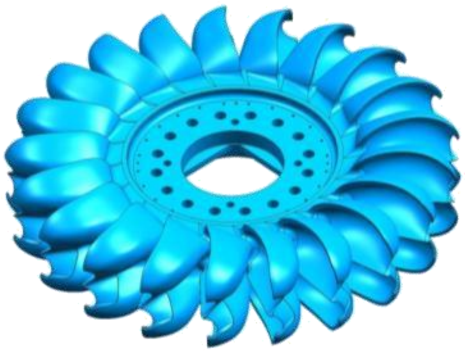
Lecture Pelton Turbines

N. Gervais



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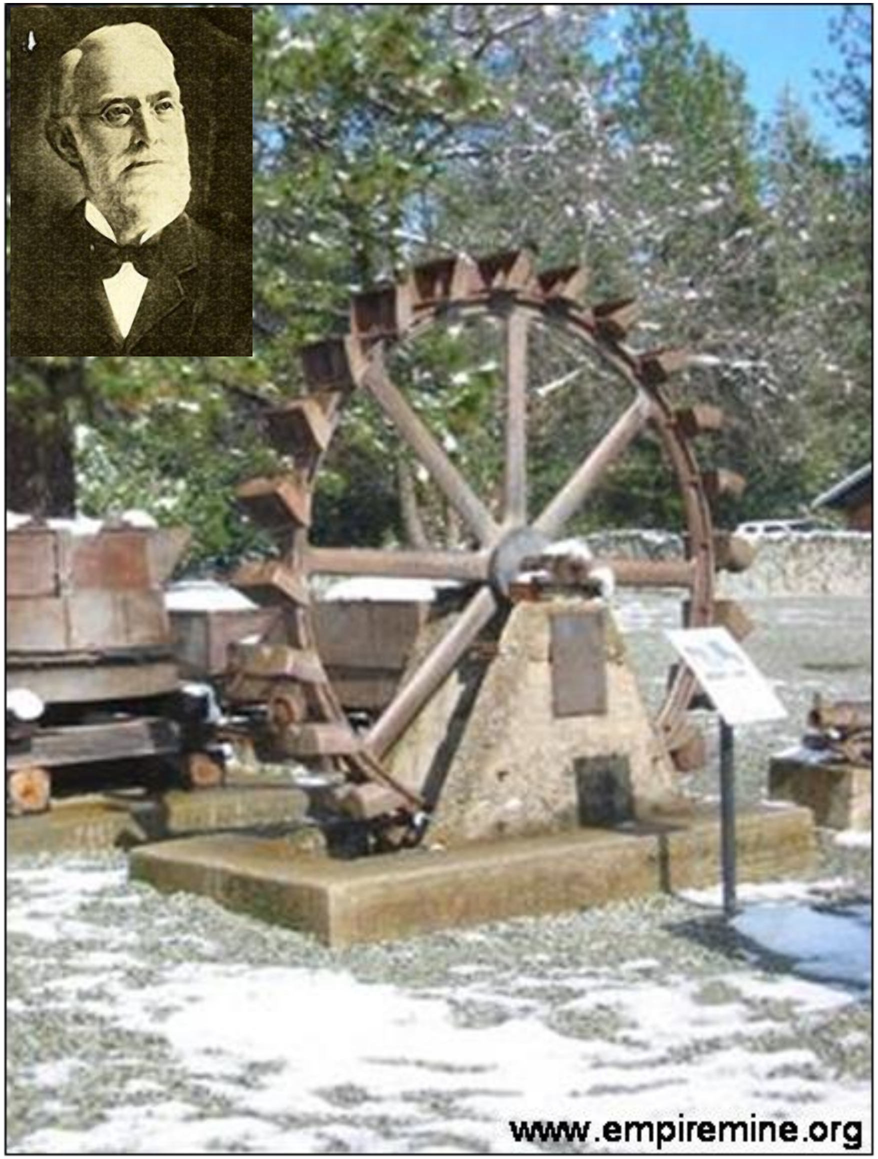
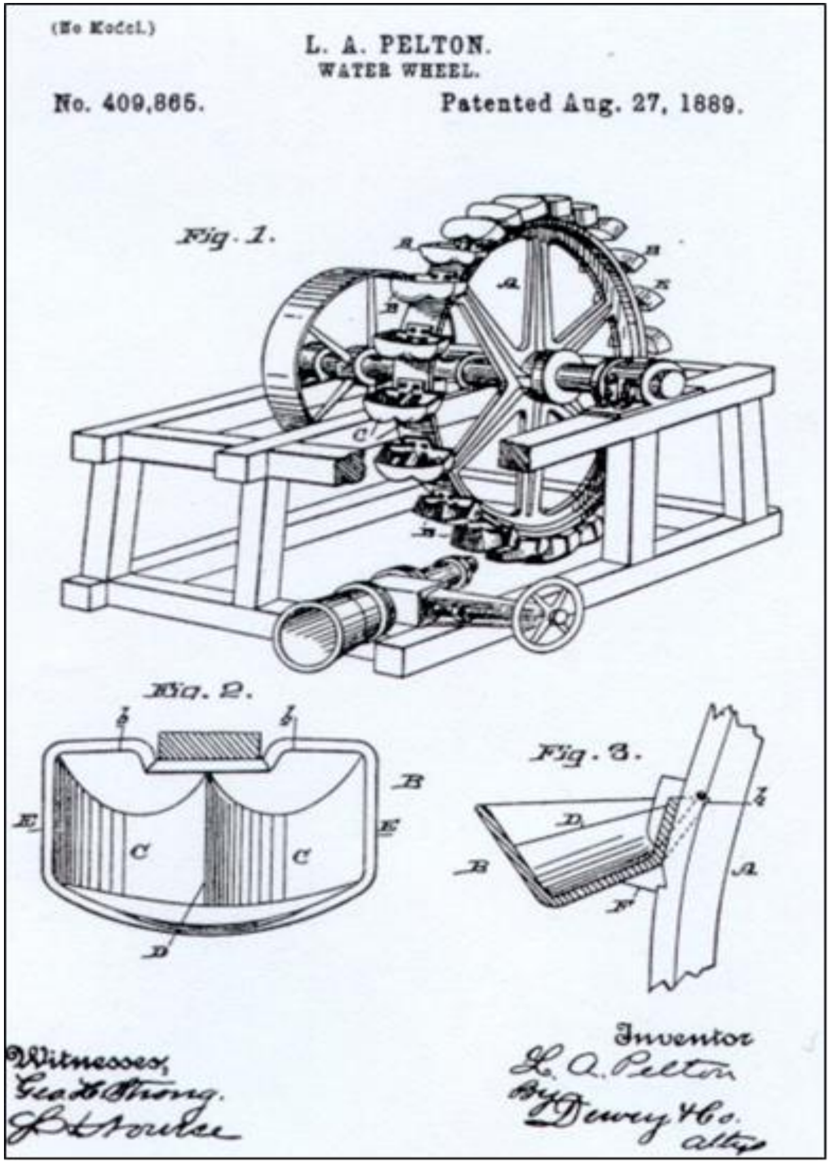
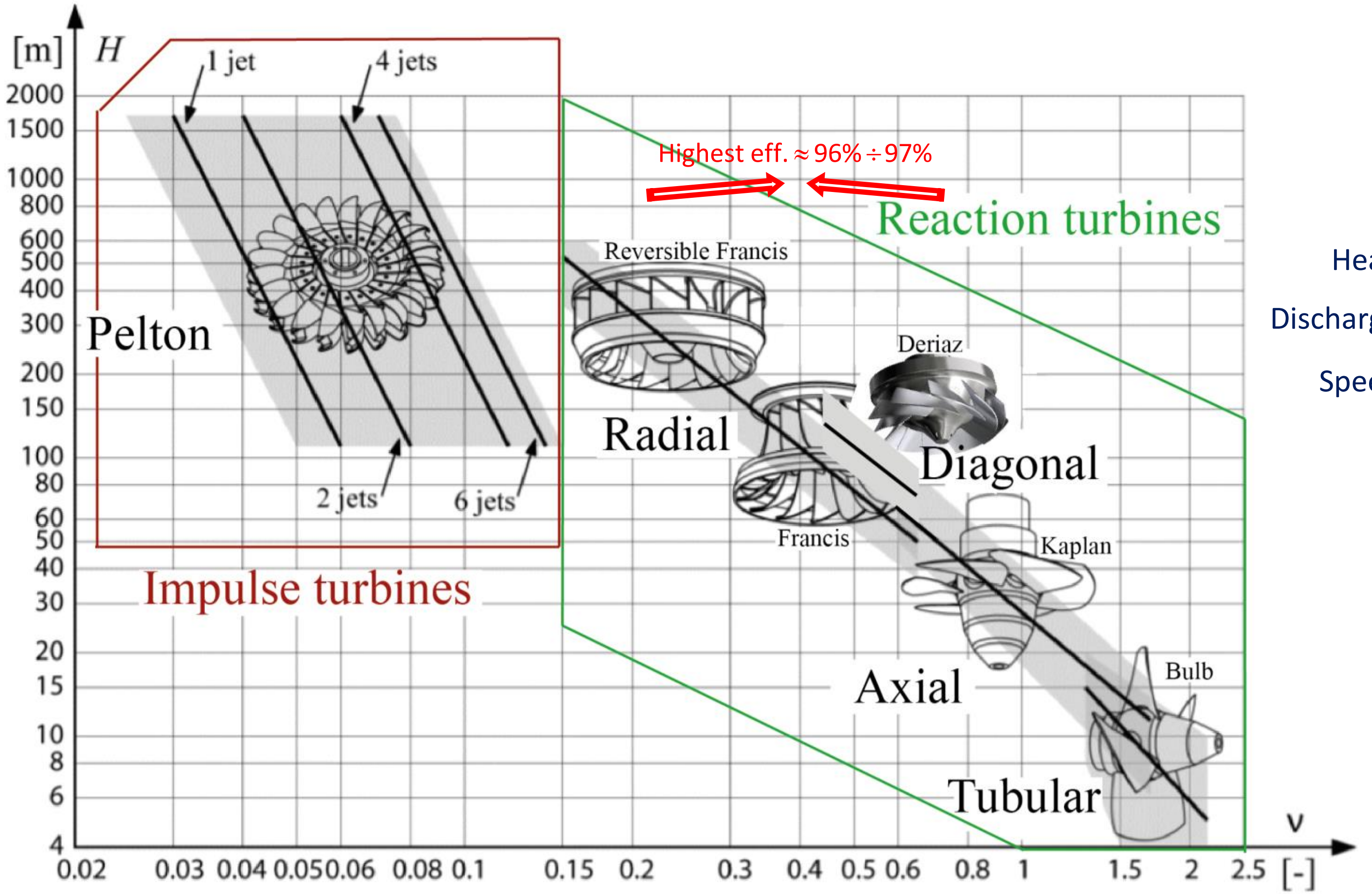
Basics

Basics: History





From L2: Classification of Hydraulic Runners



Head $= H \quad (m)$

Discharge $= Q \quad (m^3 \cdot s^{-1})$

Speed $= N \quad (min^{-1})$

EPFL

From L2: Classification of Hydraulic Runners
Runner/impeller specific energy transfer

- Transferred Specific Energy

$$gH_1 - gH_{\bar{1}} = E_t \pm E_{rb} \quad \left(\mathrm{J \cdot kg^{-1}}\right)$$

- Specific Energy

$$gH = \frac{p}{\rho} + gZ + \frac{C^2}{2} \quad \left(\mathrm{J \cdot kg^{-1}}\right)$$

- Specific Energy Balance:

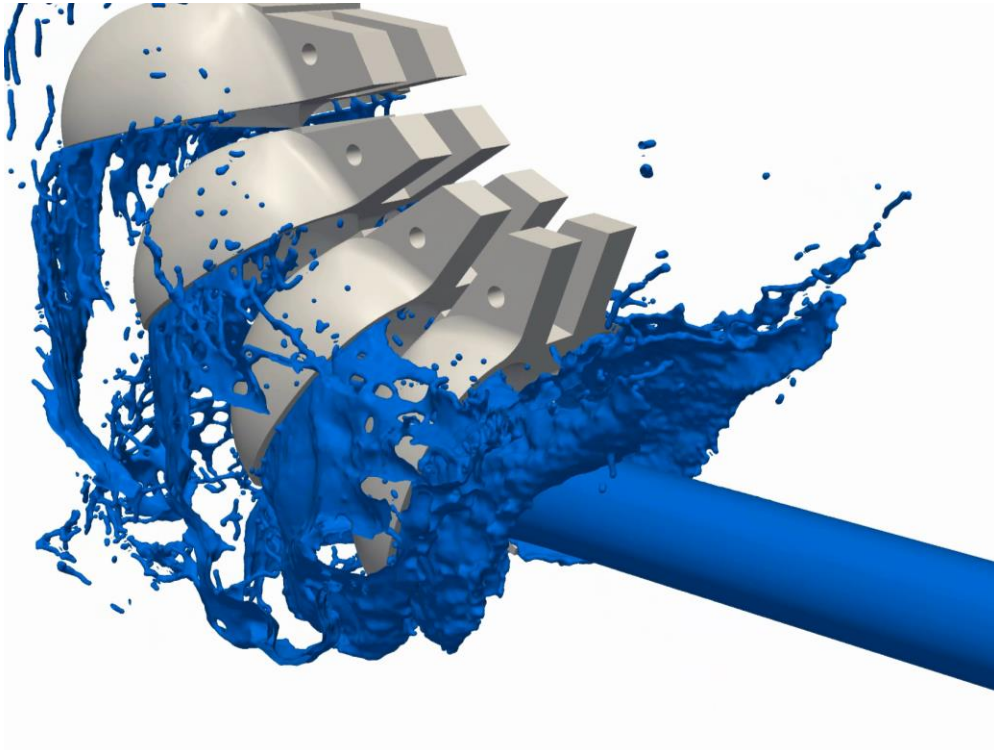
$$E_t = \overbrace{\underbrace{\left(\frac{p_1}{\rho} - \frac{p_{\bar{1}}}{\rho}\right)}_{\text{Displacement}} + \underbrace{\left(\frac{C_1^2}{2} - \frac{C_{\bar{1}}^2}{2}\right)}_{\text{Impulse}}}^{\text{Reaction}} + \underbrace{\left[gZ_1 - gZ_{\bar{1}}\right]}_{\text{Water Wheel}} \underbrace{\pm E_{rb}}_{Loss}$$

$$\left(\mathrm{J \cdot kg^{-1}}\right)$$

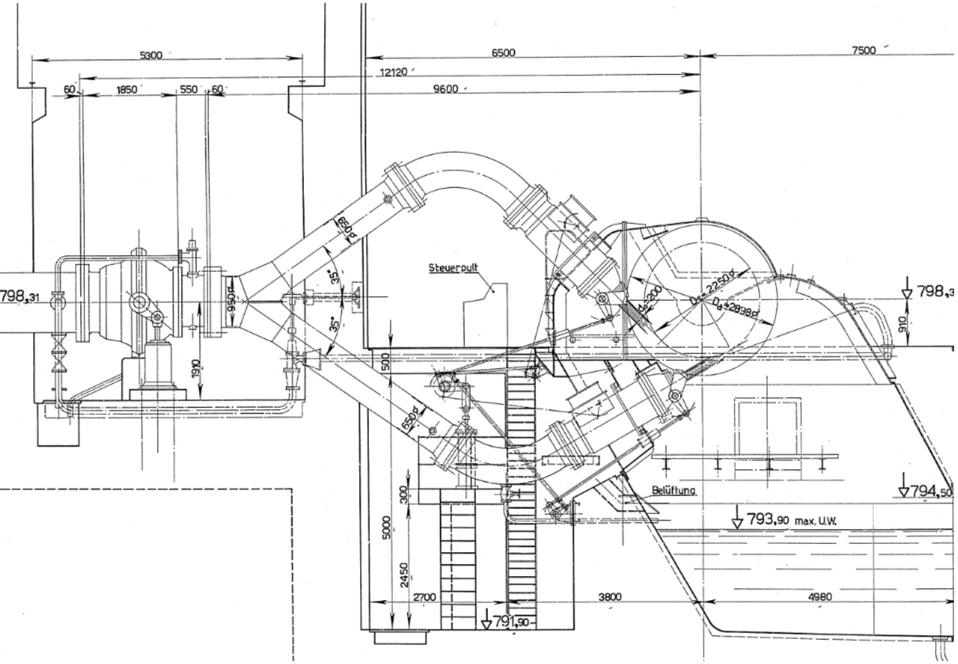
From L2: Classification of Hydraulic Runners

Pelton Runners

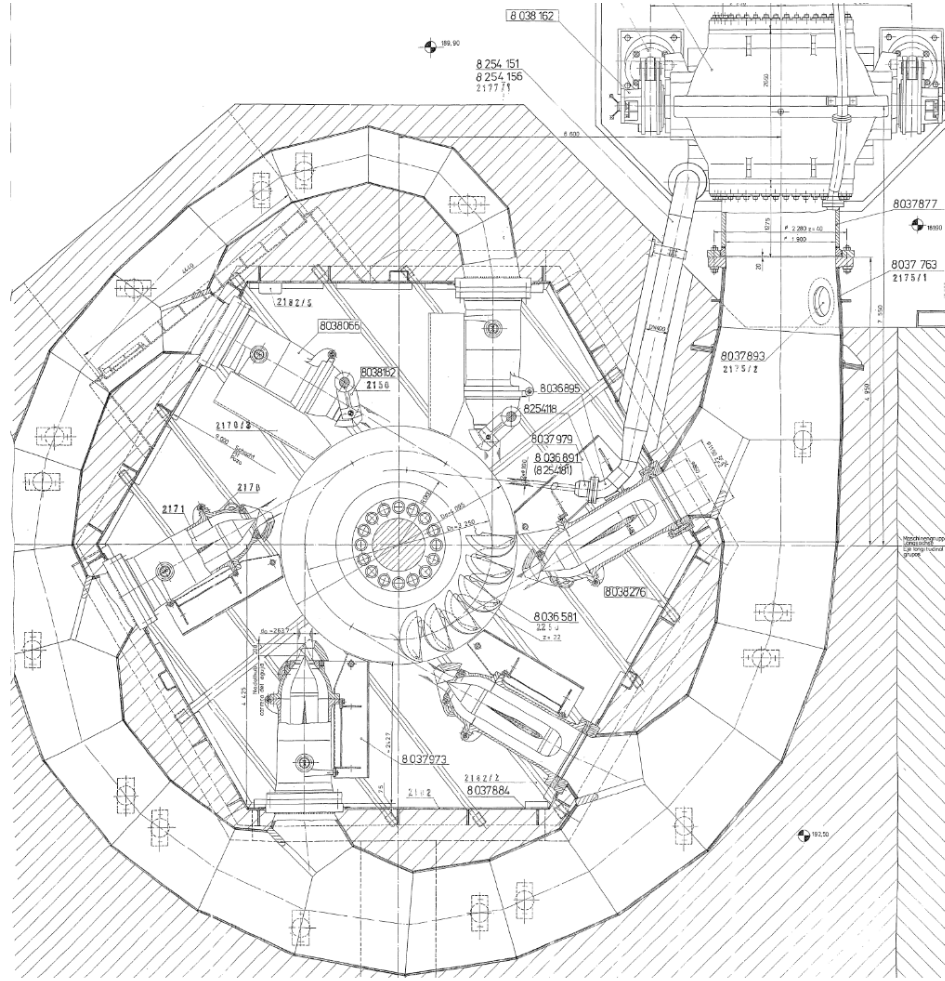
- Pelton Wheel
  - Impulse turbine
  - Tangential flow
  - High head



