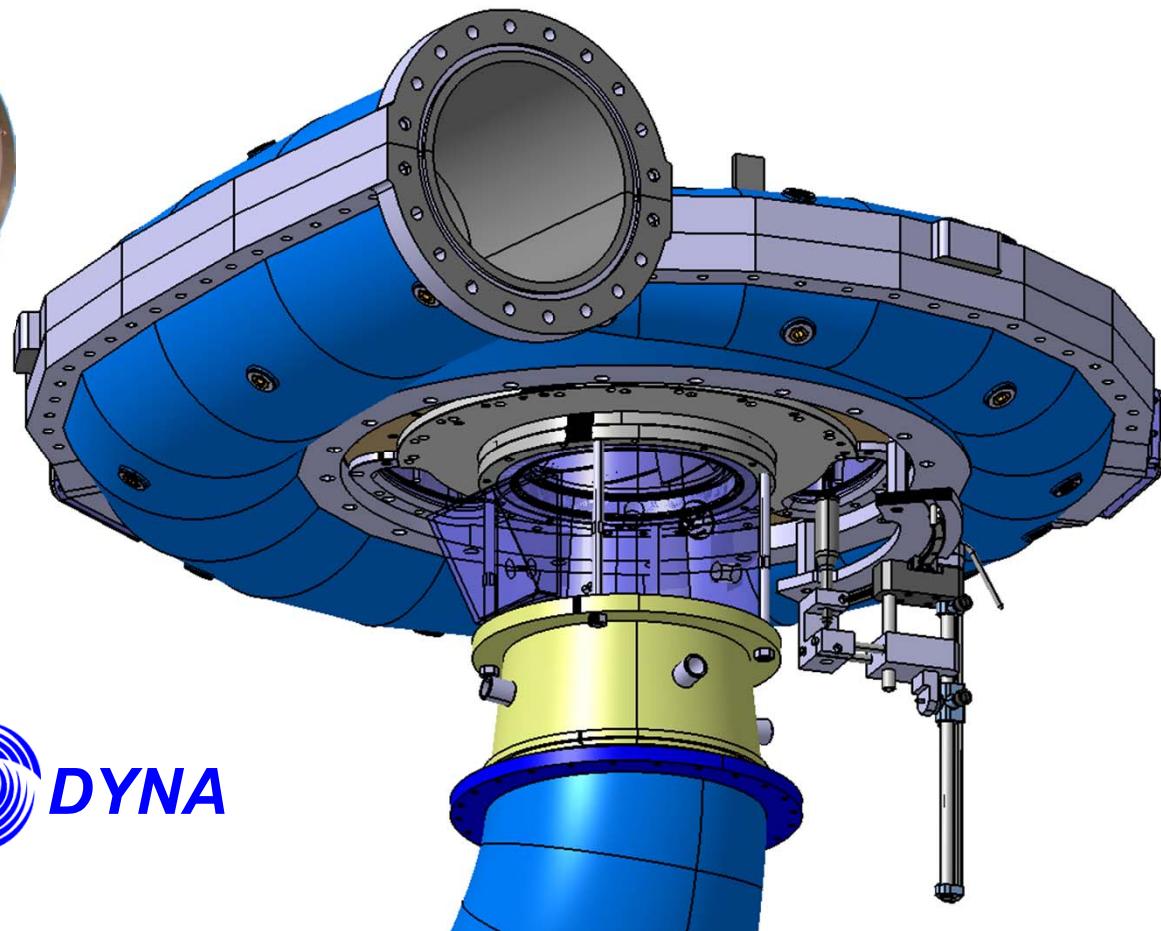




LMH *Laboratory for Hydraulic Machines*

EPFL
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