Pelton types

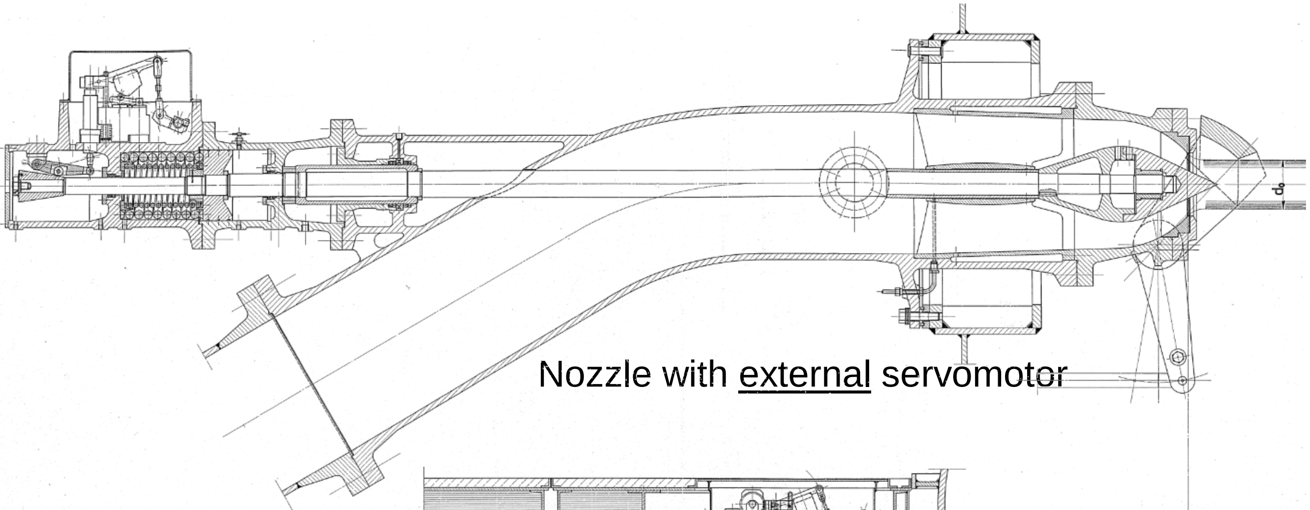


Horizontal shaft, 1, 2 or 3 jets

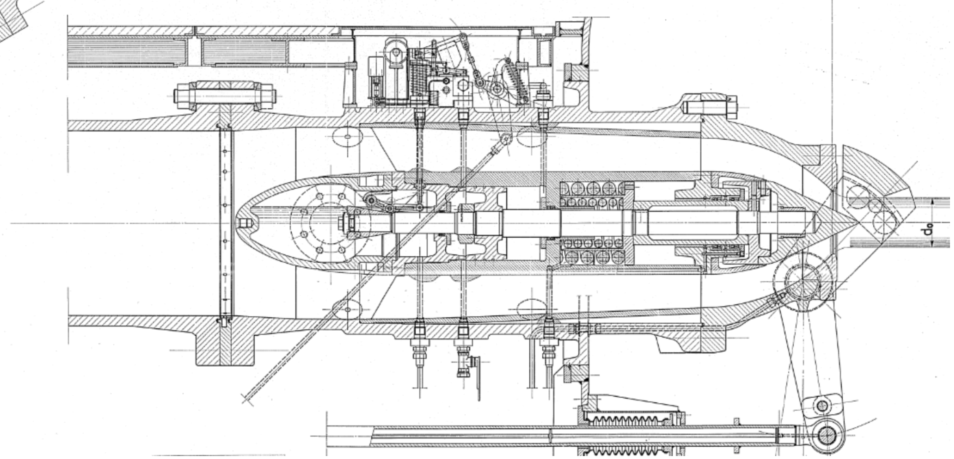


Vertical shaft, 1 to 6 jets

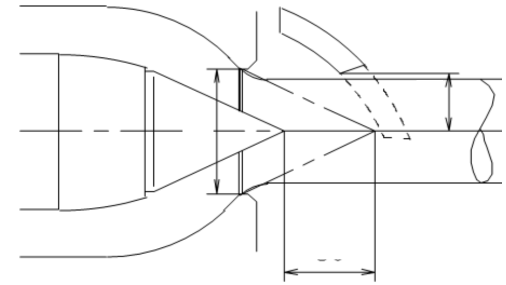
Nozzle types



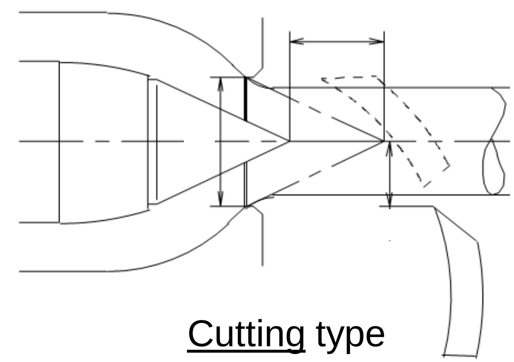
Nozzle with external servomotor



Nozzle with internal servomotor

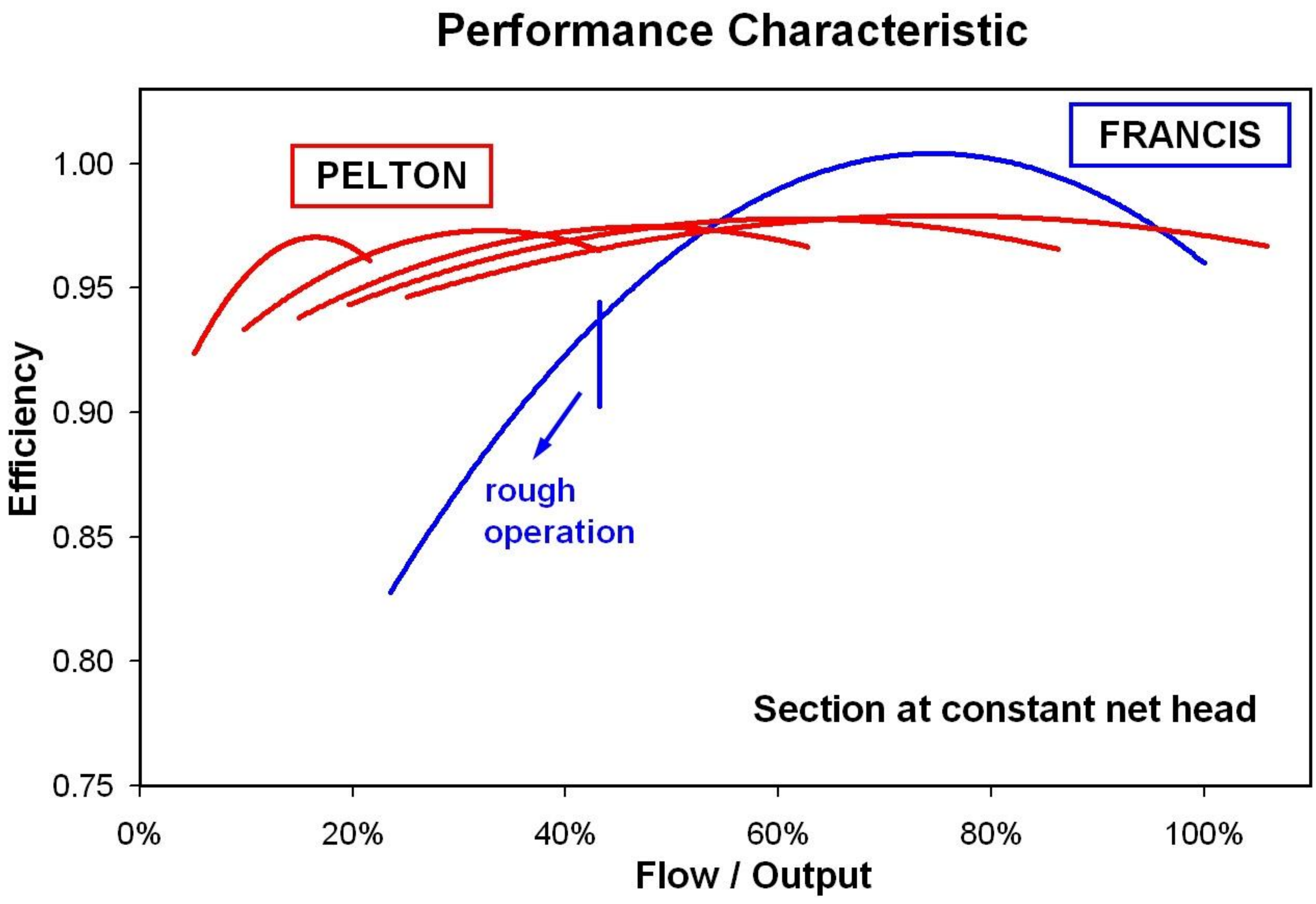


Deflecting type

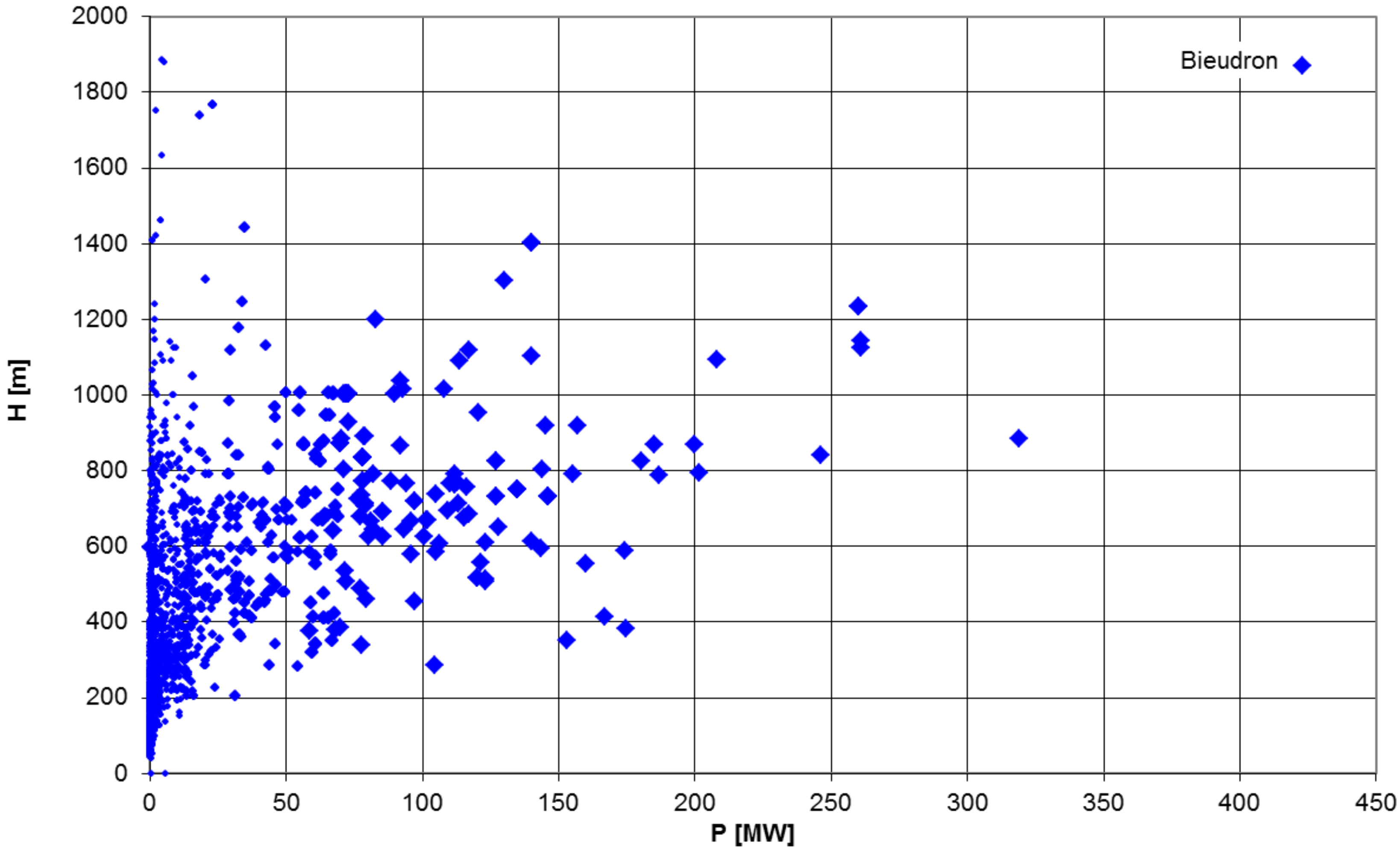


Cutting type

Typical efficiency curves



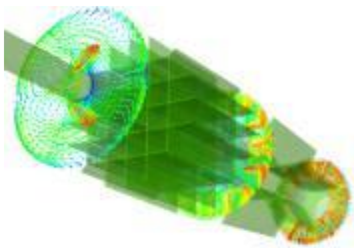
Typical range of built Pelton turbines



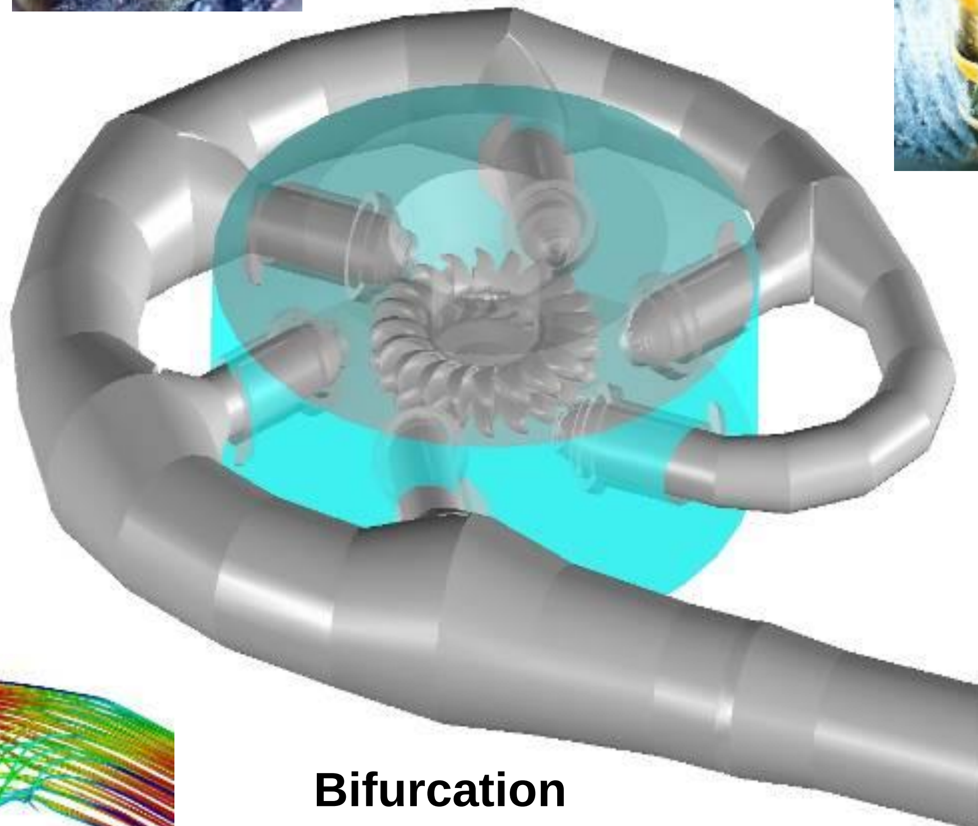
Pelton flows

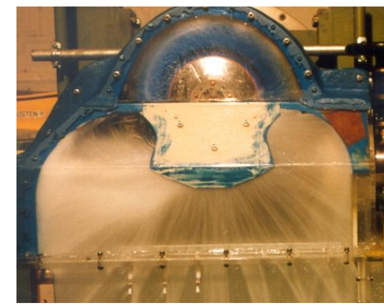
Jet
(“quality”)

Bucket flow
(flow patterns, torque, Interactions)

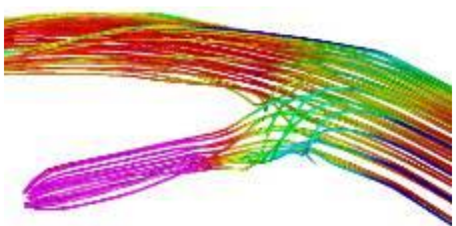


Injector
(flow “quality”)





Casing
(impact, returning water sheets)



Bifurcation
(losses)

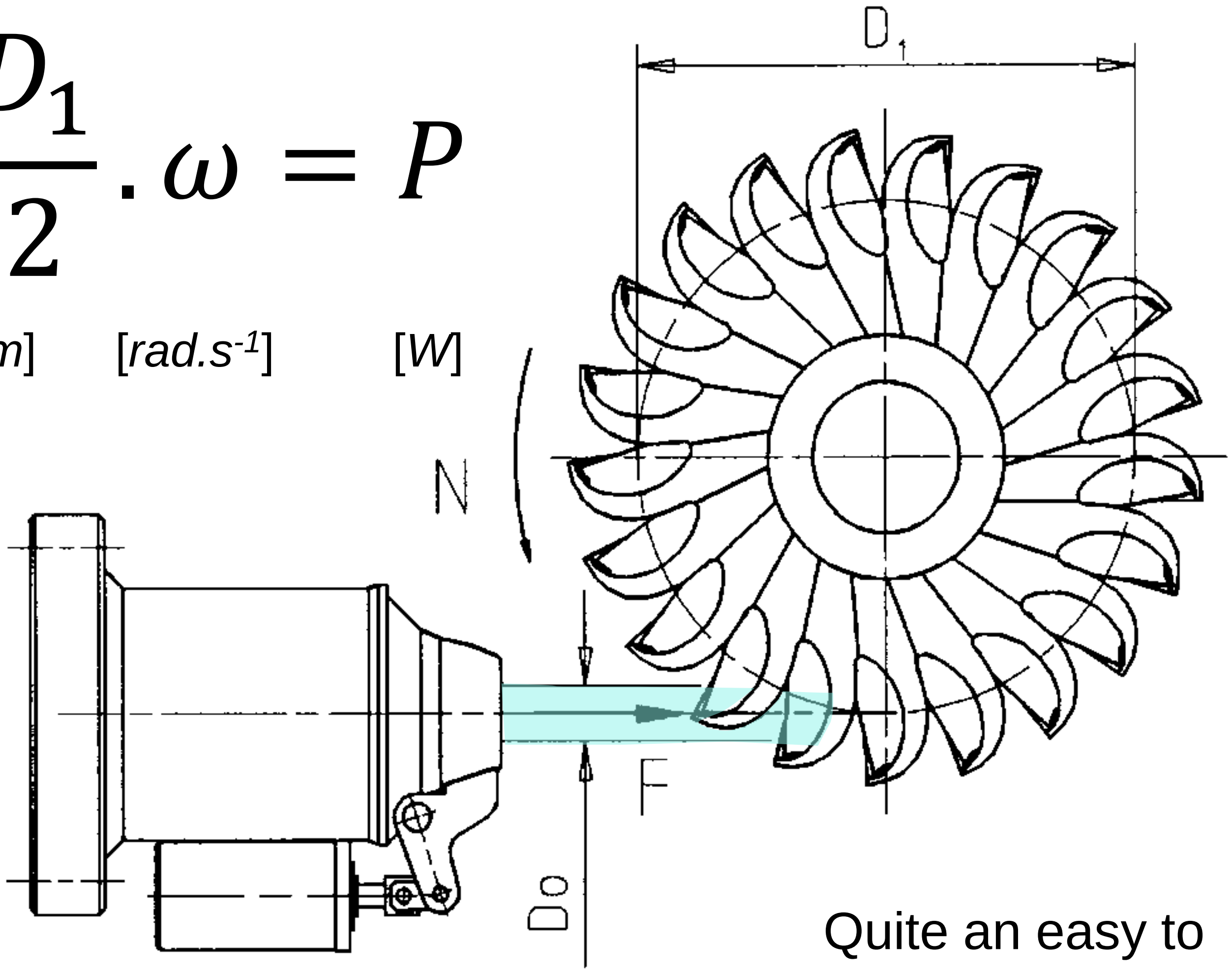
Distributor
(losses, flow quality)

Some equations…

Basics: Impulse turbine

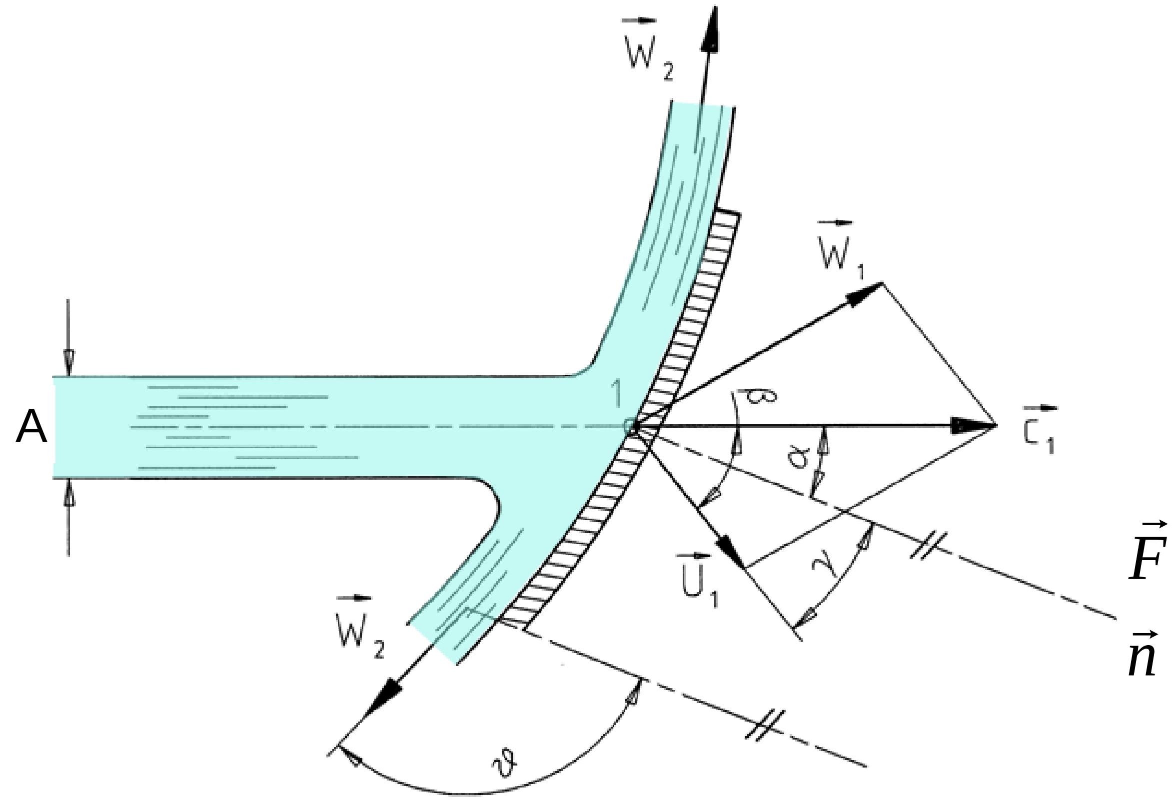
$$F \cdot \frac{D_1}{2} \cdot \omega = P$$

[*N*] [*m*] [*rad.s*$^{-1}$] [*W*]



Quite an easy to understand concept !

Effort on a moving surface

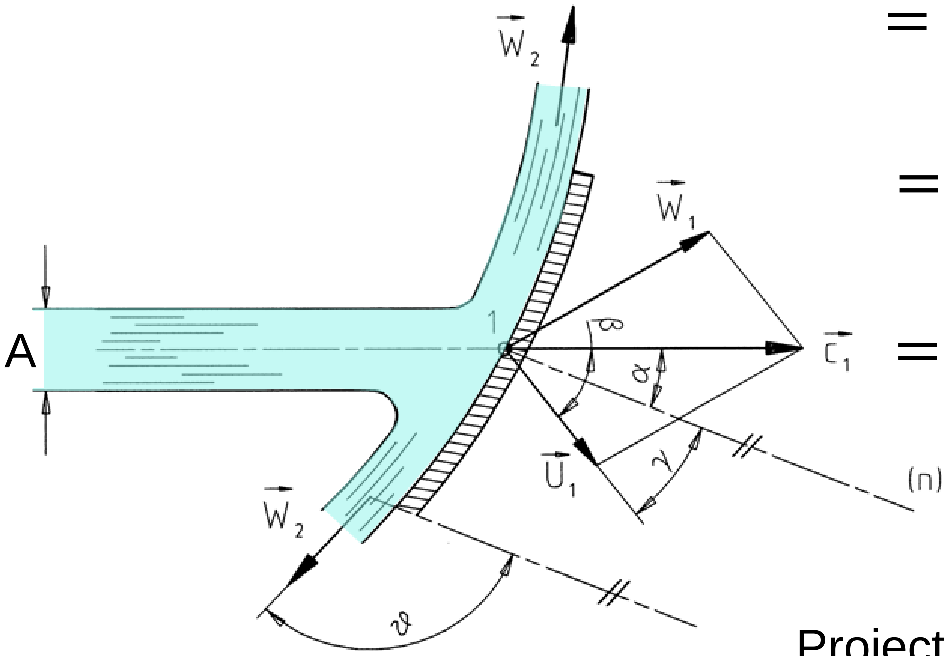


Momentum equation (Euler's theorem):

$$\vec{F} = \oiint_{Surf} \rho\, \vec{C}\, (\vec{C}.\vec{n}) dA$$

Effort on a moving surface

$$\vec{F}_{Fluid} = \oiint_{A1} \rho\, \overrightarrow{C_1}\, (\overrightarrow{C_1}.\vec{n})dA + \oiint_{A2} \rho\, \overrightarrow{C_2}\, (\overrightarrow{C_2}.\vec{n})dA$$



$$= -\rho C_1 A_1 \overrightarrow{C_1} + \rho C_2 A_2 \overrightarrow{C_2}$$

$$= \rho C_1 A_1 (\overrightarrow{C_2} - \overrightarrow{C_1})$$

$$= \rho C_1 A_1 (\overrightarrow{U_1} + \overrightarrow{W_2} - \overrightarrow{C_1})$$

Mass conservation

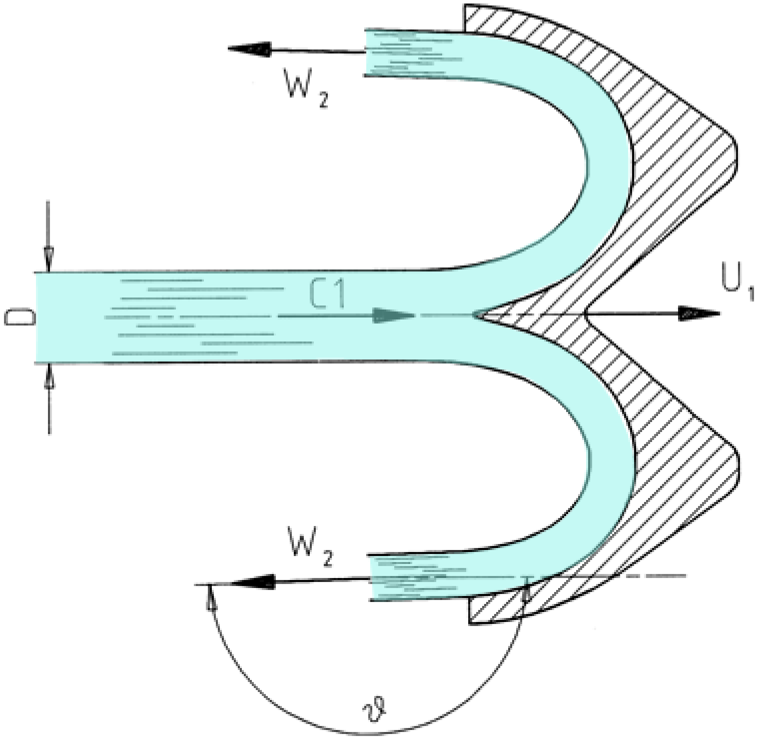
$$\begin{cases} \vec{C}_2 = \vec{U}_2 + \vec{W}_2 \\ \vec{U}_1 = \vec{U}_2 \end{cases}$$

Projection on surface normal:

$$F_{Solid} = \rho Q (C_1 \cos\alpha - U_1 \cos\gamma - W_2 \cos\vartheta)$$

Effort on a Pelton bucket

Ideal case considered $F_{Solid} = \rho Q(C_1 \cos\alpha - U_1 \cos\gamma - W_2 \cos\vartheta)$



2D bucket

$\alpha = \gamma = 0^\circ$

$\vartheta \cong 180^\circ$

$W_2 \cong W_1 = C_1 - U_1$

$F = 2\rho Q(C_1 - U_1)$

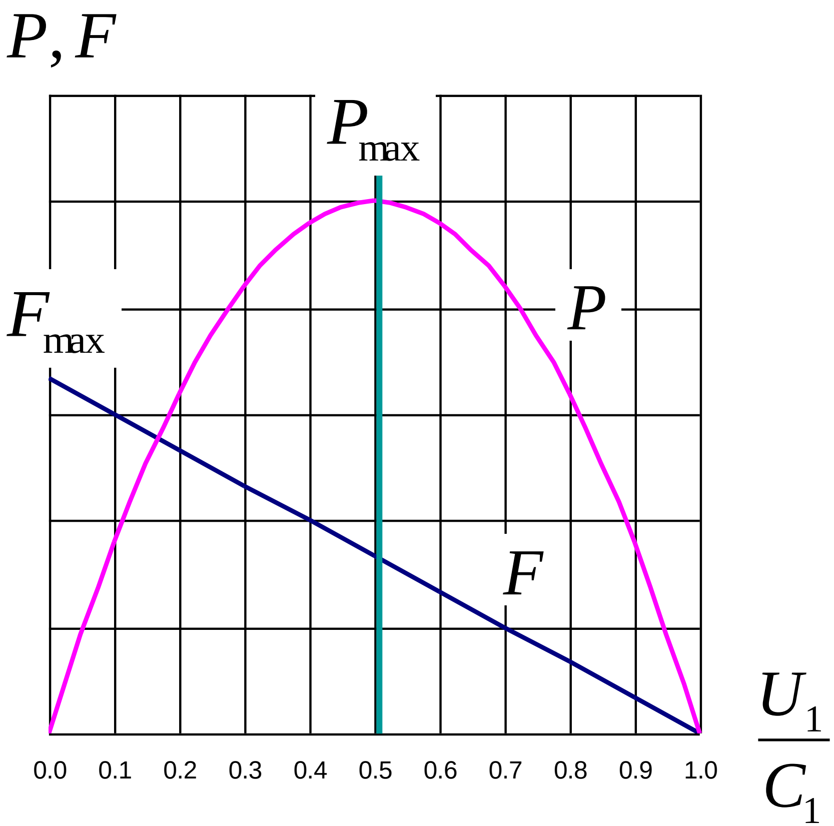
$P = F \cdot U_1$

Maximum power conditions

$$\begin{cases} F = 2\rho Q \cdot (C_1 - U_1) \\ P = F \cdot U_1 = 2\rho Q \cdot (C_1 - U_1) \cdot U_1 \end{cases}$$

$$\Rightarrow \frac{dP}{dU_1} = 2\rho Q \cdot (C_1 - 2U_1)$$

$$\Rightarrow \underbrace{\frac{dP}{dU_1} = 0 \Leftrightarrow U_1 = \frac{C_1}{2}}_{P_{max}}$$

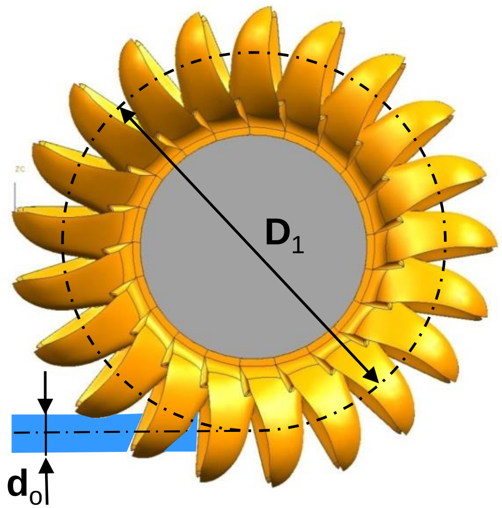


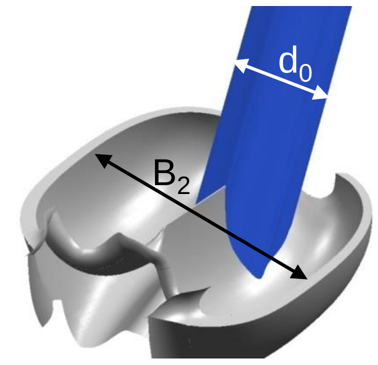
Rotating speed
=
0.5 jet speed

Operation	Power	Force
Stopped	0	Max
Normal	Max	0.5 Max
Runaway	0	0

Typical non dimensional numbers

D_1: Pitch diameter
B_2: Inner bucket width





Speed factor
(specific circumferential speed)

$$ku_1 = \frac{n\pi D_1}{\sqrt{2gH}} \qquad n_{ED} = \frac{nD_1}{\sqrt{gH}}$$

Normalized bucket load

$$\varphi_{B_2} = \left(\frac{d_0}{B_2}\right)^2 = \frac{Q/z_0}{B_2^2 \frac{\pi}{4}\sqrt{2gH}} \qquad Q_{EB} = \frac{Q/z_0}{B_2^2\sqrt{gH}}$$

n...rotational speed $[s^{-1}]$
z_0...number of nozzles $[-]$

Non dimensional hill-chart

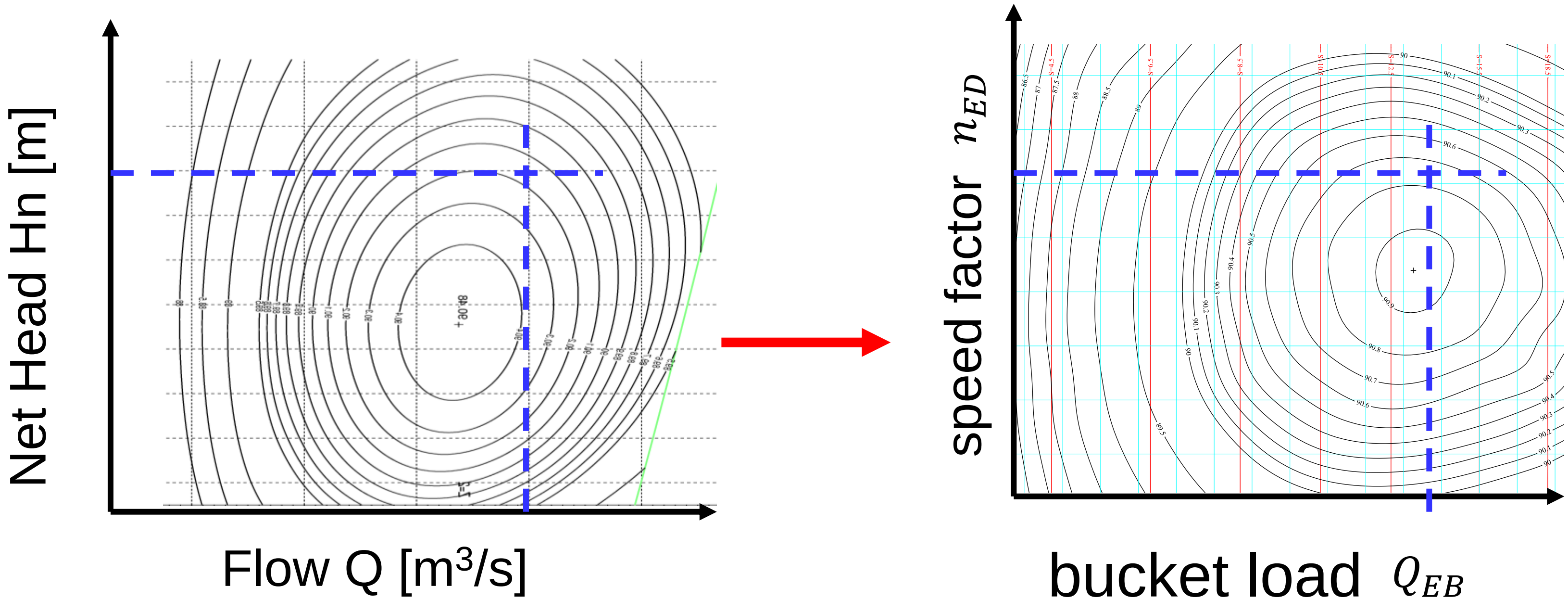
n_{ED}, Q_{EB}

indicates the operation point

$$n_{ED} = \frac{nD_1}{\sqrt{gH}}$$ Speed factor

$$Q_{EB} = \frac{Q/z_0}{B_2^2\sqrt{gH}}$$ Normalized bucket load

Any efficiency hill chart can be compared one to another.



Specific speed

$$n_{ED} \cdot \sqrt{Q_{EB}} = \frac{nD_1}{\sqrt{gH}} \cdot \sqrt{\frac{Q/z_0}{B_2^2\sqrt{gH}}}$$

$$= \frac{D_1}{B_2} \cdot \frac{n\sqrt{Q/z_0}}{(gH)^{3/4}}$$

n_{ED}: constant at nominal head

Q_{EB}: constant at nominal flow

N_{QE_jet}: **Specific speed (IEC)**

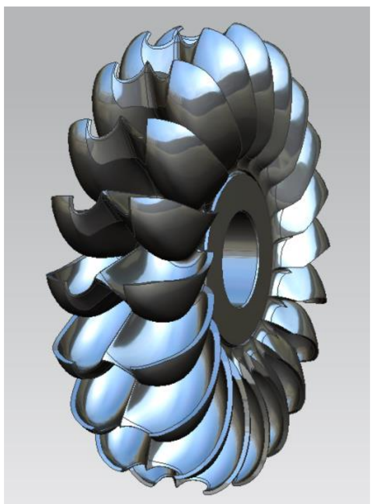
N_{QE} **: with Q instead of Q/z0**

$\frac{D_1}{B_2}$: **Similar to specific speed (Pelton)**

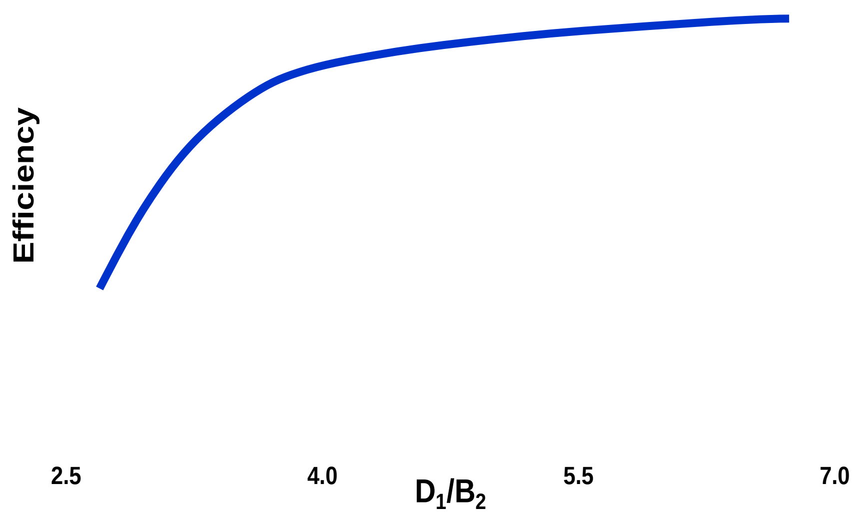
Efficiency versus specific speed

Specific speed $\frac{D_1}{B_2}$ indicates

- geometry of the runner
- efficiency level
- efficiency characteristic over operation field (H, Q)



(less space for flow)



$\frac{D_1}{B_2}$ characterized hydraulic behavior of a Pelton turbine

Layout of a Pelton turbine

Hydraulic layout: **given H, Q**

1. Definition of net head — $H = (Z_B - Z_{\bar{B}}) - \sum H_r^T$
2. Calculation of the jet speed — $c_{jet} = (2*g*H)^{0.5}$
3. Choose a appropriate speed — n = f(jet number, grid frequency, pole number)
4. Calculation of pitch circle — $ku_1 = \frac{n\pi D_1}{\sqrt{2gH}} \approx 0.48$ → D_1
5. Assumption of the jet number — z_0
6. Discharge per nozzle — $Q_D = Q / z0$
7. Jet diameter — $d_0 = (4*Q_D / (c_{jet} * pi))^{0.5}$
8. Bucket width — $\varphi_{B_2} = \frac{Q}{z_0 B_2^2 \frac{\pi}{4} \sqrt{2gH}} \approx 0.1$ → B_2
9. Calculation of D1/B2-ratio — $D_1/B_2 > 2.7$ => feasibility check
10. Bucket number — $z_2 = f(D_1/B_2)$ from table
11. Define efficiency — eta = f(D_1/B_2, profile, losses, differences, ..)
12. Calculate output — $P = \rho * g * H * Q * \eta$

Layout of a Pelton turbine

Training-Example

H = 600 m

Q = 25 m^3/s

eta = 91.0 %

f = 50 Hz

N = 375 rpm

z0 = 6

Required results:

D1, B2, D1/B2, P

Layout of a Pelton turbine

Training-Example

H = 600 m

Q = 25 m^3/s

eta = 91.0 %

f = 50 Hz

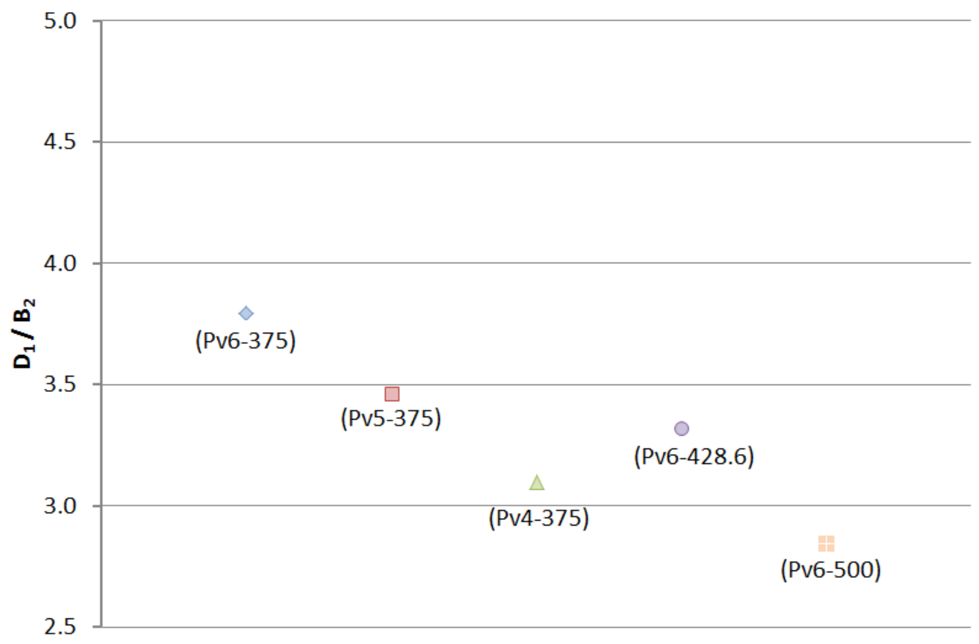
N = 375 rpm

z0 = 6

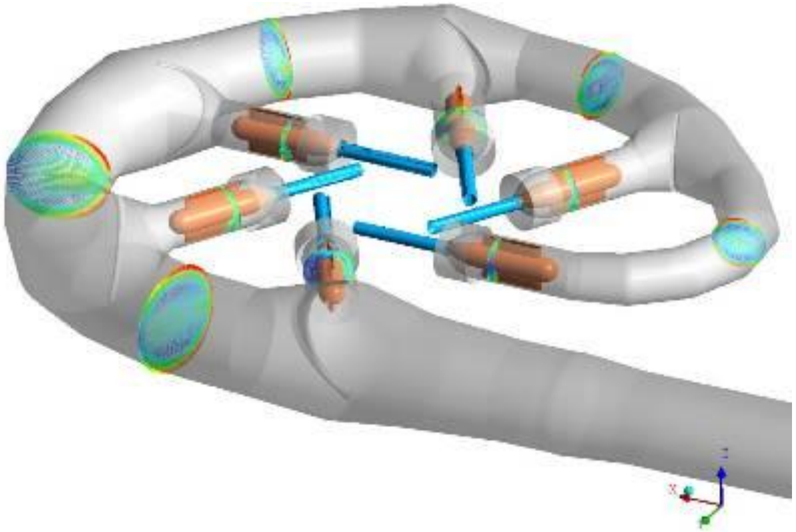
Required results:

D1, B2, D1/B2, P

		(Pv6-375)	(Pv5-375)	(Pv4-375)	(Pv6-428.6)	(Pv6-500)
H	[m]	600	600	600	600	600
Q	[m^3/s]	25	25	25	25	25
Eta	[%]	91	91	91	91	91
f	[Hz]	50	50	50	50	50
N	[rpm]	375	375	375	**428.6**	**500**
z_0	[-]	6	**5**	**4**	6	6
D_1	[mm]	2652	2652	2652	**2320**	**1989**
B_2	[mm]	**699**	**766**	**856**	699	699
D_1/B_2	[-]	**3.79**	**3.46**	**3.10**	**3.32**	**2.84**
P	[MW]	134	134	134	134	134



From penstock to water jet…

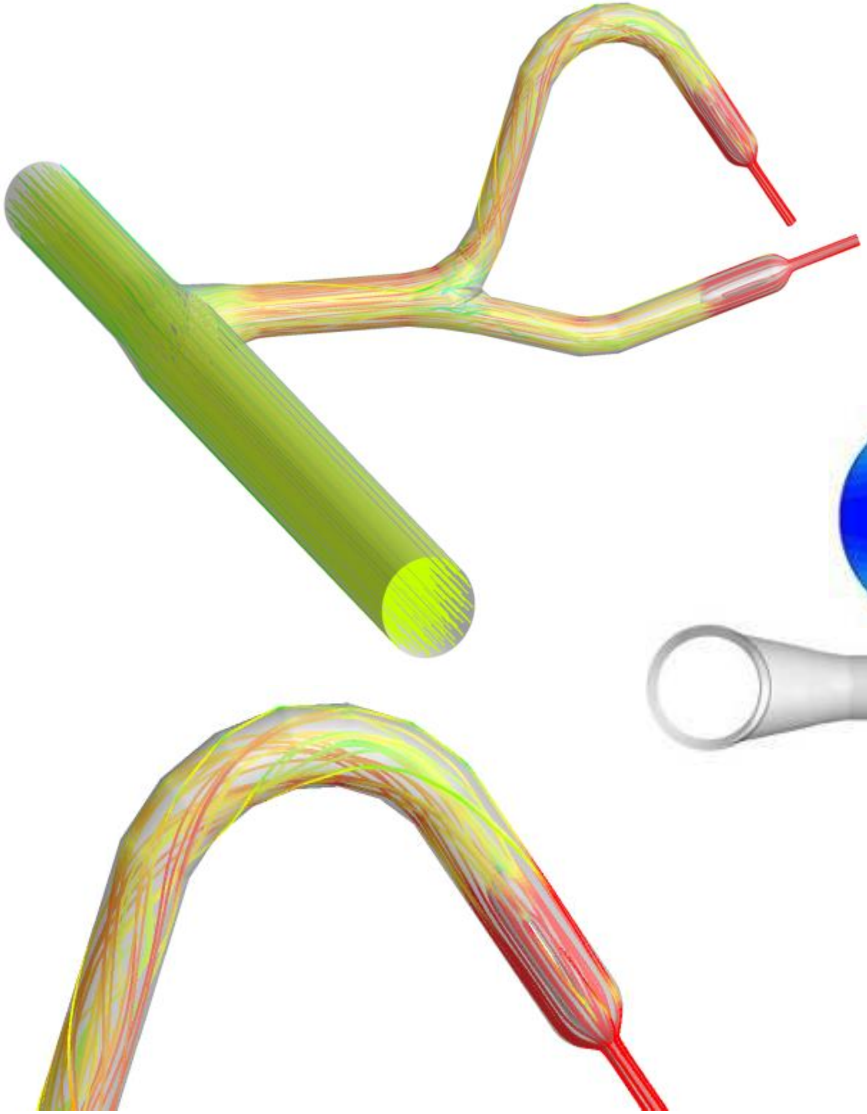


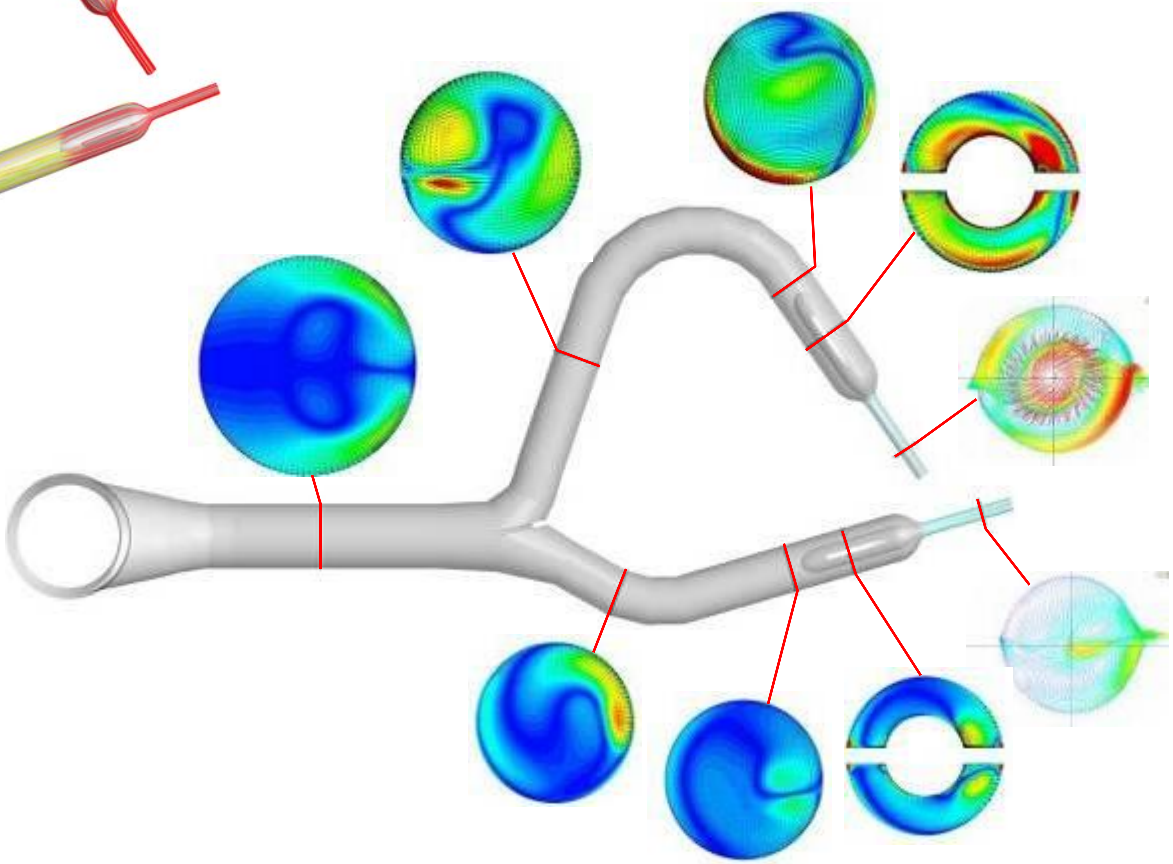
Flow field

Following a fluid particle

ANDRITZ Hydro

2 jet Pelton flow





Experimental jet analysis

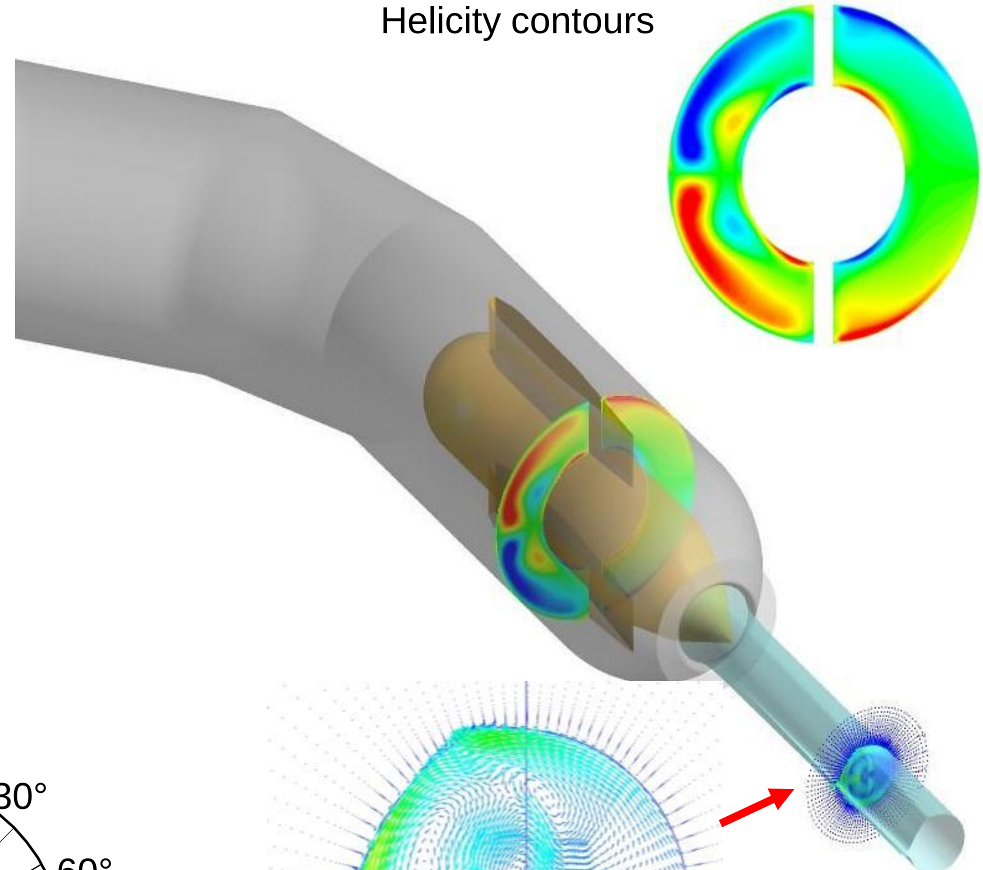
Bifurcations and bends

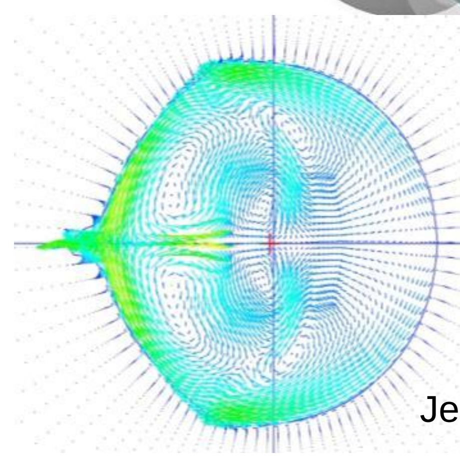
- Secondary structures
- Uneven flow / energy distribution
  - Jet deformation, deviation

Turbulence (head, disturbances)