HYDRODYNA Pump-Turbine Scale Model

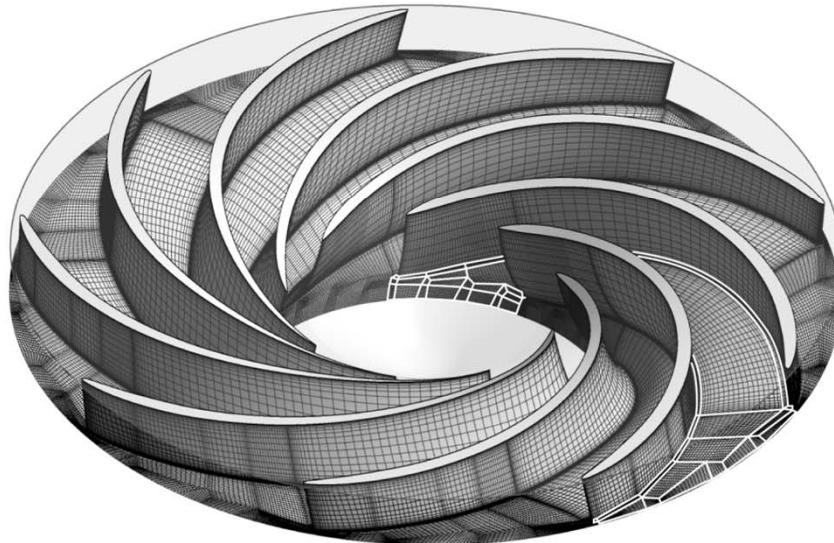
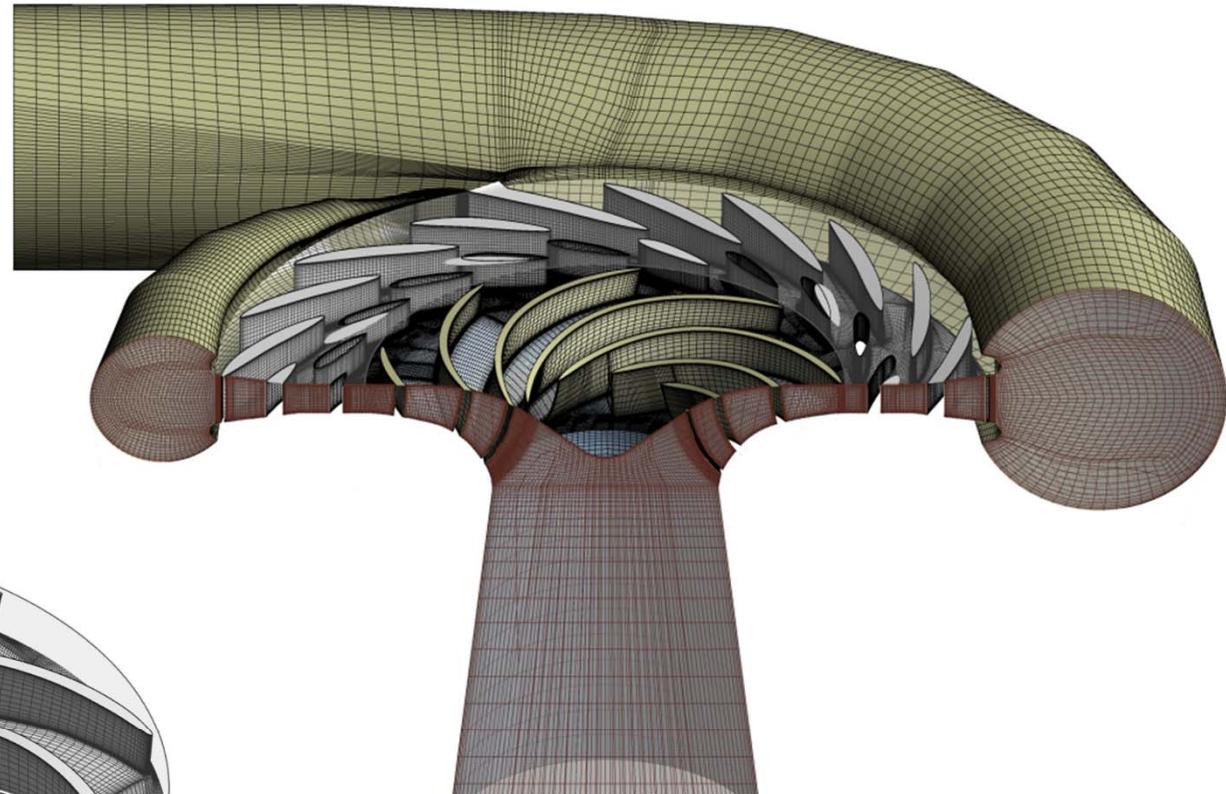