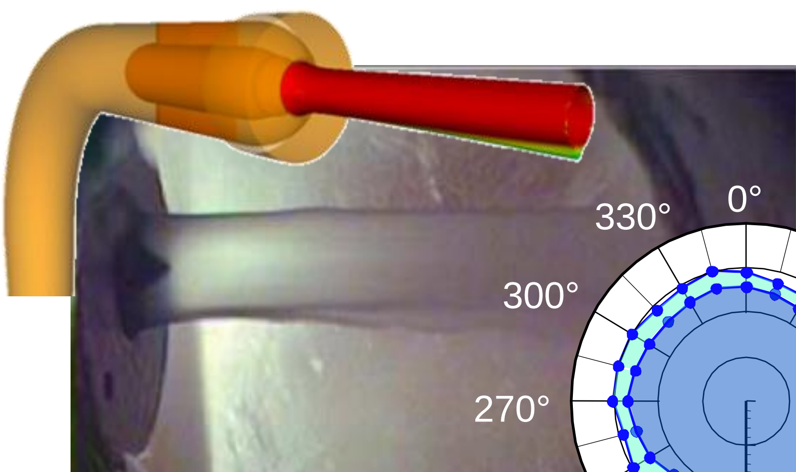
  - Jet dispersion

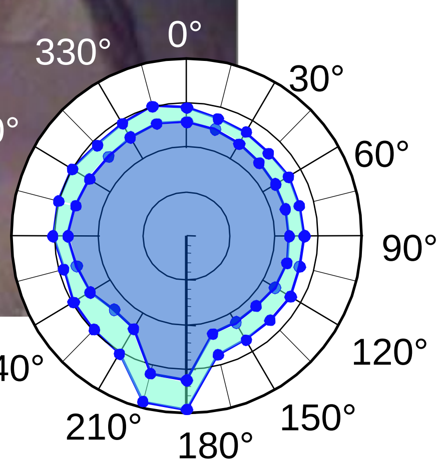
Helicity contours





Jet cross-section

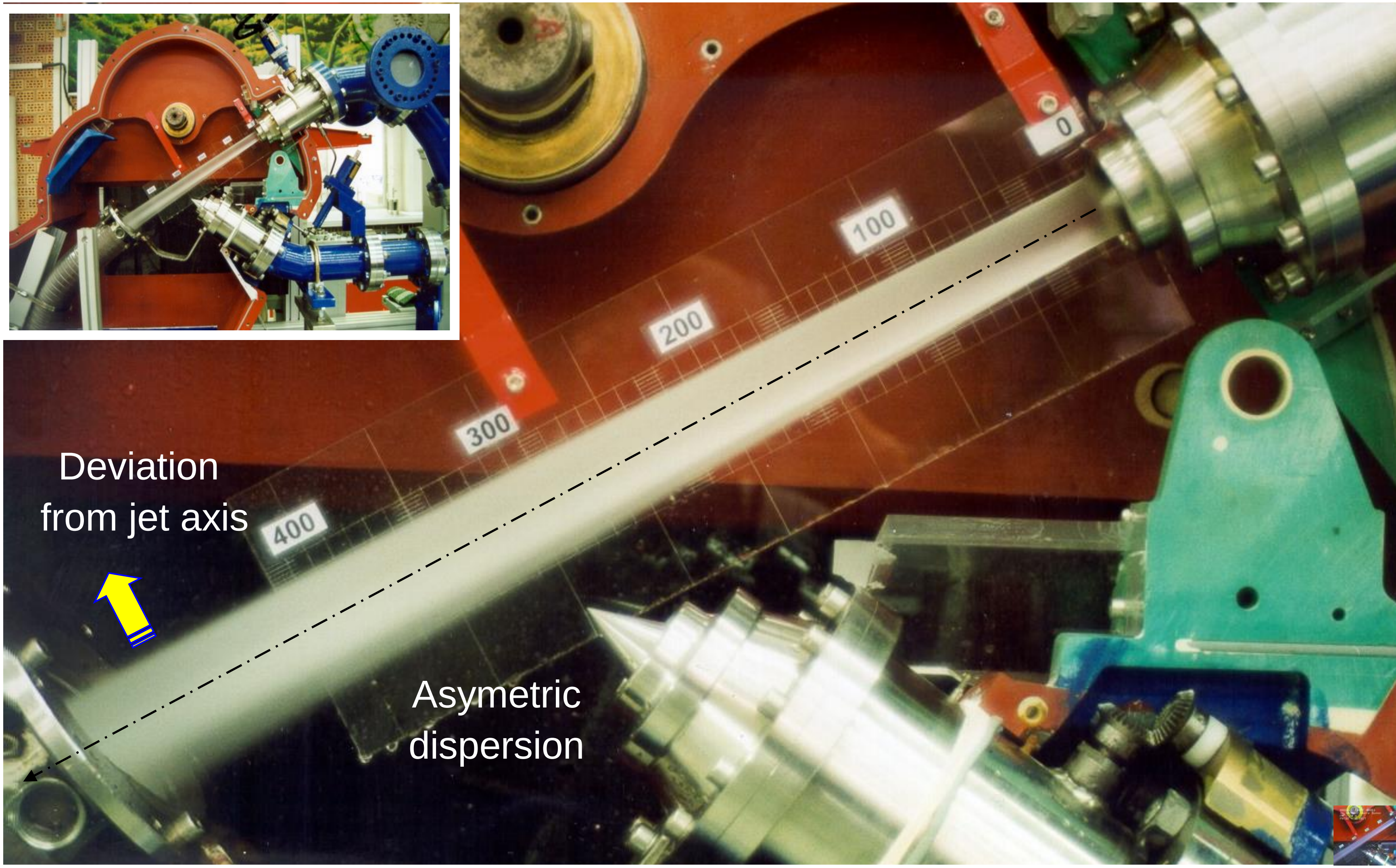




Experimental visualisation

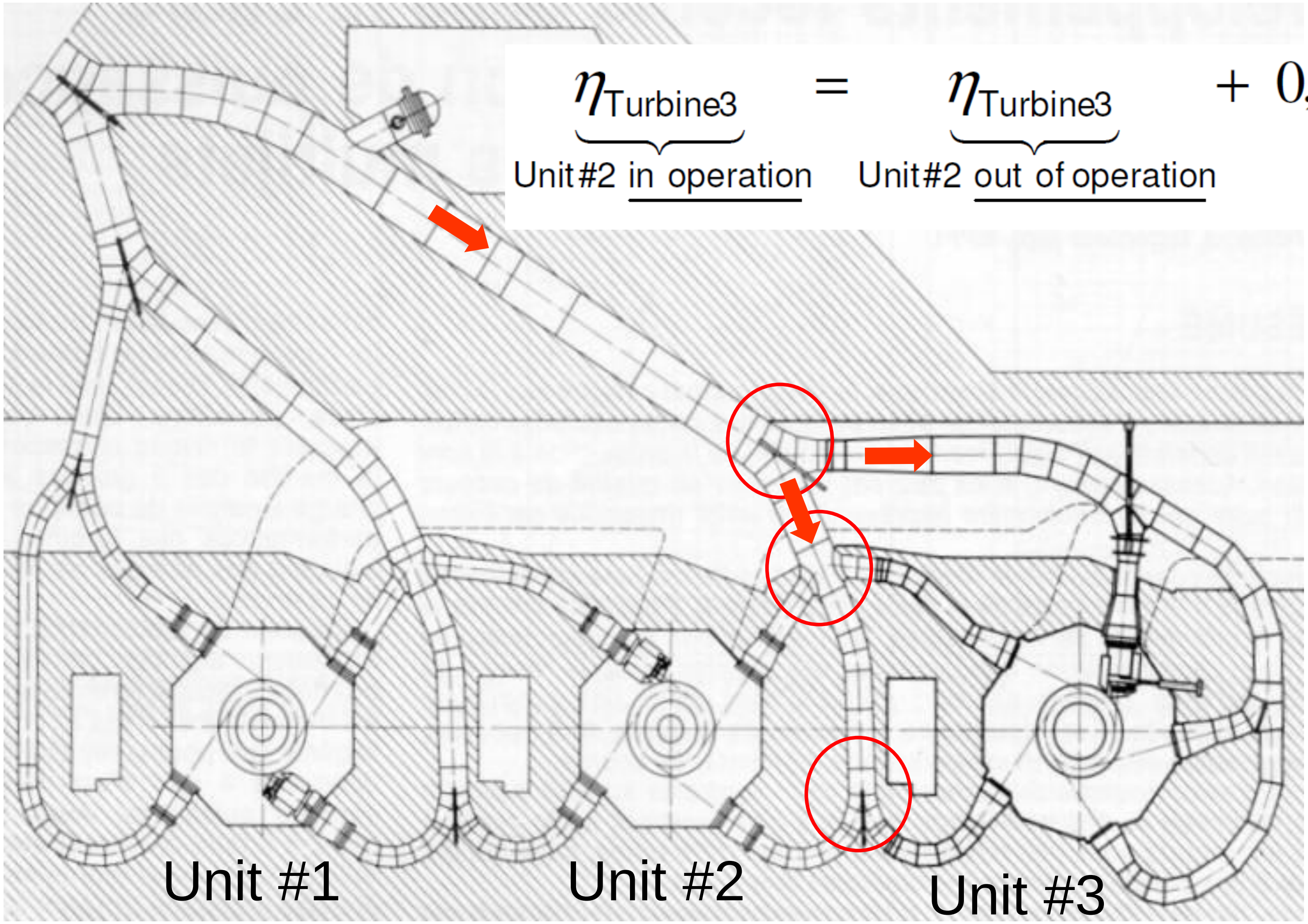
& jet shape measurement

Experimental jet analysis

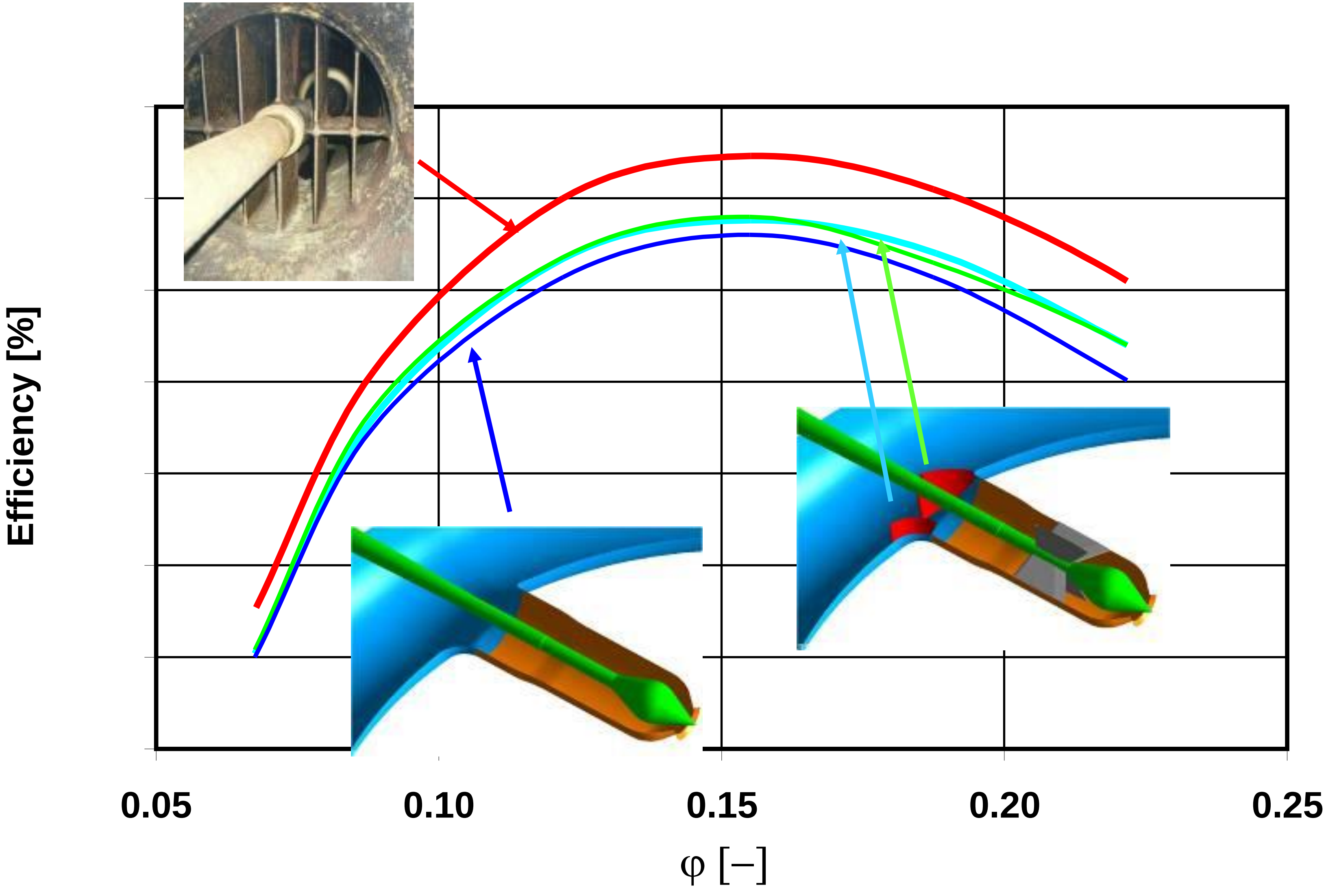


Influence on performances

$$\underbrace{\eta_{\text{Turbine3}}}_{\text{Unit\#2 in operation}} = \underbrace{\eta_{\text{Turbine3}}}_{\text{Unit\#2 out of operation}} + 0{,}5\%$$

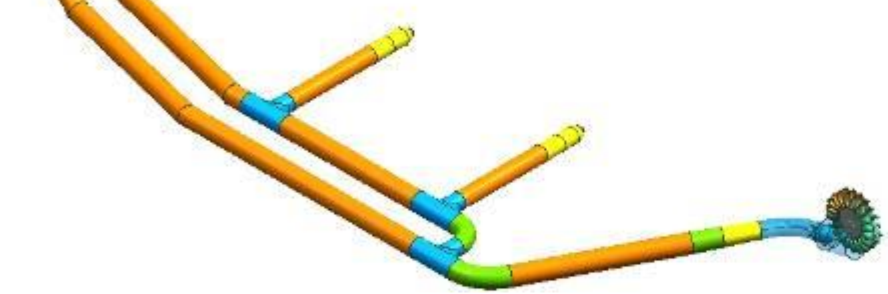


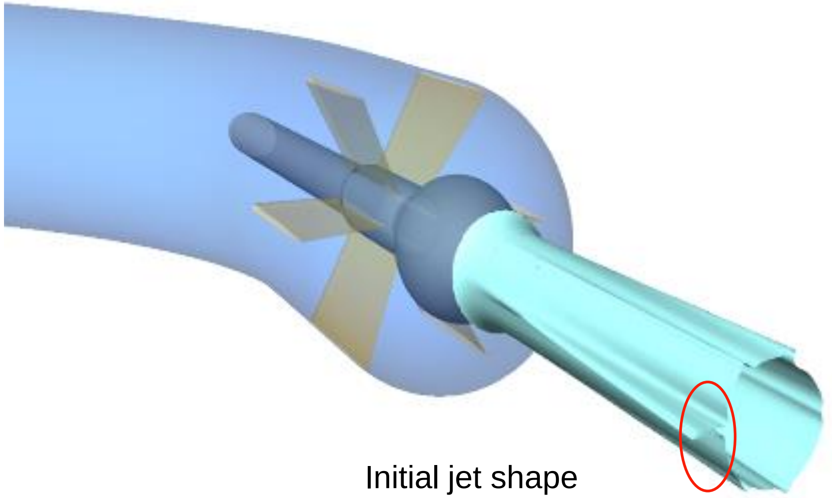
Influence of jet secondary structures



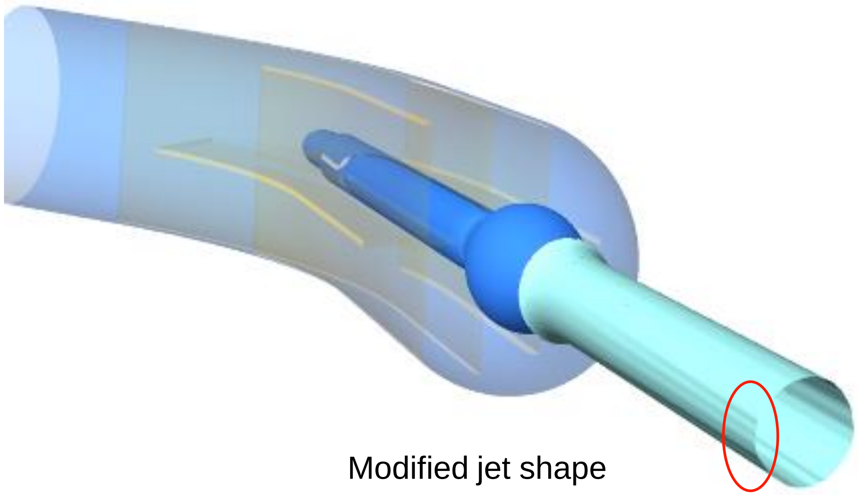
Influence on damages

- Asymmetric damages on buckets
- Noisy “turbine”
  - ➢ Added inserts to control the flow

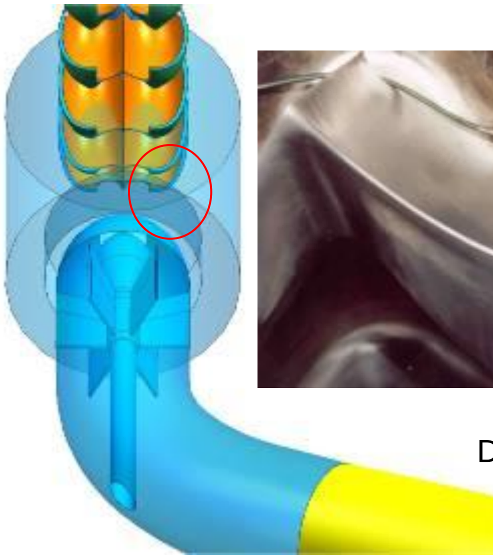




Initial jet shape

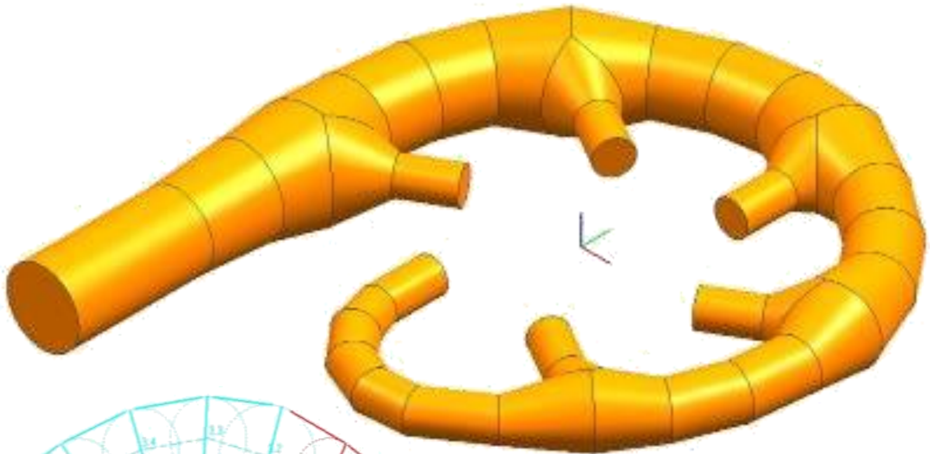


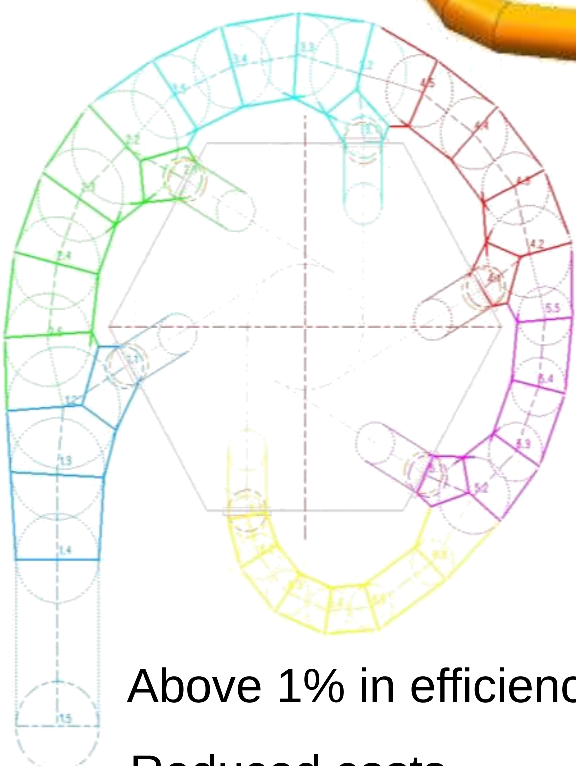
Modified jet shape

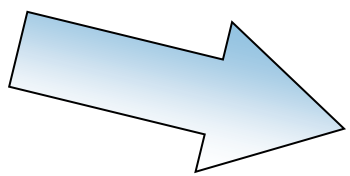


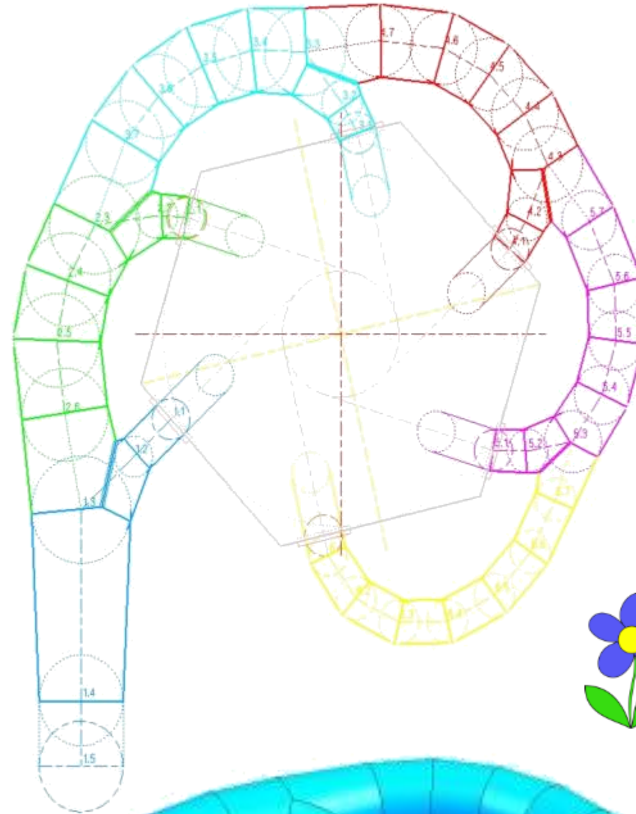
Damages on buckets

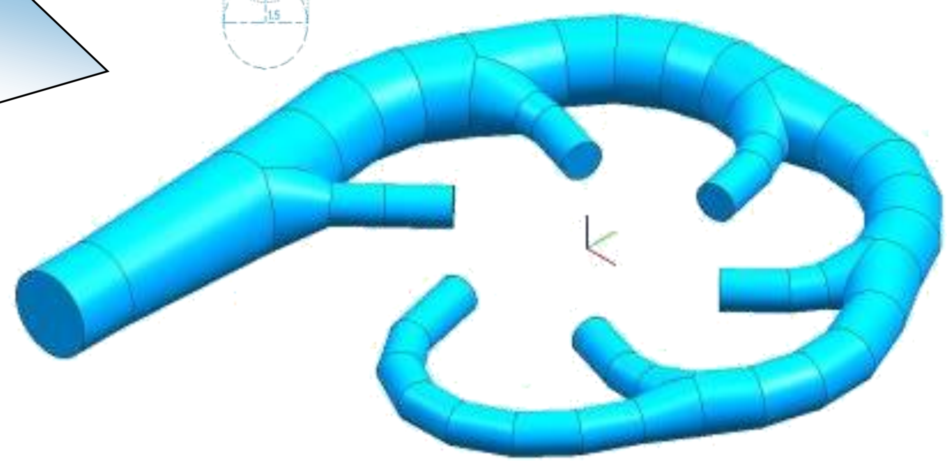
Distributor design







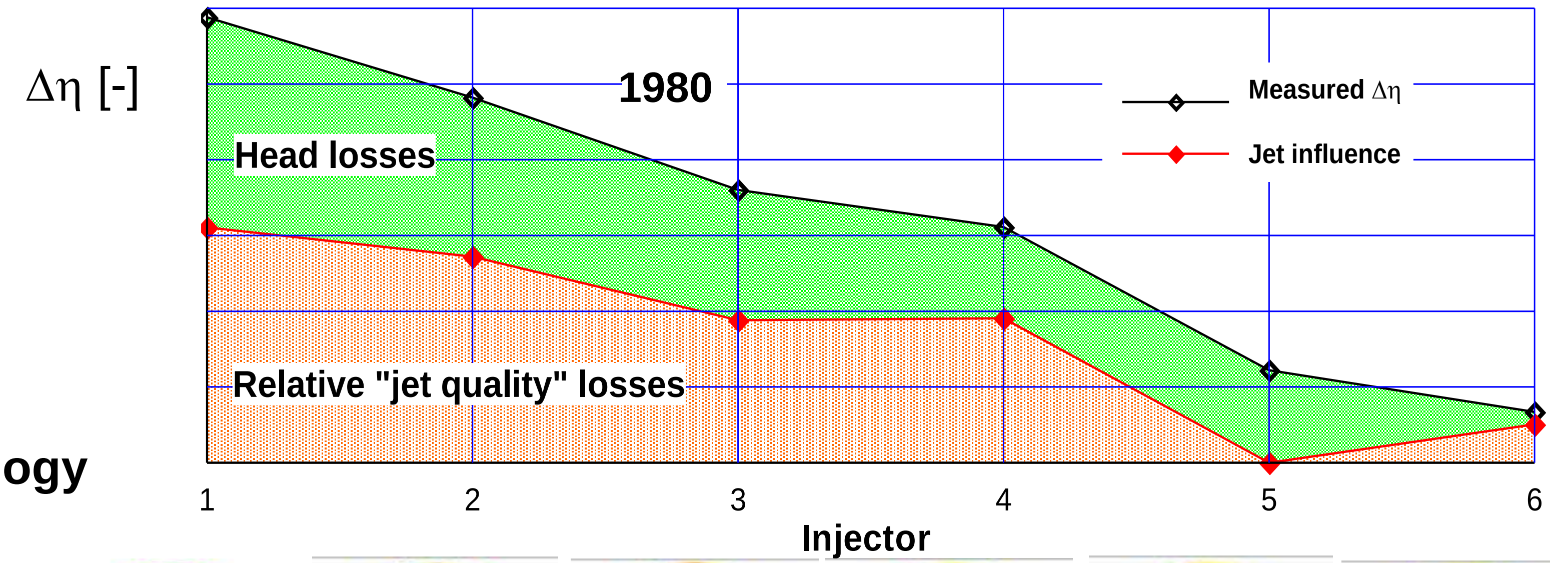




Above 1% in efficiency gained between these two generations

Reduced costs

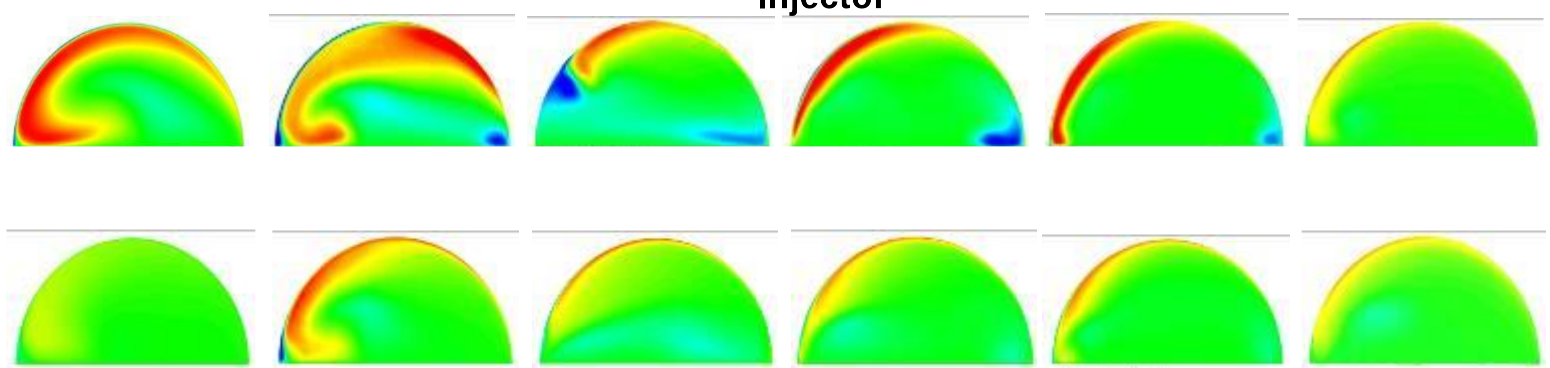
Influence of flow on performances



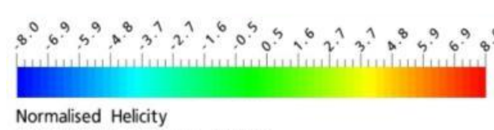
Flow topology

1980

2005



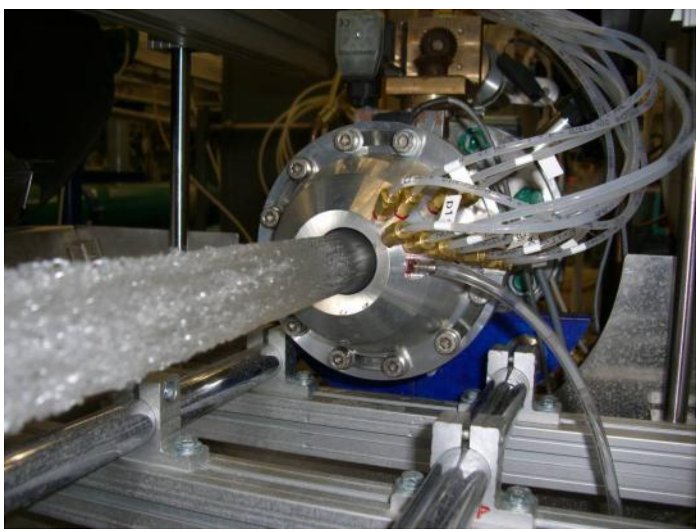
Secondary flow intensity

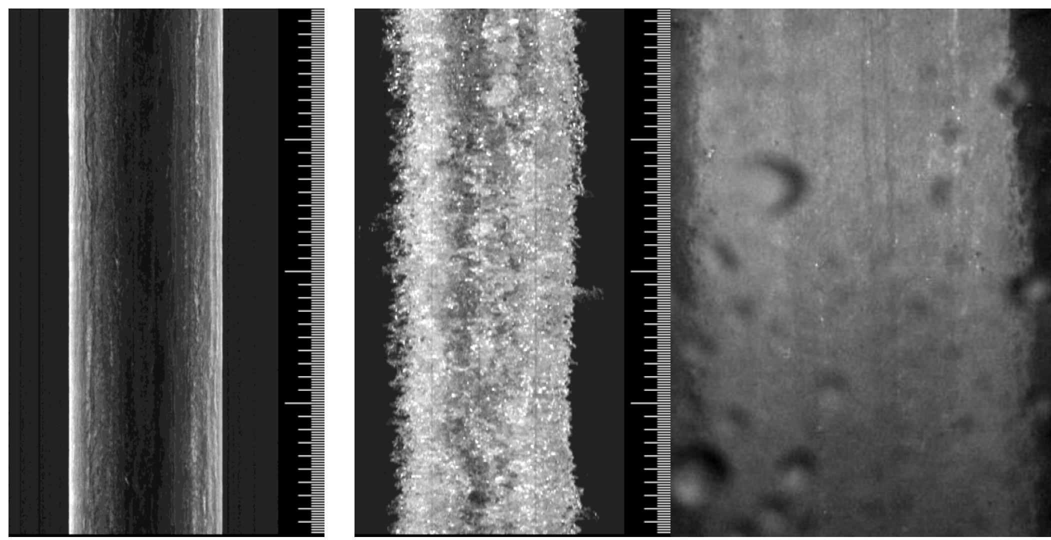


Head influence on jet

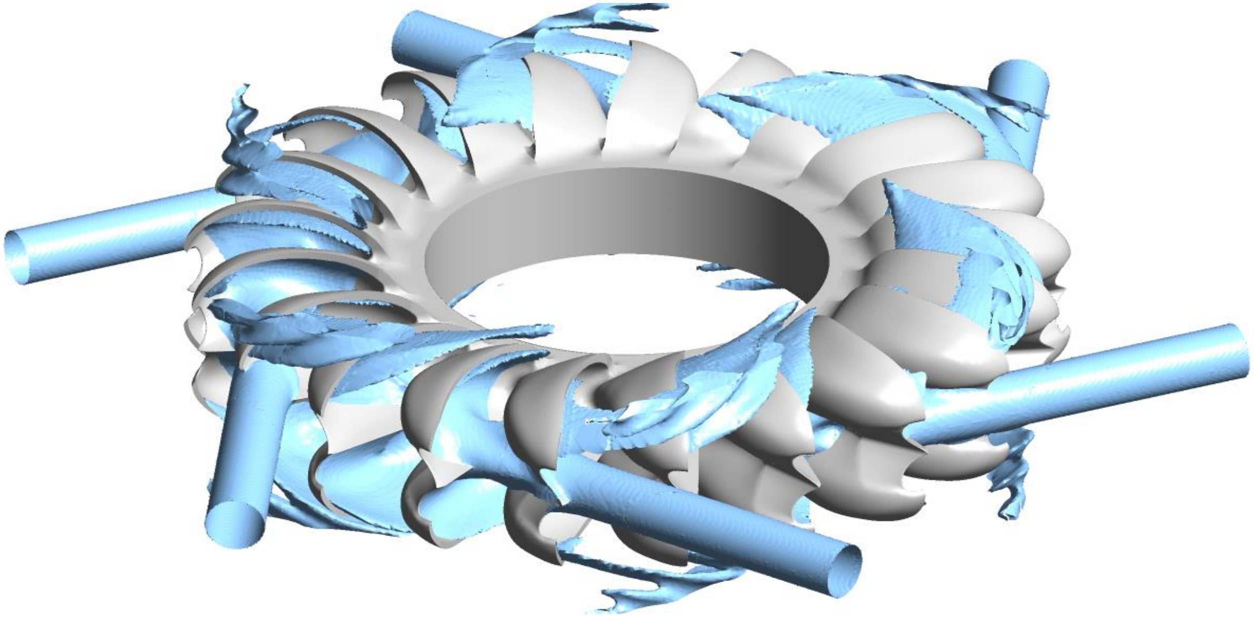
- Nozzle discharge & jet patterns vary with head
  - ✓ Static & dynamic analysis of the jet
  - ✓ Dimensions, structures, turbulence
    - ➢ Prediction of dispersion
    - ➢ Performances

Head ↗





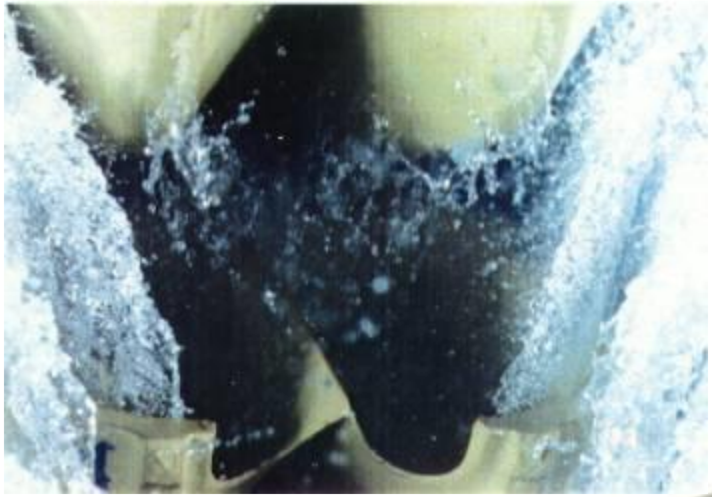
Runner



Jet flow into a bucket

- Periodic flow
- Simultaneous operation of many buckets
- Evolution of the bucket position into the jet
- Each flow stream line works different
- Stochastic characteristic of the flow

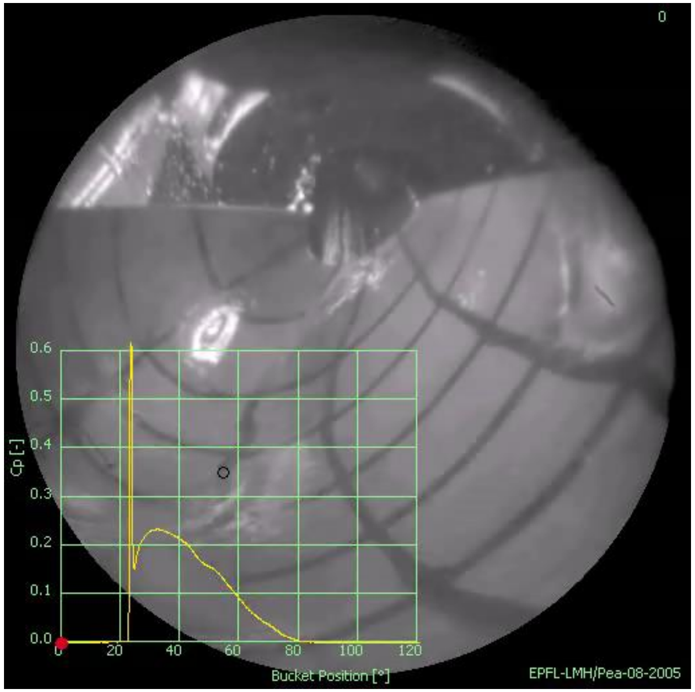
Flow observation in buckets

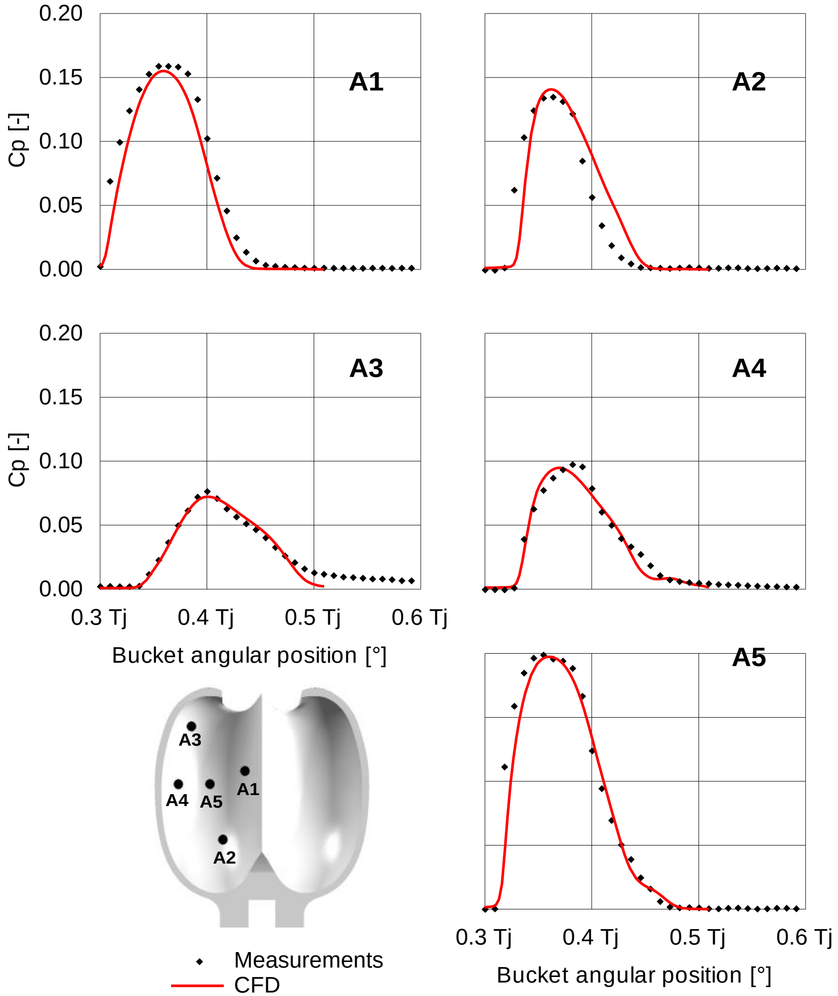


Pressure measurement

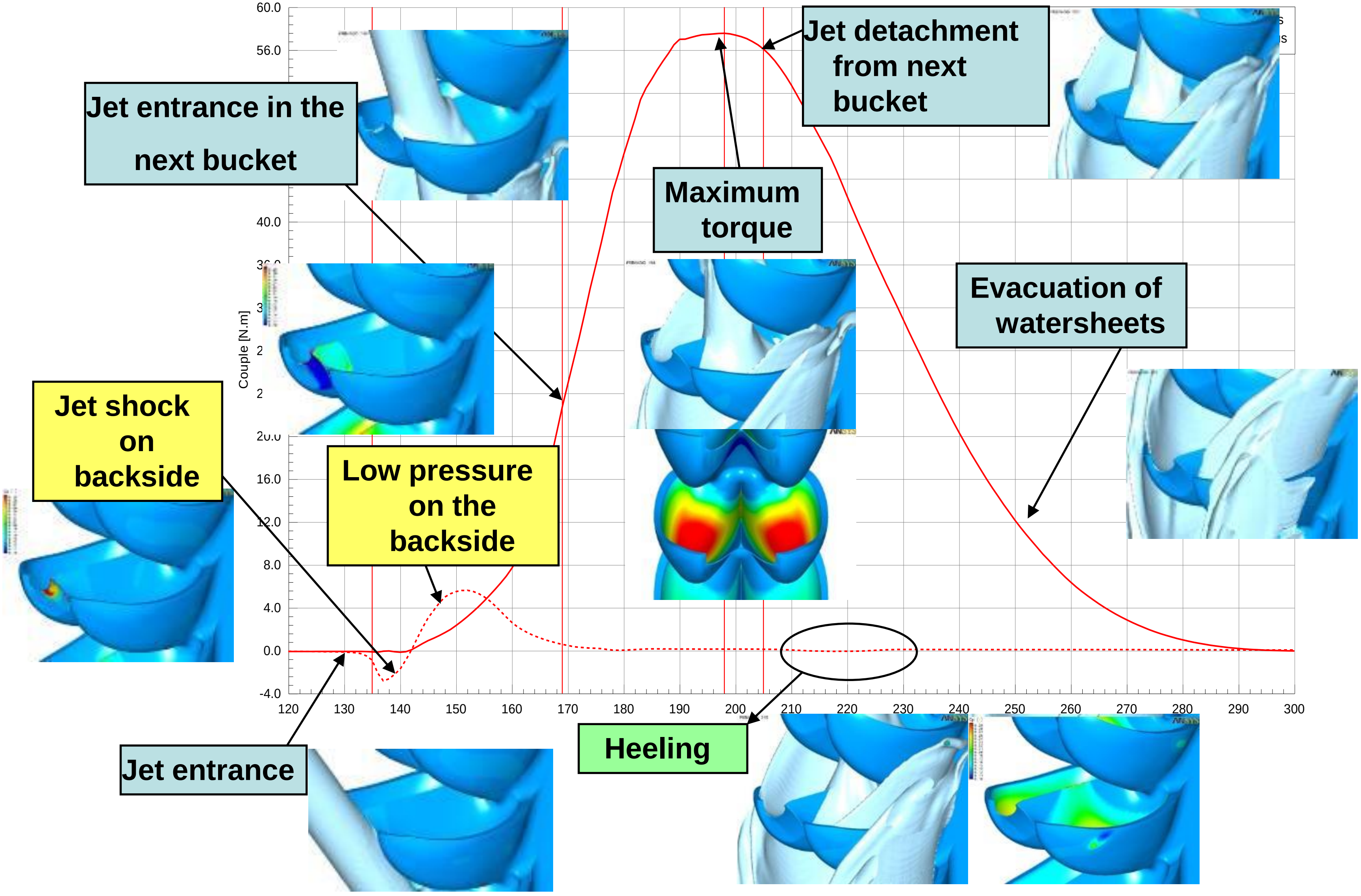
Runner design is based on

- Theoretical analysis
- Experimental tests at model scale,
- Prototype return of experience
- CFD

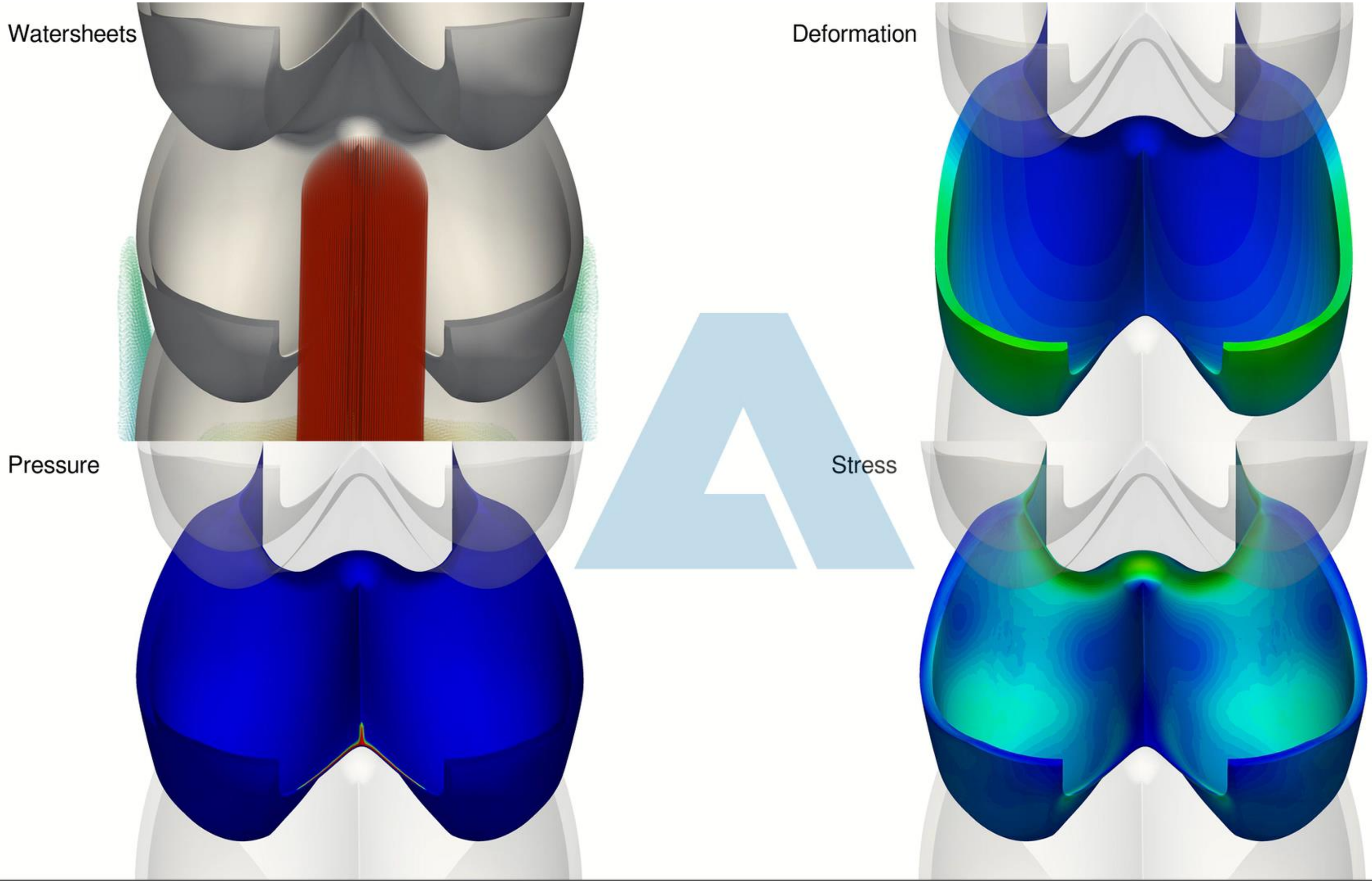




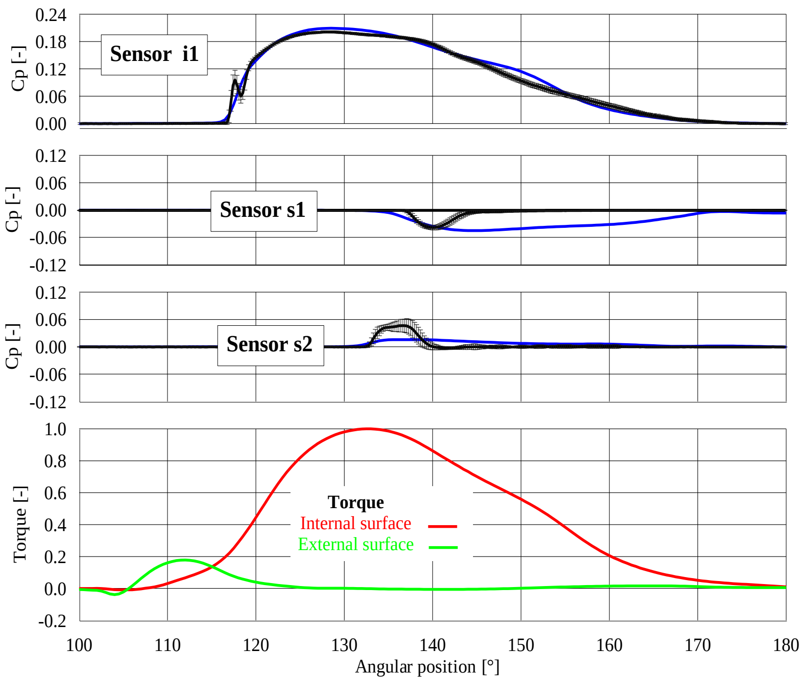
Loading cycle in a bucket

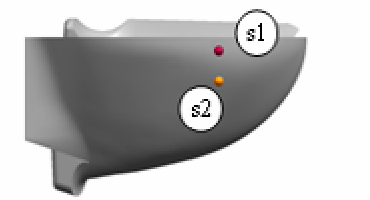


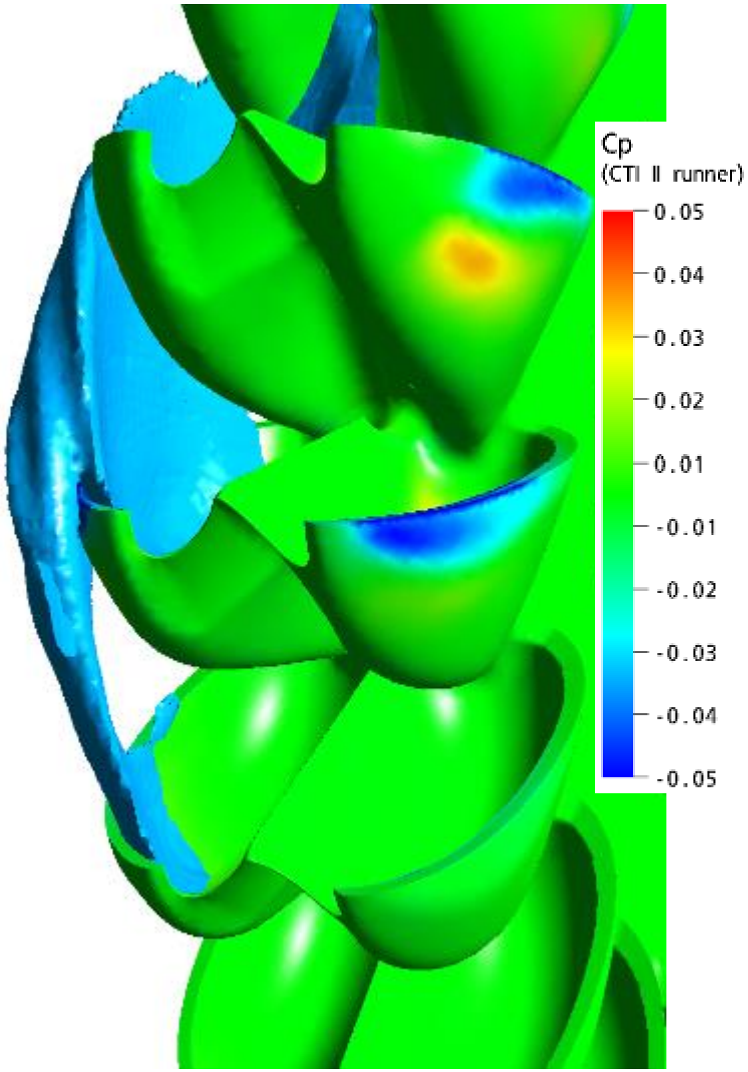
Flow in buckets



Experimental heeling (forced)