HYDR  **DYNA**

Experimental Investigations



Computing Domain

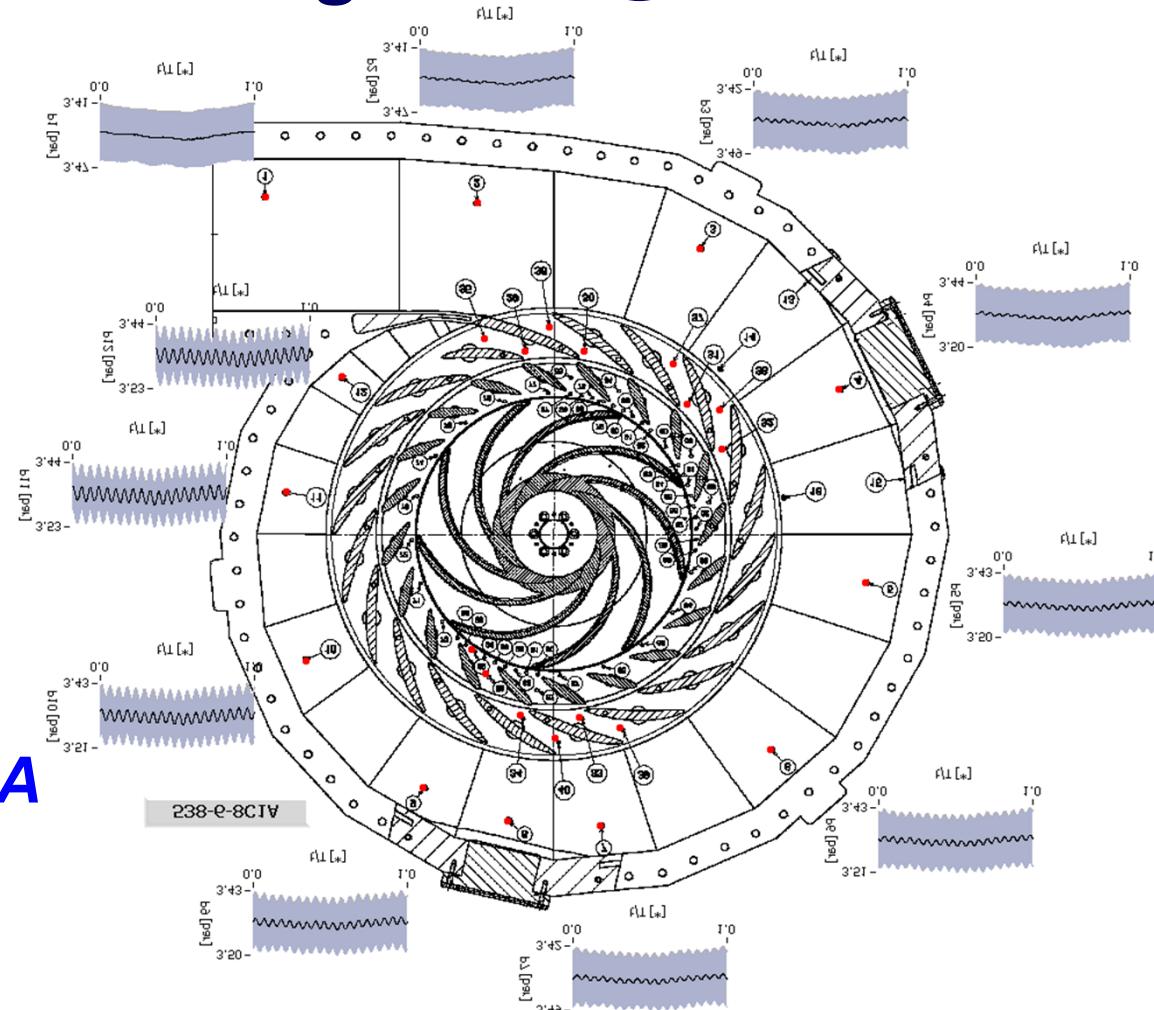


	Nodes per Channel	Nodes Total	y^+
Cone	14'000	126'000	120-180
Impeller	184'000	1'656'000	30-90
Guide, Stay Vane	110'000	2'200'000	60-100
Spiral Casing	—	490'000	150-200
Total	—	4'472'000	—