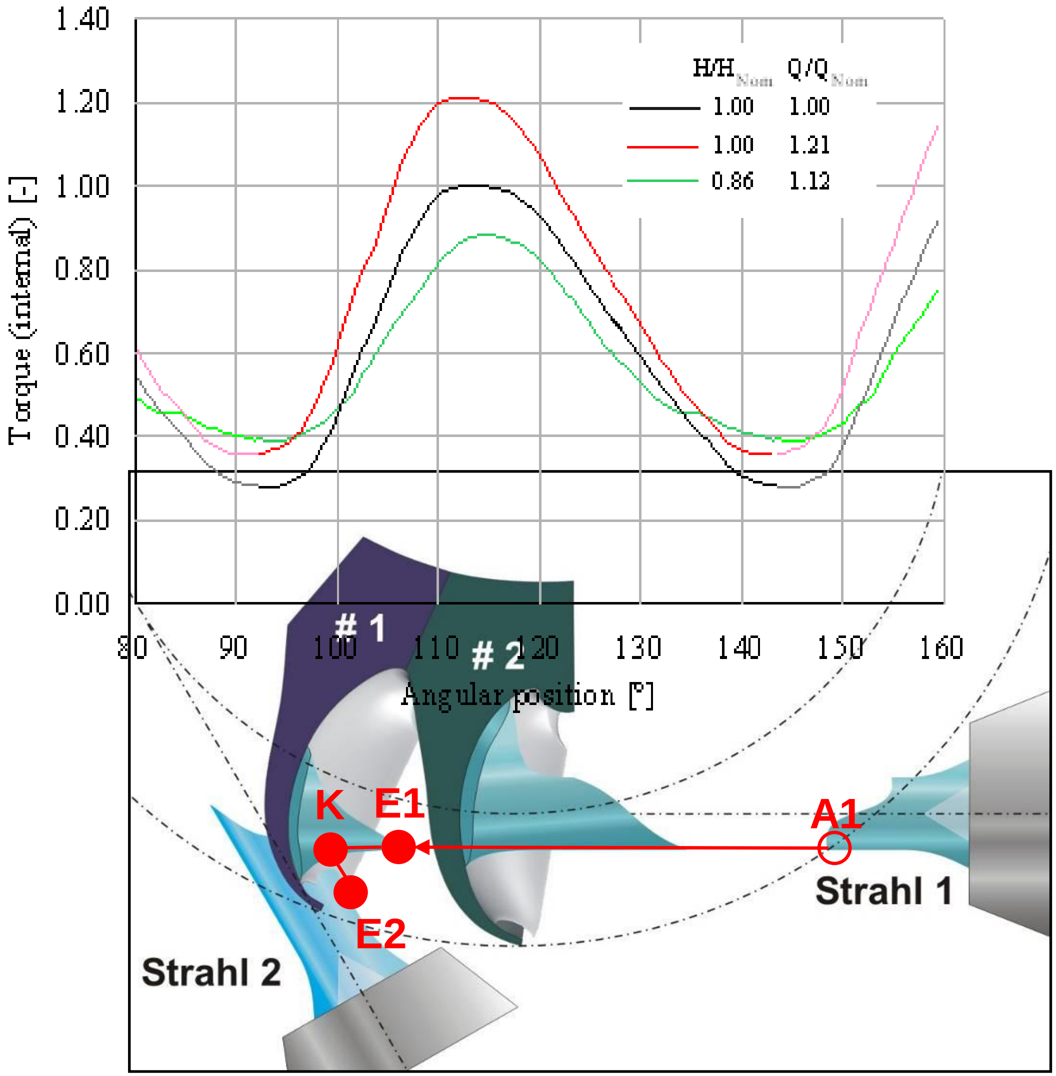


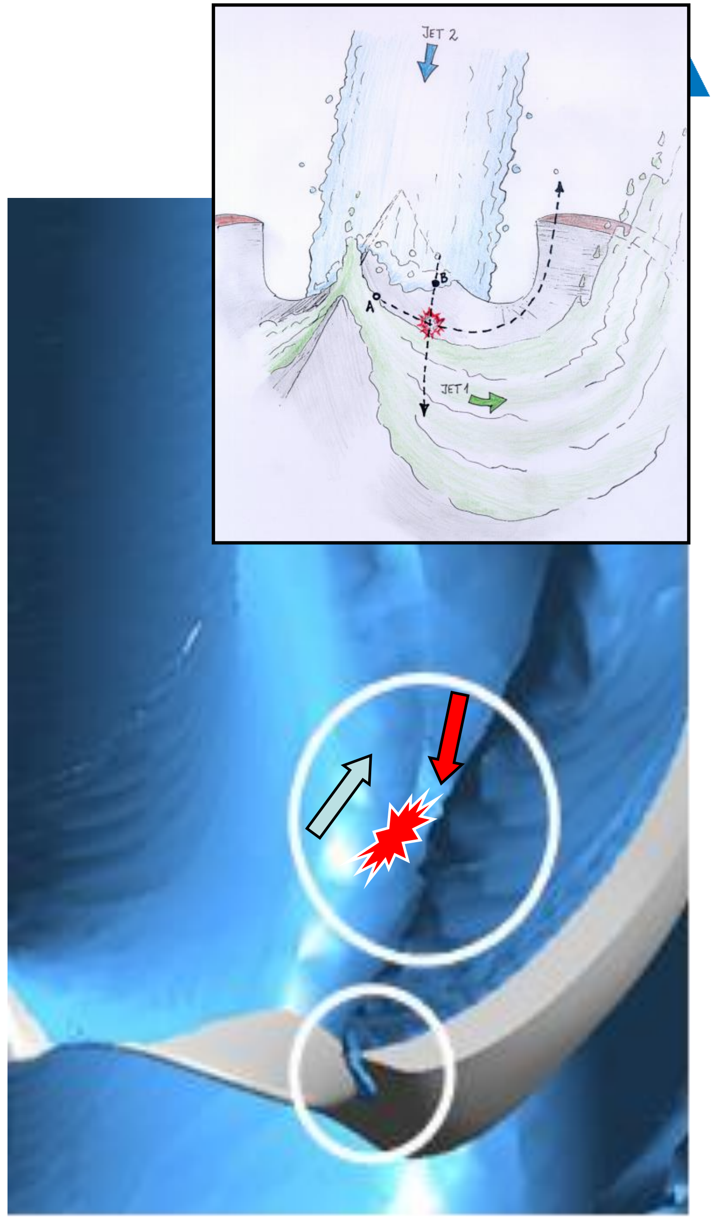


Contact between water sheet and bucket surface

Multi jet operation

Calculation for 3 different discharges





“Interference”

Cinematic study "Overlapping"

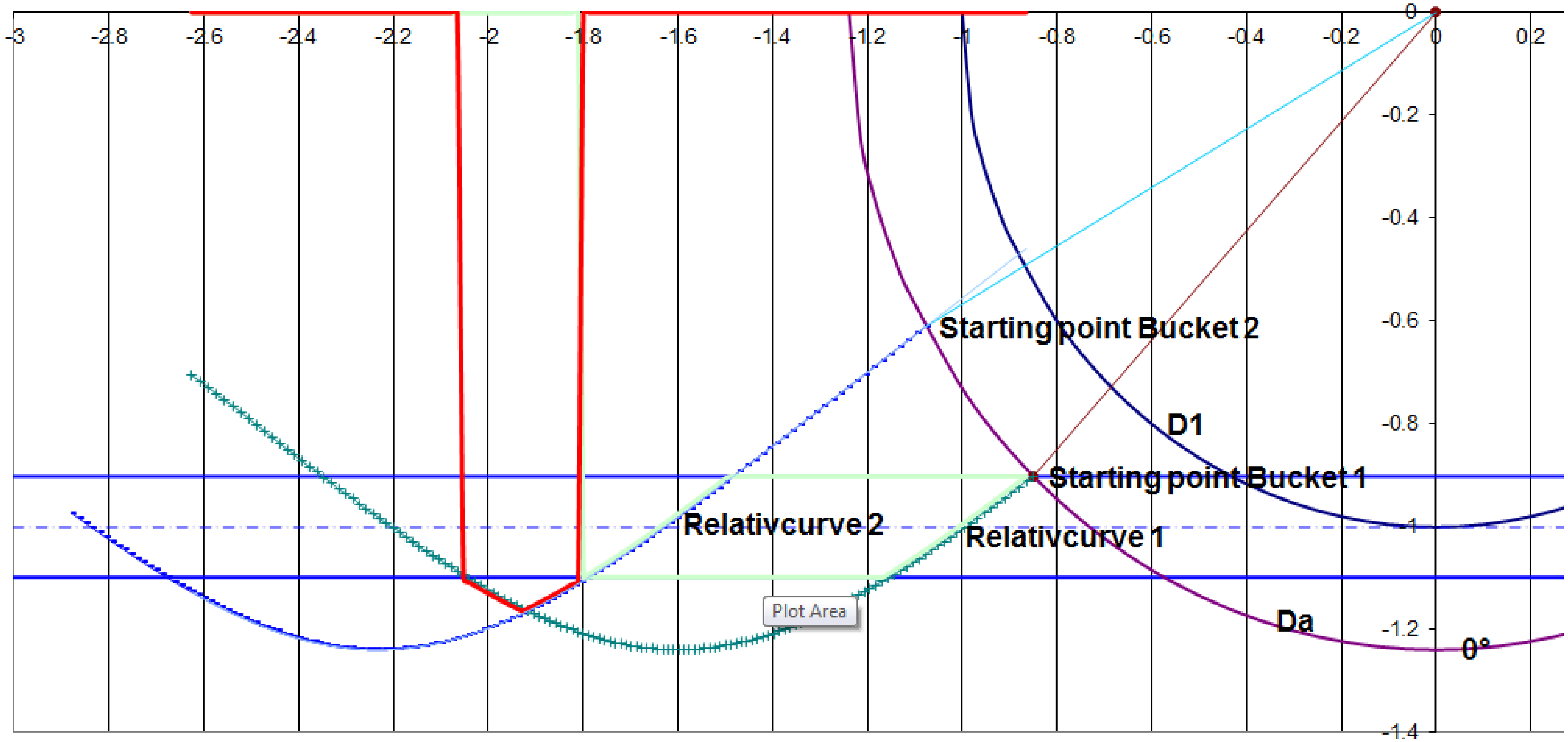
$$\vec{C} = \vec{U} + \vec{W}$$

$$\vec{C}\Delta t = \vec{U}\Delta t + \vec{W}\Delta t$$

$$\vec{\Delta}_{Lc} = \vec{\Delta}_{Lu} + \vec{\Delta}_{Lw}$$

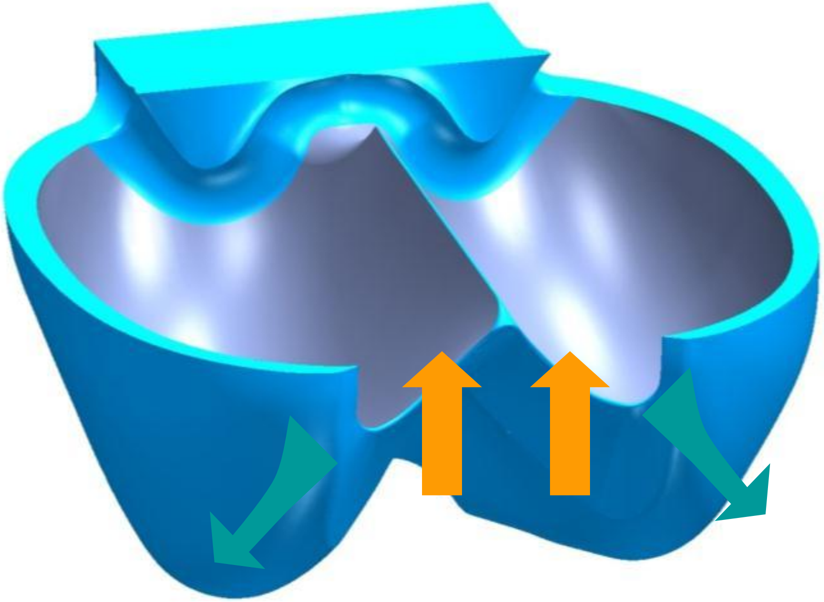
Overlap

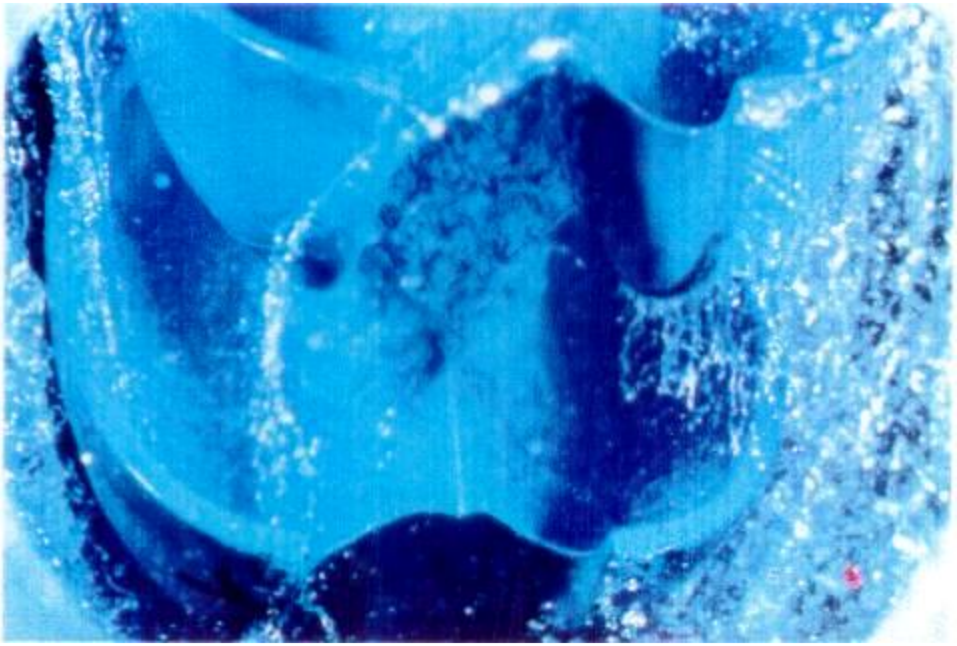
minimum overlap required to ensure water of jet does not "slip" through buckets



Inlet "Heeling" phenomena:

At cut out back surfaces



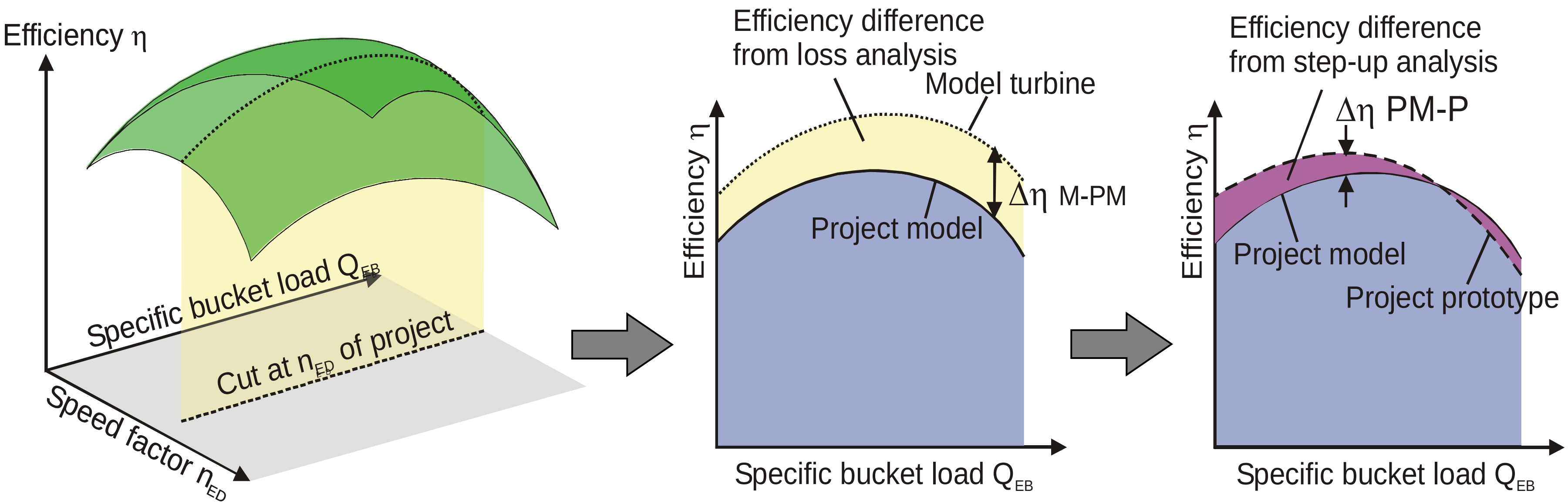


From model to prototype

Loss Analysis with a defined model

Three-step procedure

Efficiency hill chart of a model turbine	Efficiency of project-model	Efficiency of project



$$\Delta\eta = k_1 + k_2 \cdot n_{ED} + k_3 \cdot Q_{EB} + k_4 \cdot n_{ED}^2 + k_5 \cdot Q_{EB}^2 + k_6 \cdot n_{ED} \cdot Q_{EB}$$

Some losses vary strongly with n_{ED} or Q_{EB} → loss equations that account for varying Q_{EB} & n_{ED}
e.g. interference losses in 6-jet turbines

Model to prototype

Comparison between tests results (model or prototype) implies the respect of similarities:

- Geometric
- Cinematic (velocity triangles, same (φ_{B2}, ψ_1) points)
- Dynamic (Froude, Reynolds & Weber numbers)

$$\begin{cases} \mathrm{Re} = \dfrac{C \cdot L}{\upsilon} = \dfrac{1}{\upsilon} \cdot B_2 \cdot \sqrt{H} \\ Fr = \dfrac{C}{\sqrt{gL}} = \dfrac{1}{\sqrt{g}} \cdot \sqrt{\dfrac{H}{B_2}} \\ We = \dfrac{C\sqrt{\rho L}}{\sqrt{\gamma}} = \sqrt{\dfrac{\rho}{\gamma}} \cdot \sqrt{H} \cdot \sqrt{B_2} \end{cases}$$

$$\begin{cases} \mathrm{Re}_M = \mathrm{Re}_P \Rightarrow \dfrac{B_2^M}{B_2^P} = \sqrt{\dfrac{H_P}{H_M}} \\ Fr_M = Fr_P \Rightarrow \dfrac{B_2^M}{B_2^P} = \dfrac{H_M}{H_P} \\ We_M = We_P \Rightarrow \dfrac{B_2^M}{B_2^P} = \dfrac{H_P}{H_M} \end{cases}$$

*assuming equal gravity and water characteristics

Step-up formula for Pelton turbines

$$\Delta\eta = \eta_{\text{proto}} - \eta_{\text{model}} = 5.7\left(1 - C_{Fr}^{0.3}\right)\left(\frac{\varphi_{B_2}}{\sqrt{\psi_1}}\right)^2 + 1.95\cdot 10^{-6}\left(C_{We} - 1\right)\left(\frac{\sqrt{\psi_1}}{\varphi_{B_2}}\right)^2 + 10^{-8}\left(C_{\text{Re}} - 1\right)^2\left(\frac{\sqrt{\psi_1}}{\varphi_{B_2}}\right)^2$$

IEC 60193, appendix K

Froude

$$C_{Fr} = \frac{Fr_P}{Fr_M} = \sqrt{\frac{B_{2M}}{B_{2P}}}\cdot\sqrt{\frac{H_P}{H_M}}$$

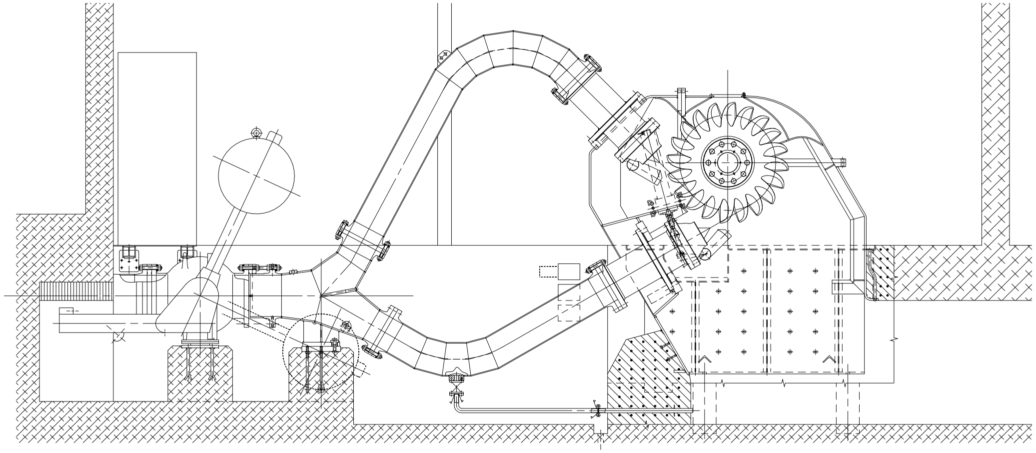
Weber

$$C_{We} = \frac{We_P}{We_M} = \sqrt{\frac{B_{2P}}{B_{2M}}}\cdot\sqrt{\frac{H_P}{H_M}}\cdot\sqrt{\frac{g_P}{g_M}}\cdot\sqrt{\frac{\rho_P}{\rho_M}}\cdot\sqrt{\frac{\gamma_M}{\gamma_P}}$$

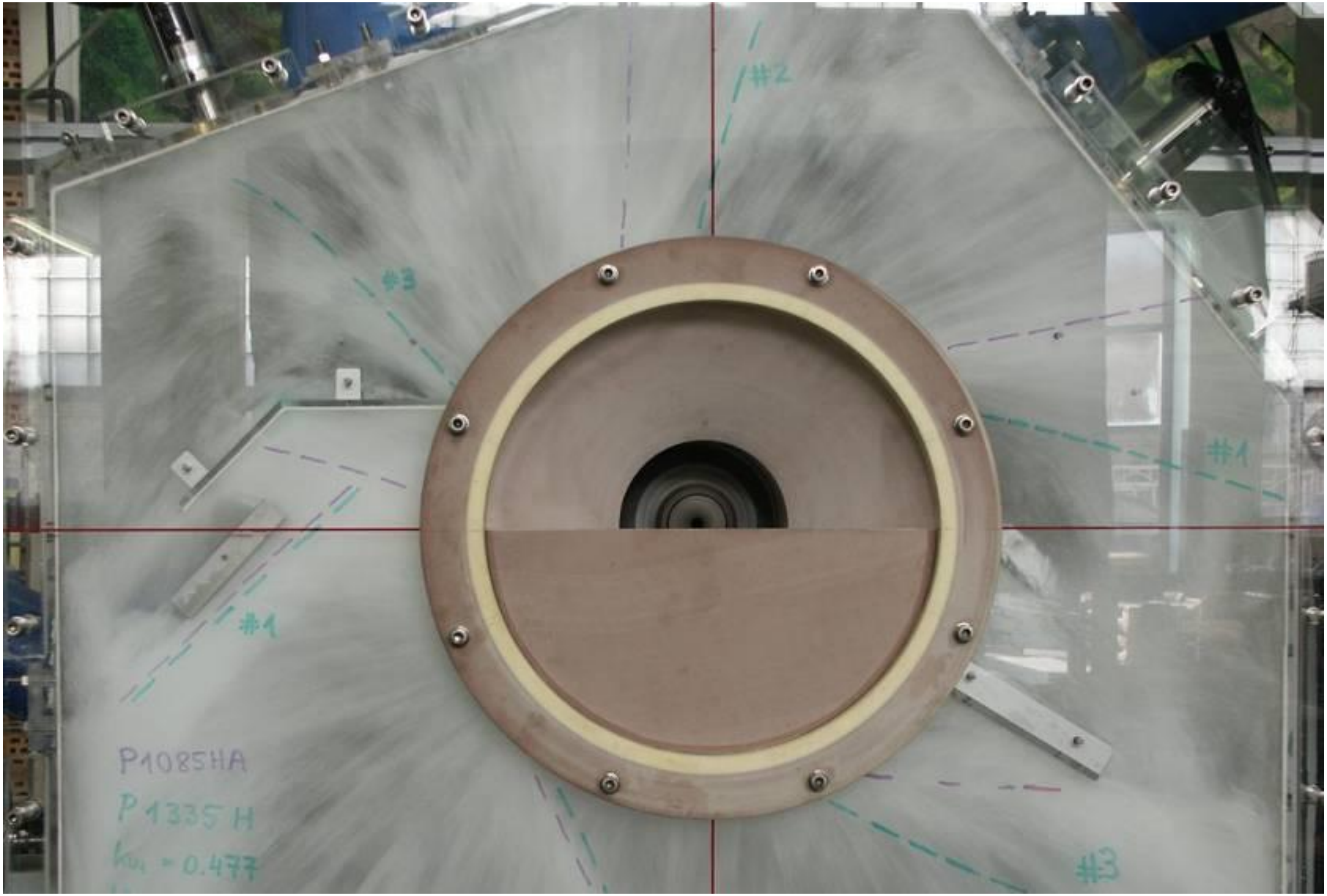
Reynolds

$$C_{Re} = \frac{\text{Re}_P}{\text{Re}_M}\left(\frac{B_{2P}}{B_{2M}}\right)\sqrt{\frac{H_P}{H_M}}\sqrt{\frac{g_P}{g_M}}\left(\frac{\upsilon_M}{\upsilon_P}\right)$$