Rotor-Stator Interaction

Generating Mode @ Full Load





K = -2 Mode of 9 x 20 RSI

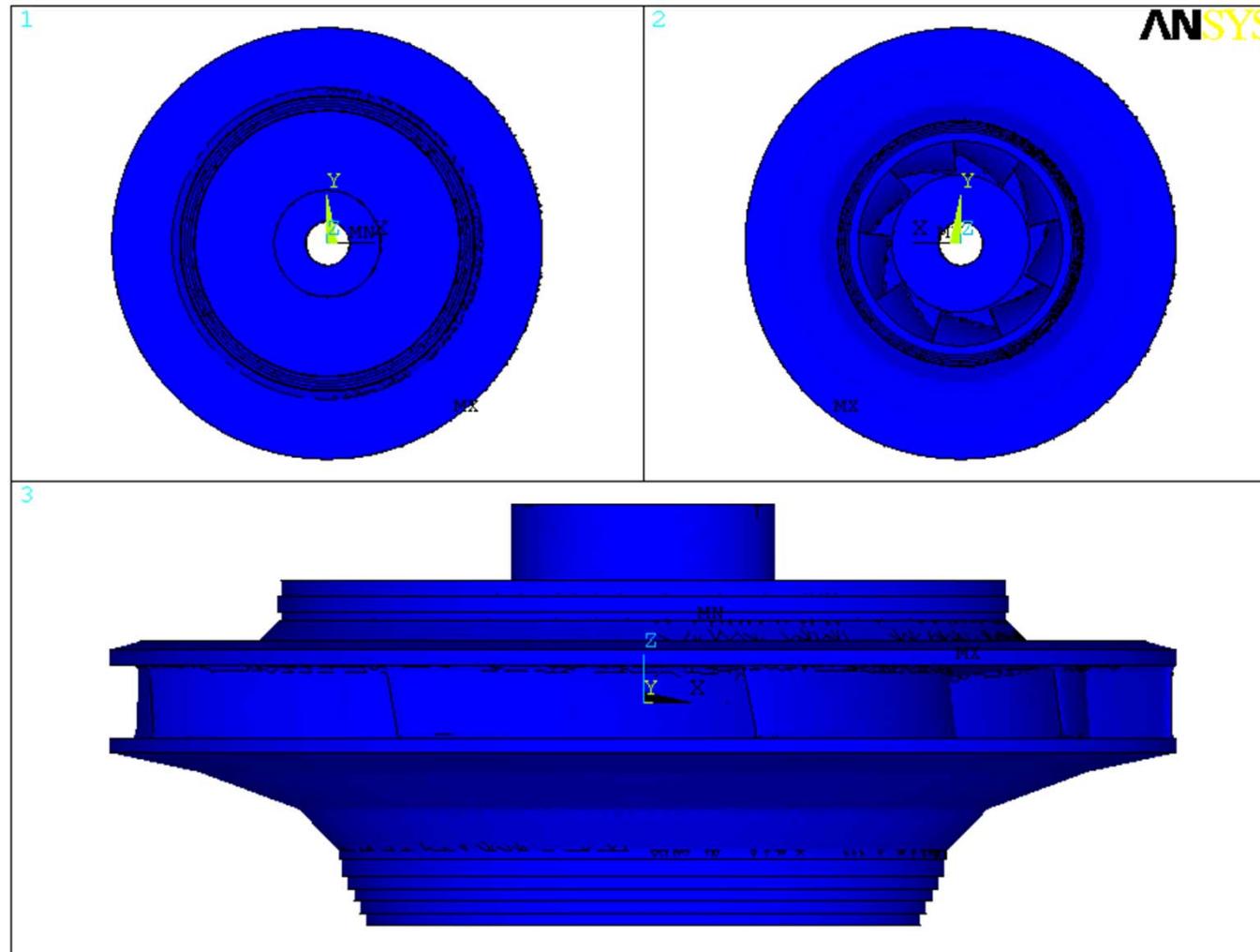


Numerical Comparison

Pressure Fluctuation in
Guide Vanes



Impeller Modal Analysis: 2D Mode





Toward a Sustainable CO₂-Free Power Generation System

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



Conclusions

- **Pumped Storage Plants (PSP) are the key component for enabling the development and the optimum use of primary renewable energy.**
- **The business model is driven by the energy spot market, the services to the grid and the public policy.**
- **The pump-turbine technology needs to be further developed to meet the market needs and to ensure and enhance, reliability availability maintainability and safety of the power plants. Attention must be paid when utilizing existing hydraulic infrastructure, e.g. penstock.**
- **The on-going Swiss projects of PSP are an opportunity for further investigations in the field of enabling energy technology.**



EPFL Doctoral Theses

- Nicolas RUCHONNET: "*Multiscale Computational Methodology Applied to Hydroacoustic Resonance in Cavitating Pipe Flow*", EPFL Doctoral Thesis N°4778 , 2010.
- Berten STEFAN: "*Hydrodynamics of High Specific Power Pumps at Off-Design Operating Conditions*", EPFL Doctoral Thesis N°4642, 2010.
- Philippe AUSONI: "*Turbulent Vortex Shedding from a Blunt Trailing Edge Hydrofoil*", EPFL Doctoral Thesis N°4475, 2009.
- Olivier BRAUN : "*Part Load Flow in Radial Centrifugal Pumps*", EPFL Doctoral Thesis N°4422, 2009.
- Alireza ZOBEIRI : "*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.



LMH *Laboratory for Hydraulic Machines*



Thanks for your Kind Attention 😊

swiss**electric**
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KTI

EOS
HOLDING

ALSTOM
Power Hydro



ANDRITZ
Hydro

VOITH

FNSNF
FONDS NATIONAL SUISSE
DE LA RECHERCHE SCIENTIFIQUE

ccem.ch

the **ark**

Sulzer Pumps

Renewables
Grid Initiative

RGI Storage Workshop, Montreux Jan. 27, 2011

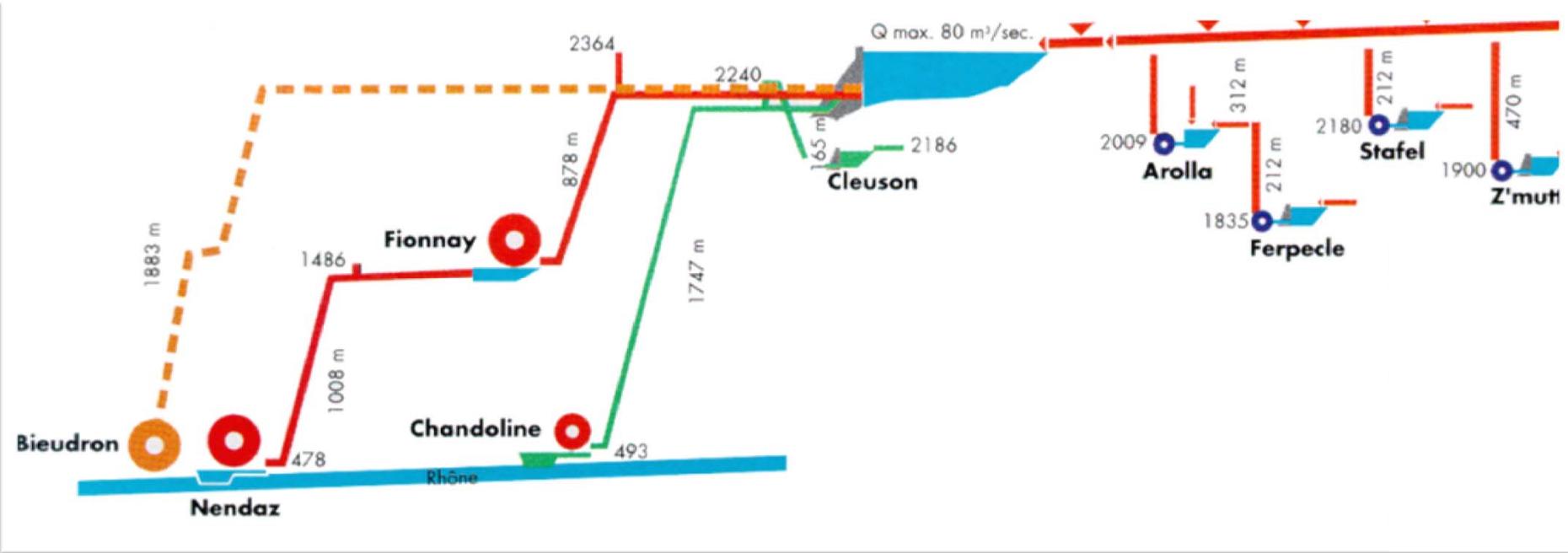


Grande Dixence Hydropower Scheme



400 Millions m³ Reservoir Storage Capacity: Maximum Value

Grande Dixence Hydropower Scheme:



- Generating Power Station: Seasonal Operation
 - ✓ 1'269 MW Bieudron
 - ✓ 685 MW Nendaz-Fionnay
 - ✓ 100 MW Chandoline
- Collecting Water from 35 Glaciers
 - ✓ 170 MW Pumping Power

400 Millions m^3 Reservoir Storage Capacity: Maximum Value



1'269 MW Bieudron Power Plant

3 Pelton Turbines

- **500 MVA Generators**

- ✓ **428.5 min⁻¹**
 - ✓ **14 poles, 35.7 MVA/pole**
 - ✓ **Water Cooled**

- **423 MW Pelton**
Turbines, 5 injectors

- ✓ **1'883 mWC Head**
 - ✓ **25 m³/s Discharge**
 - ✓ **$D_1 = 3.993 \text{ m}$**
 - ✓ **~28 t Runner Mass**