Coupling of components

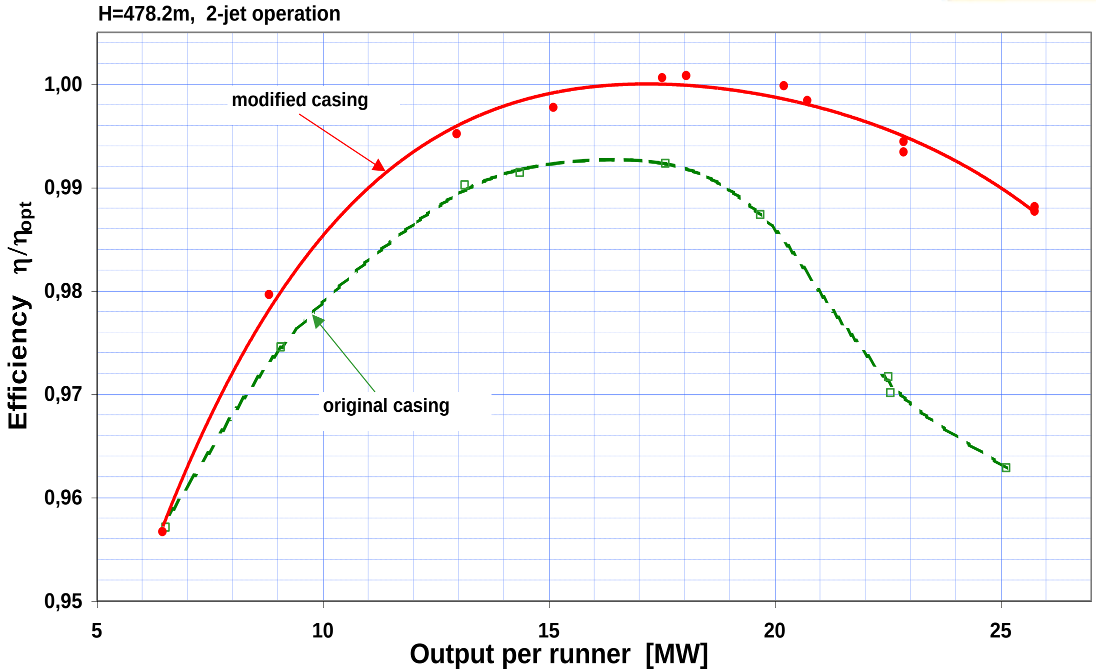


Horizontal casing flow



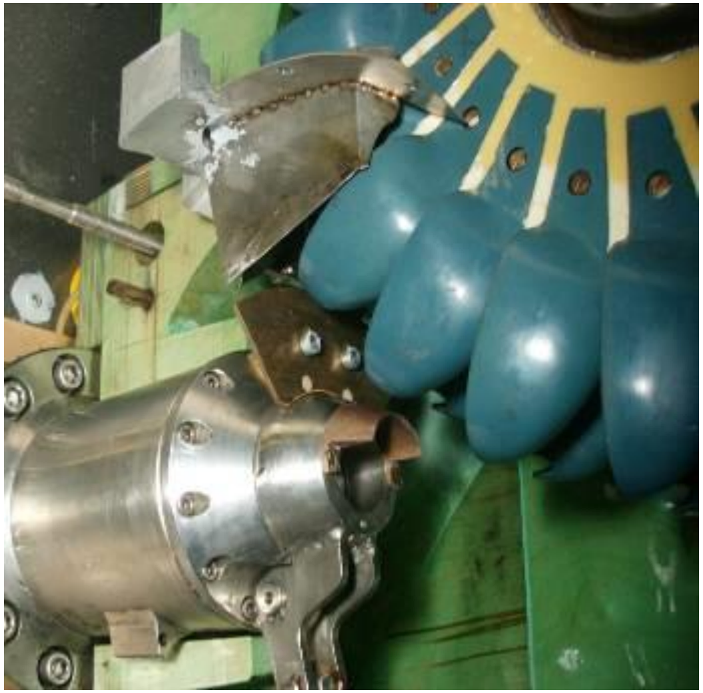
Casing modification

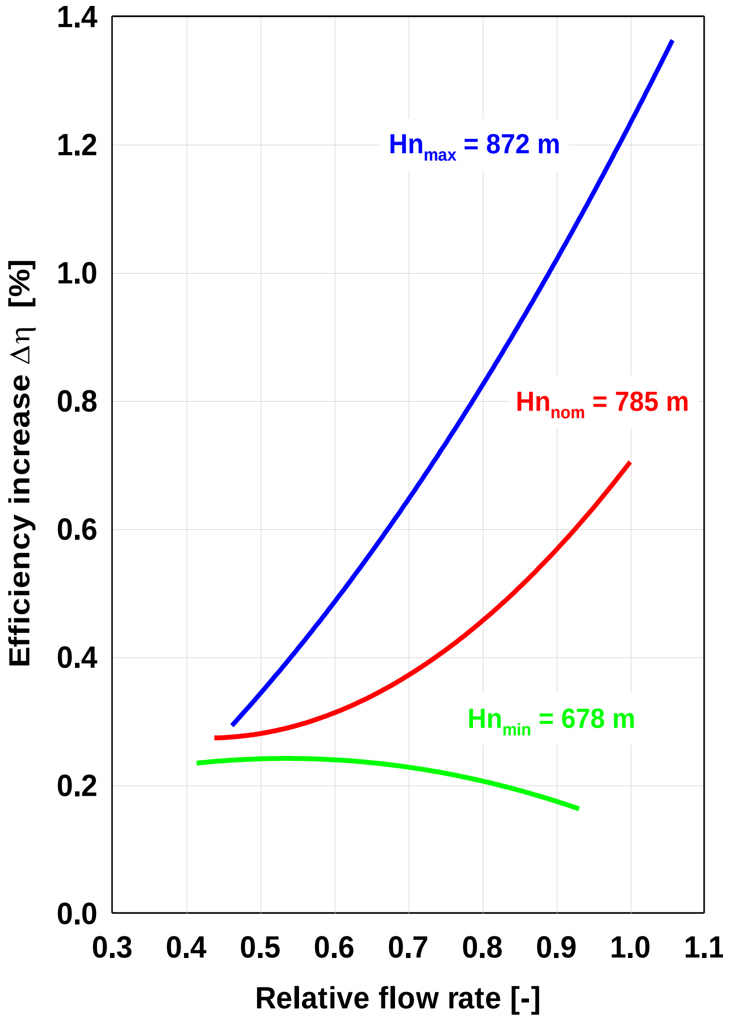
A new runner may have a different evacuation process, requiring casing adaptations to take full profit of modern designs.



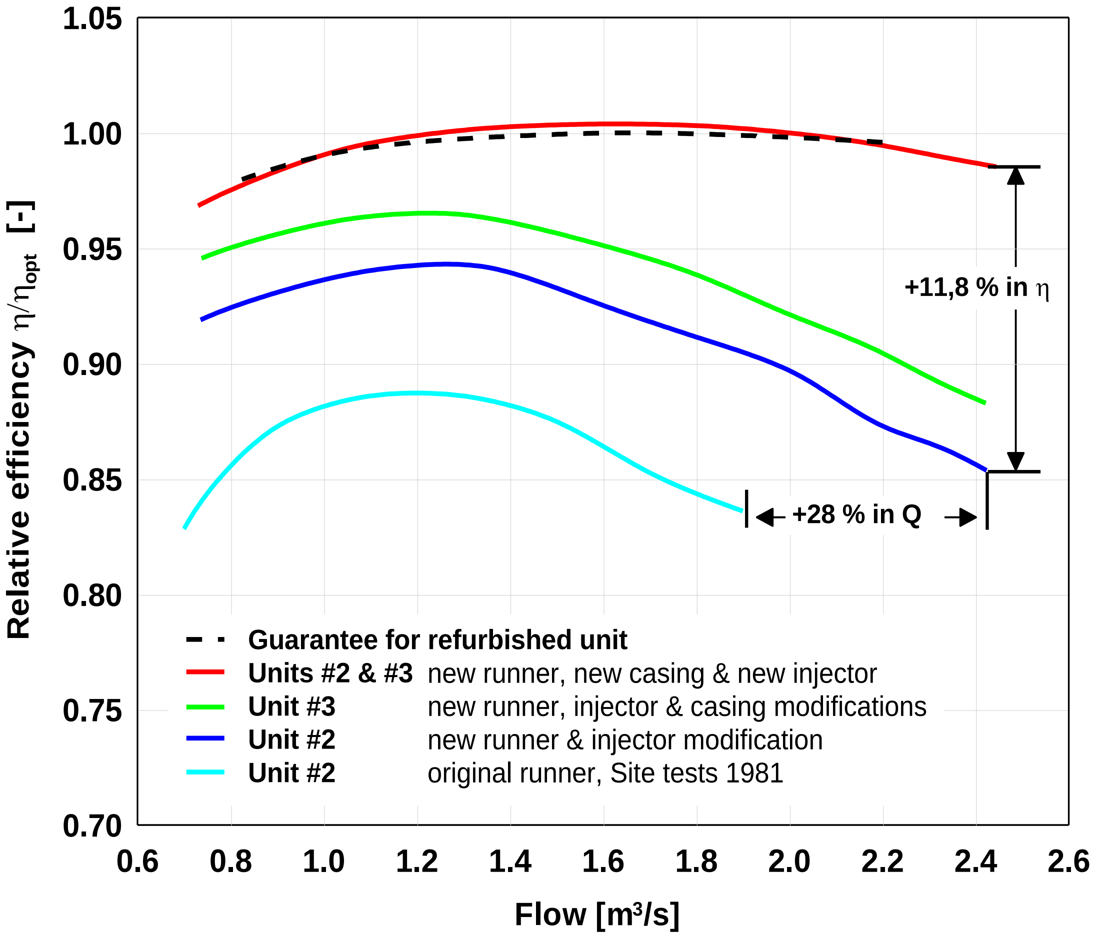
Modernization

Proposed casing modifications and corresponding efficiency increase



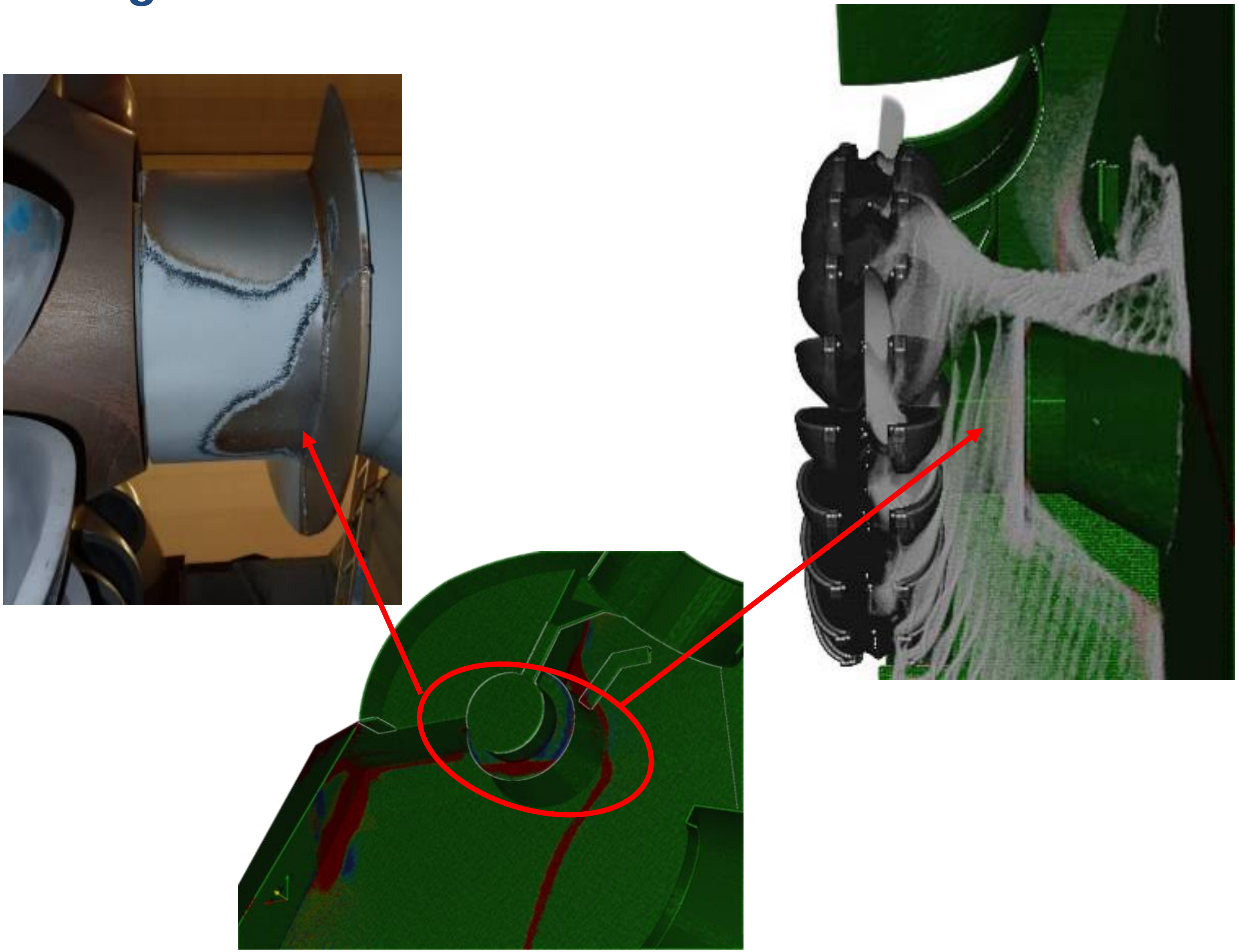


Modernization



Simulation of water sheets to optimize / develop casings

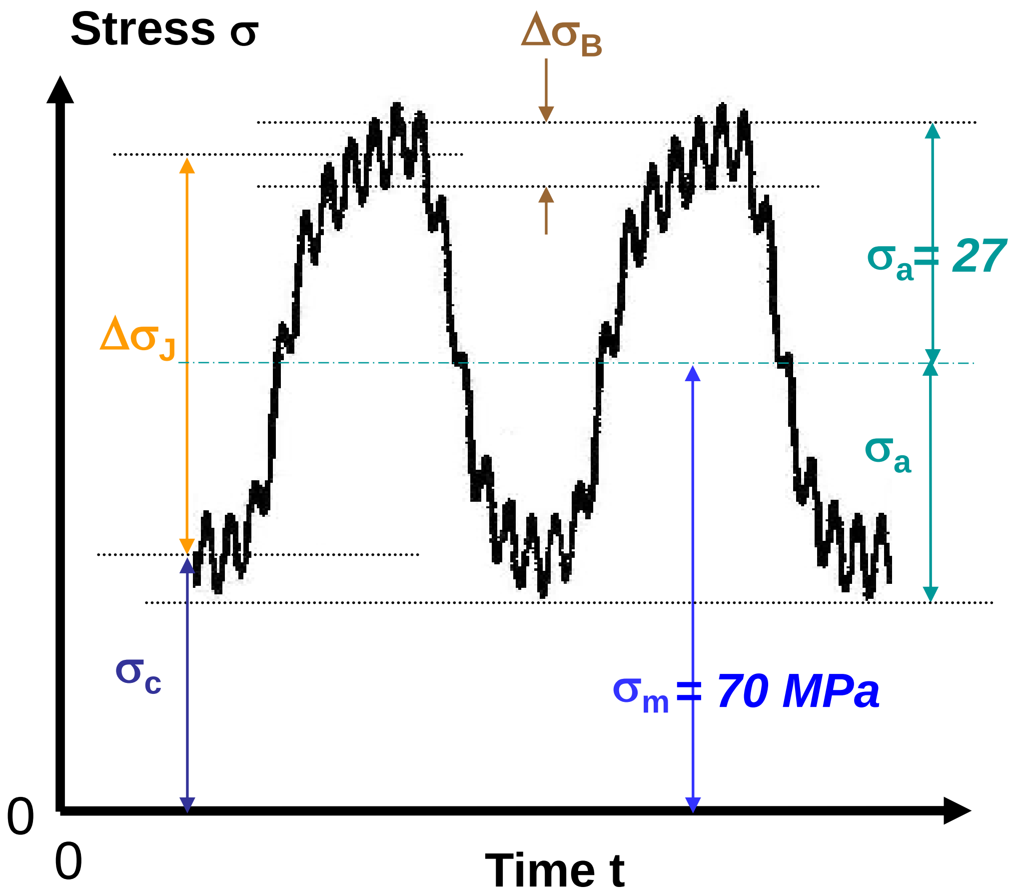
Casings



Mechanics

Forces acting in bucket root of a Pelton runner

Sellrain Silz runner measurement: 6 jets, 262 MW, head = 1233m



$\Delta\sigma_J$ = Stress due to jet action

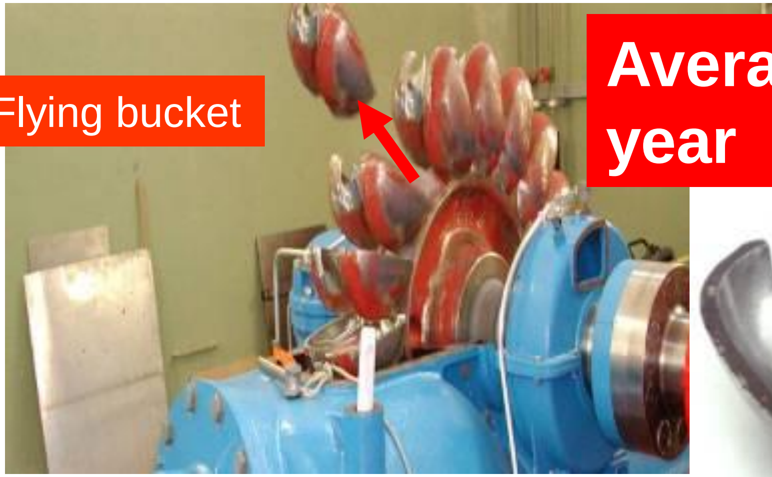
$\Delta\sigma_B$ = Stress due to bucket vibration (5 to 10 MPa)

σ_c = Centrifugal stress

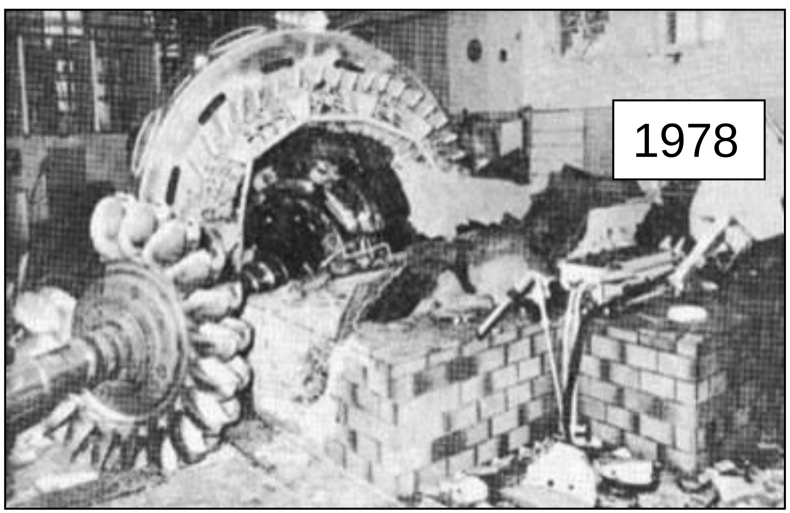
σ_a = Dynamic stress (<30 MPa for EDF, based on statistics) ⇒ **Life time**

σ_m = Mean stress

Cracks and bucket rupture on cast runners



Average 3-5 bucket ruptures per year



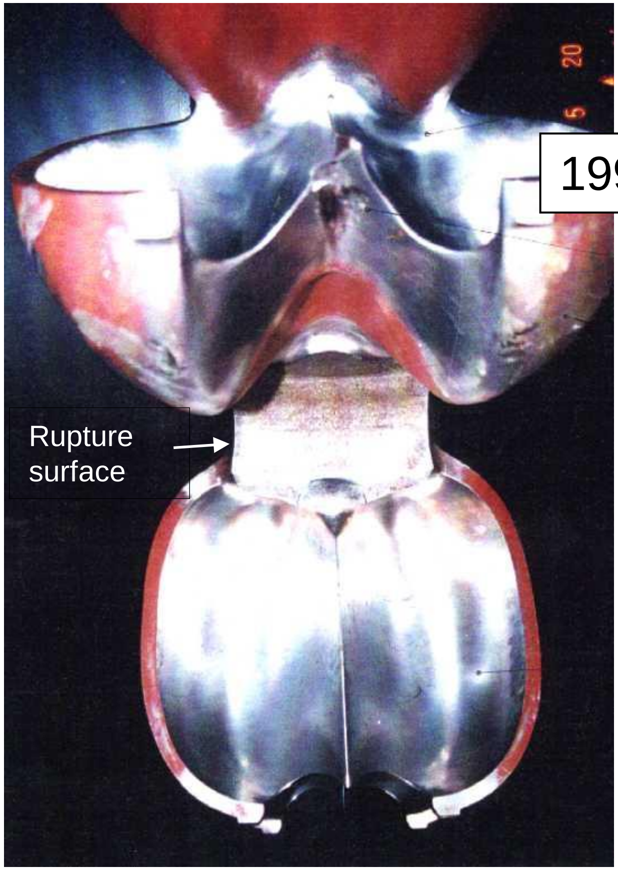
Main reason:

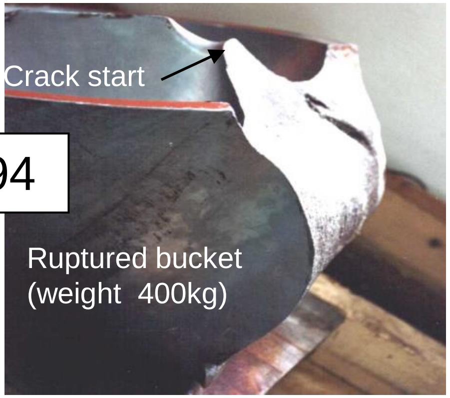
Cracks (which are closed to surface) not detected by UT or MT

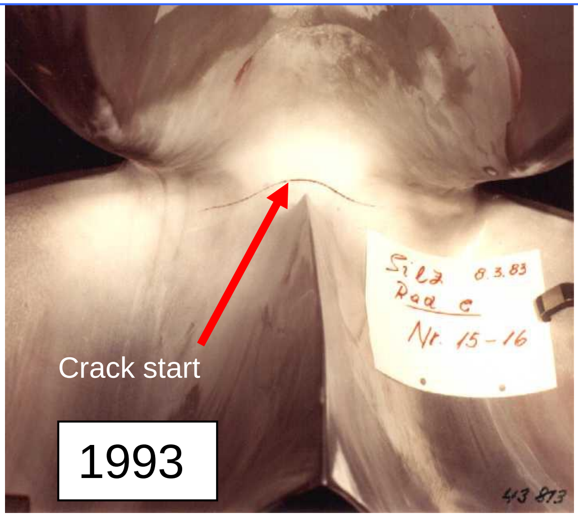
Cracks and bucket rupture on cast runners

Damage: 300 mm long and 100 mm deep crack in the root area of bucket No. 15 runner C after **2700 operation hours** on 08.03.1983

Reasons: 2-3 mm large slag inclusion (Casting defect)

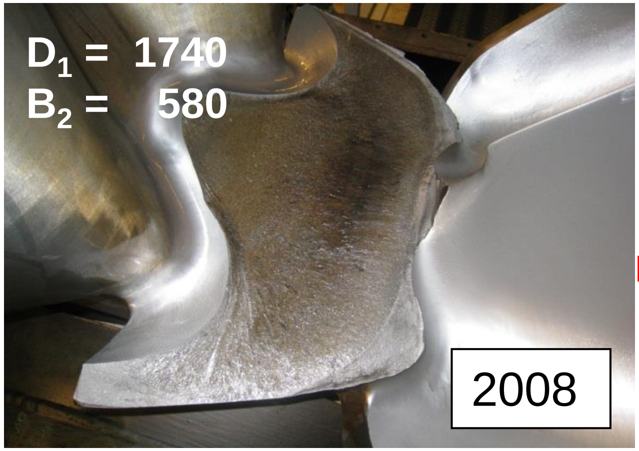






Operation hours: **4854**

Load cycles: 6.55×10^8



H = 474 m

P = 21.4 MW

Buckets rupture after 24‘000 operation hours

Material properties

Fatigue behavior, tests from LDF Darmstadt

Test conditions:

Type of material
Type of test pieces
Environment
Stress conditions

Results:

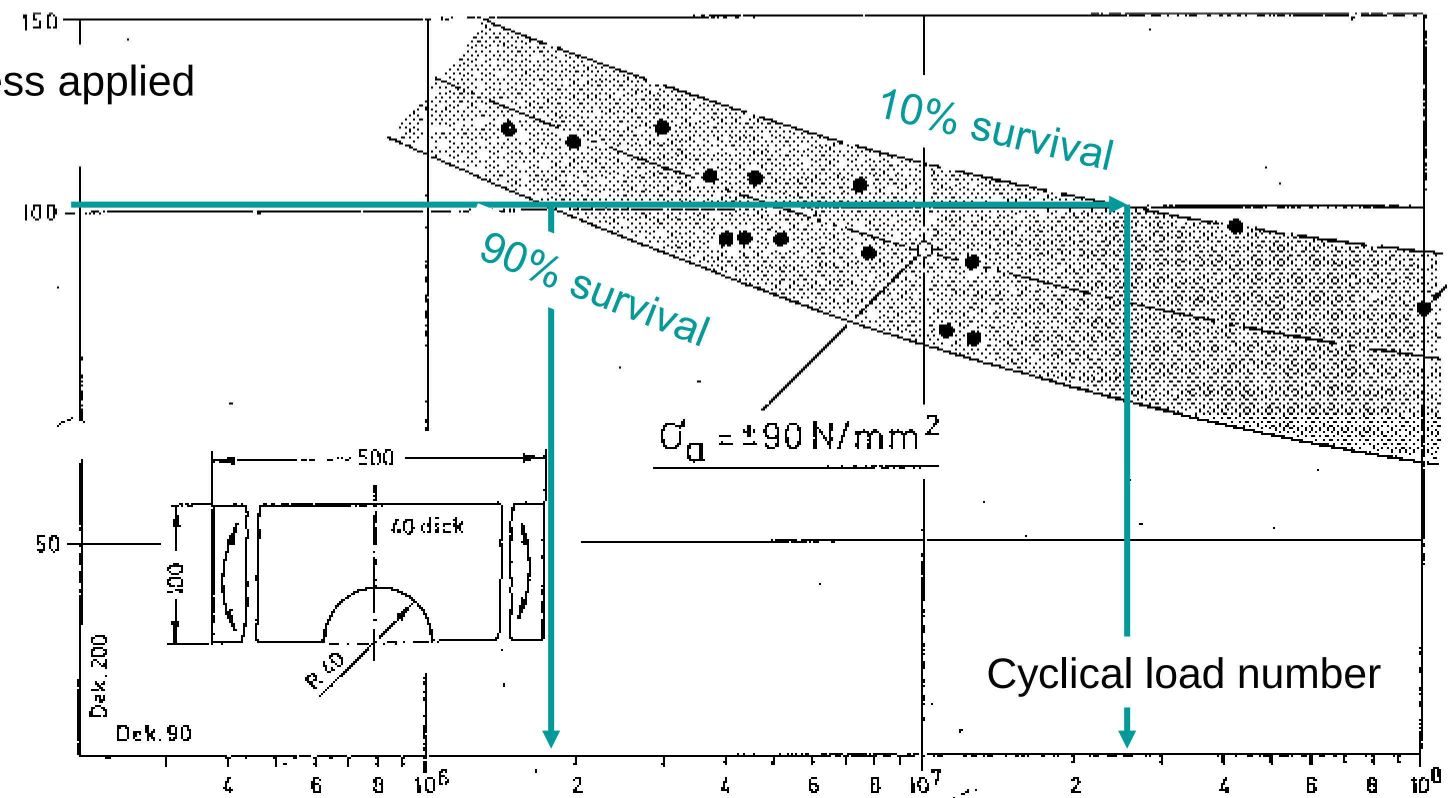
WÖHLER Curve
HAIGH diagram
Security-fatigue relation

Typical WÖHLER curve

(For a given R mode)

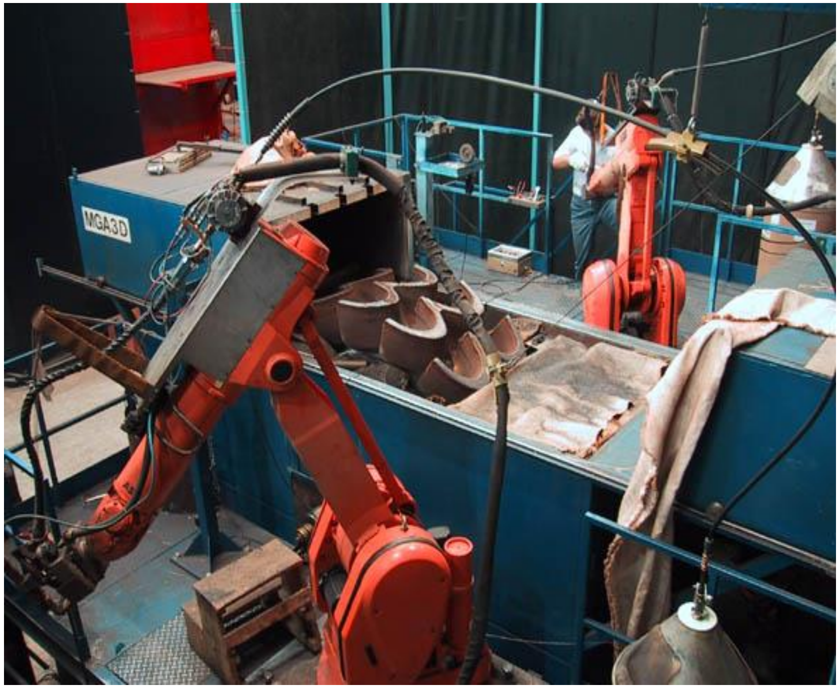
$$R = \frac{\sigma_{\min}}{\sigma_{\max}} = \frac{\sigma_m - \sigma_a}{\sigma_m + \sigma_a}$$

Dynamic stress applied
$\pm \sigma_a$ [N/mm²]



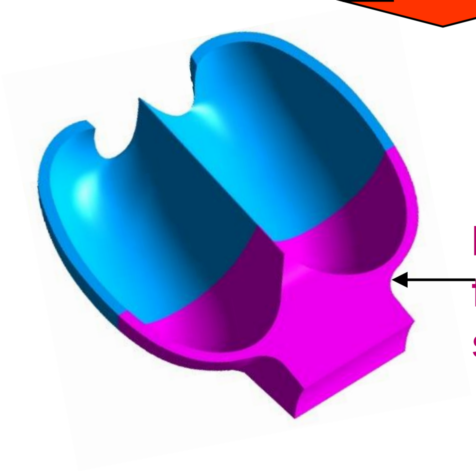
Samples for different steels of Pelton runners,
in wet atmosphere (curves not saturating)

Manufacturing

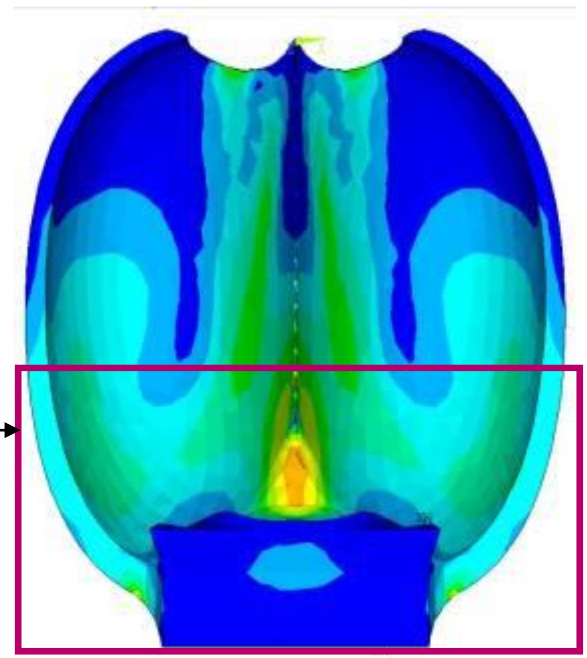


Concept: the right material in the right place

Solution



Forged steel for high stressed area



FEM stress calculation

High stress

Low stress

Fabrication technologies, which fulfill our quality requirements:

- **MicroGuss - since 1991**
- **Hiweld - since 1998**
- **Fully Forged - since 2003**

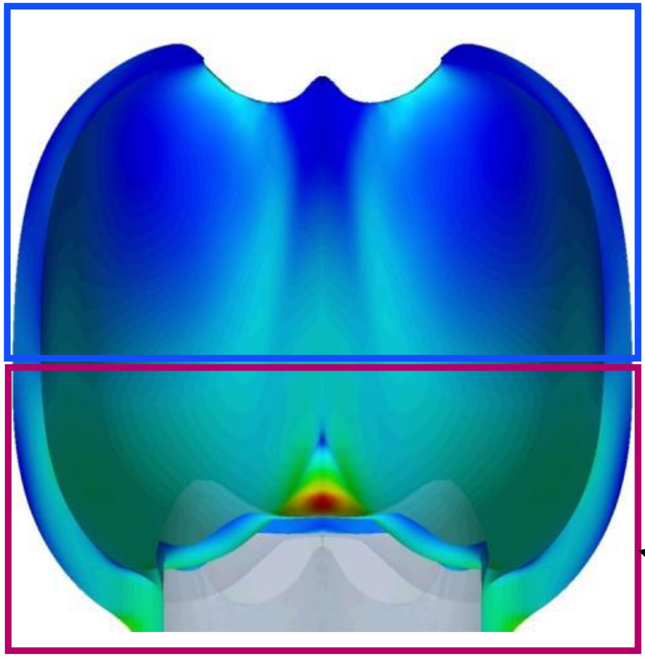
Manufacturing

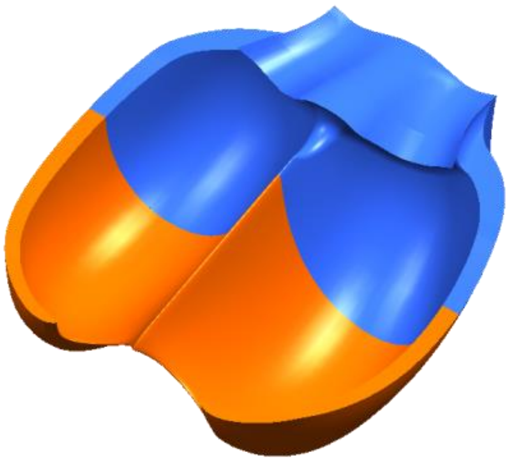
MicroGuss™

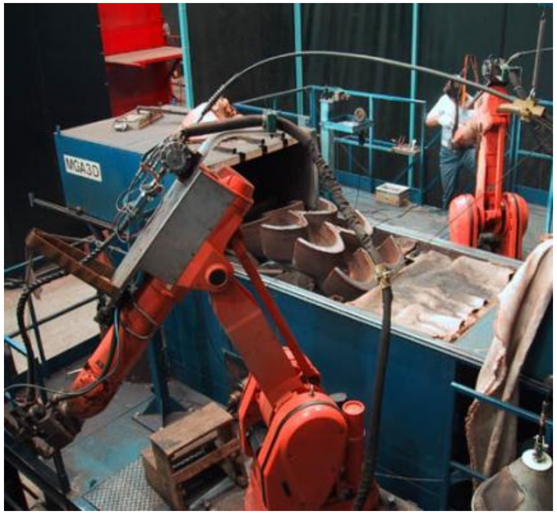
MicroGuss™ sinces 1991, a succes story

Forged material in the high stressed areas

Base concept: the right material on the right zone



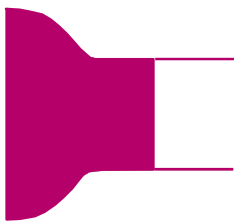


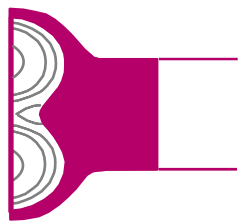


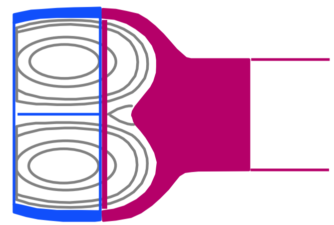
MicroGuss™
Base concept

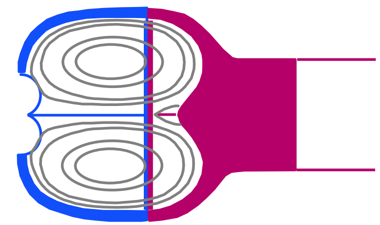
Cast material in the low stressed areas

Main fabrication stages of MicroGuss™ runners









Forged disk with pre milling

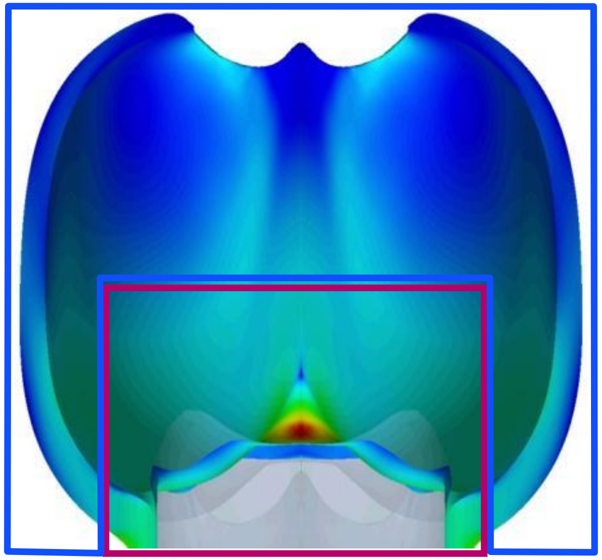
Pre milling of coupling and NC milling of buckets roots

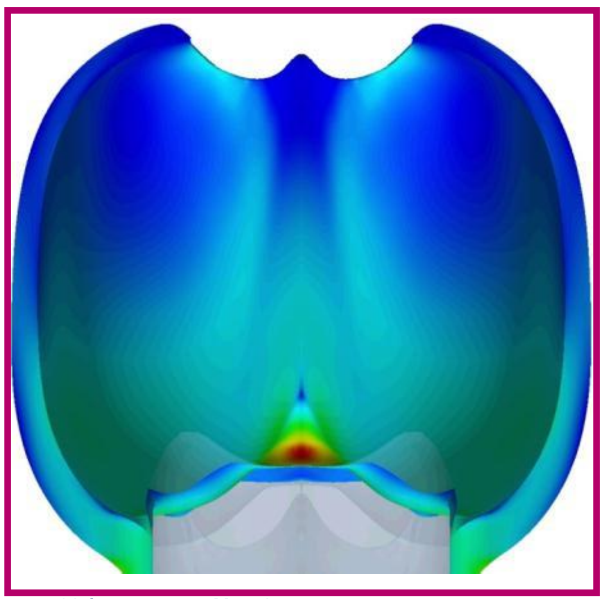
Buckets generation by automatic MicroGuss™ welding

NC milling of bucket profile and final grinding

Manufacturing

HIWELD™ & FullyForged

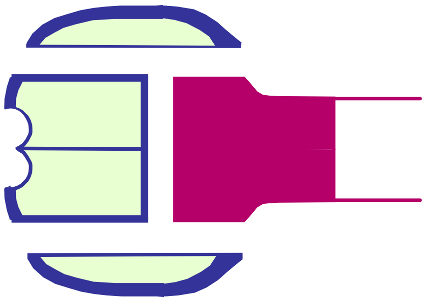


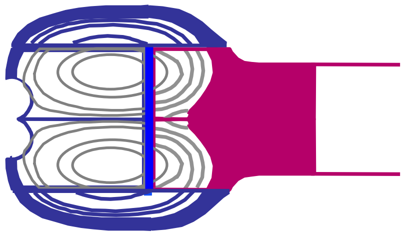


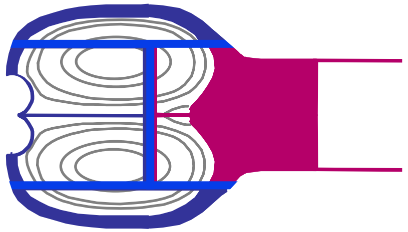
HIWELD™
Forged or cast buckets welded on forged runner hub

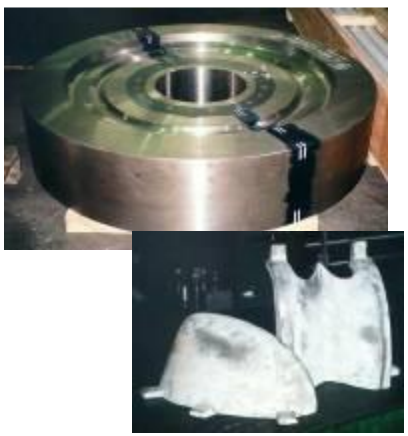
FullyForged
Fully machined runner out of a forged runner hub (mainly for runners < 4 t)

Main fabrication stages of Hiweld™ runners









Pre milled forged disk

Forged or cast buckets pieces

Pre milling of coupling and NC milling of buckets roots

Hiweld™ welding of middle parts

NC milling of profile

Welding of pre milled buckets lateral parts

NC milling and final grinding

Main fabrication stages of fully forged runners

Forged disc pre machined and checked by UT

Between 60-70% of material will be taken out

CNC machining of the buckets and runner hub

Grinding and polishing of the buckets

Examples

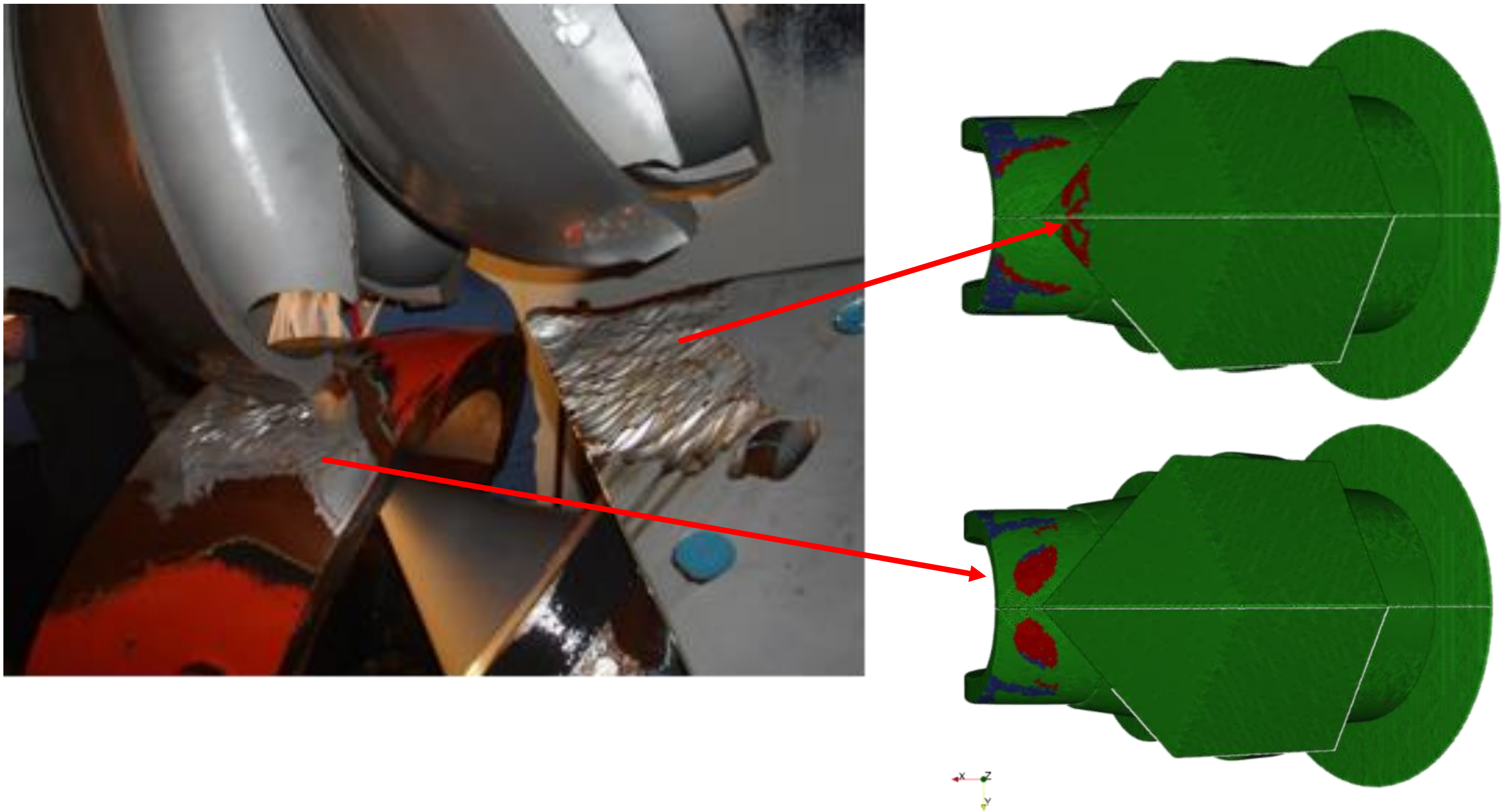
Power up to 423 MW per runner

Runner weight
from
2 to 35 tons

Head up to 1869 meters

Coating

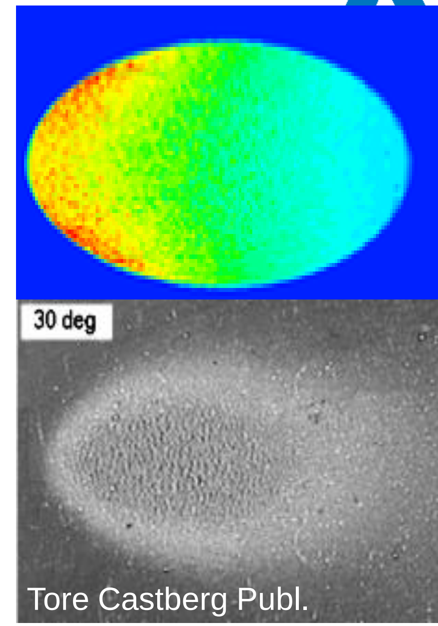
Casings Flow Patterns

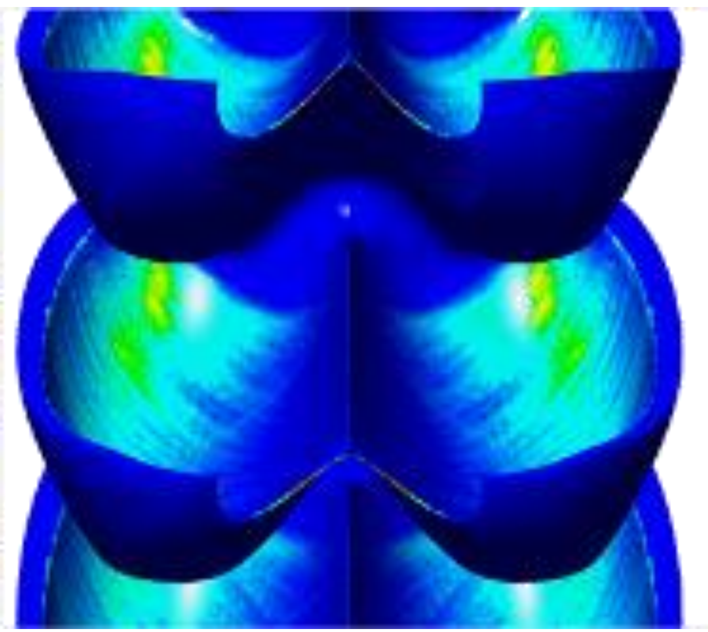


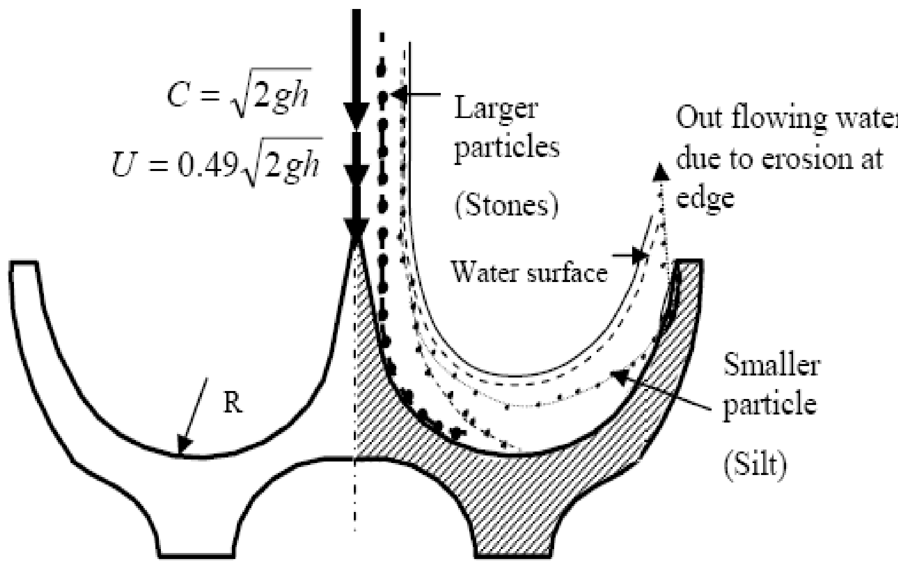
Erosion

- Prediction of eroded zones, function of particles contents
- Selection of most appropriate zones for protection
- Specific numerical simulation with different CFD modelling

Jet on flat plate



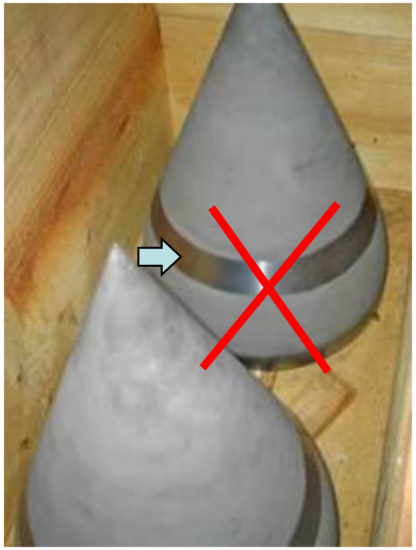




Applications of coating

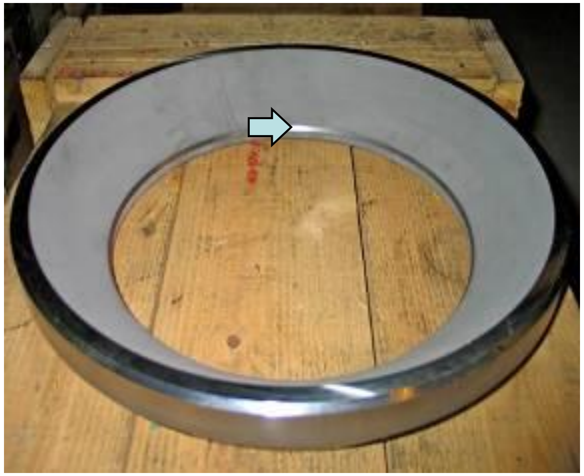
Runner: bucket inside and inlet-area outside.

→ complete needle to be polished by diamond.



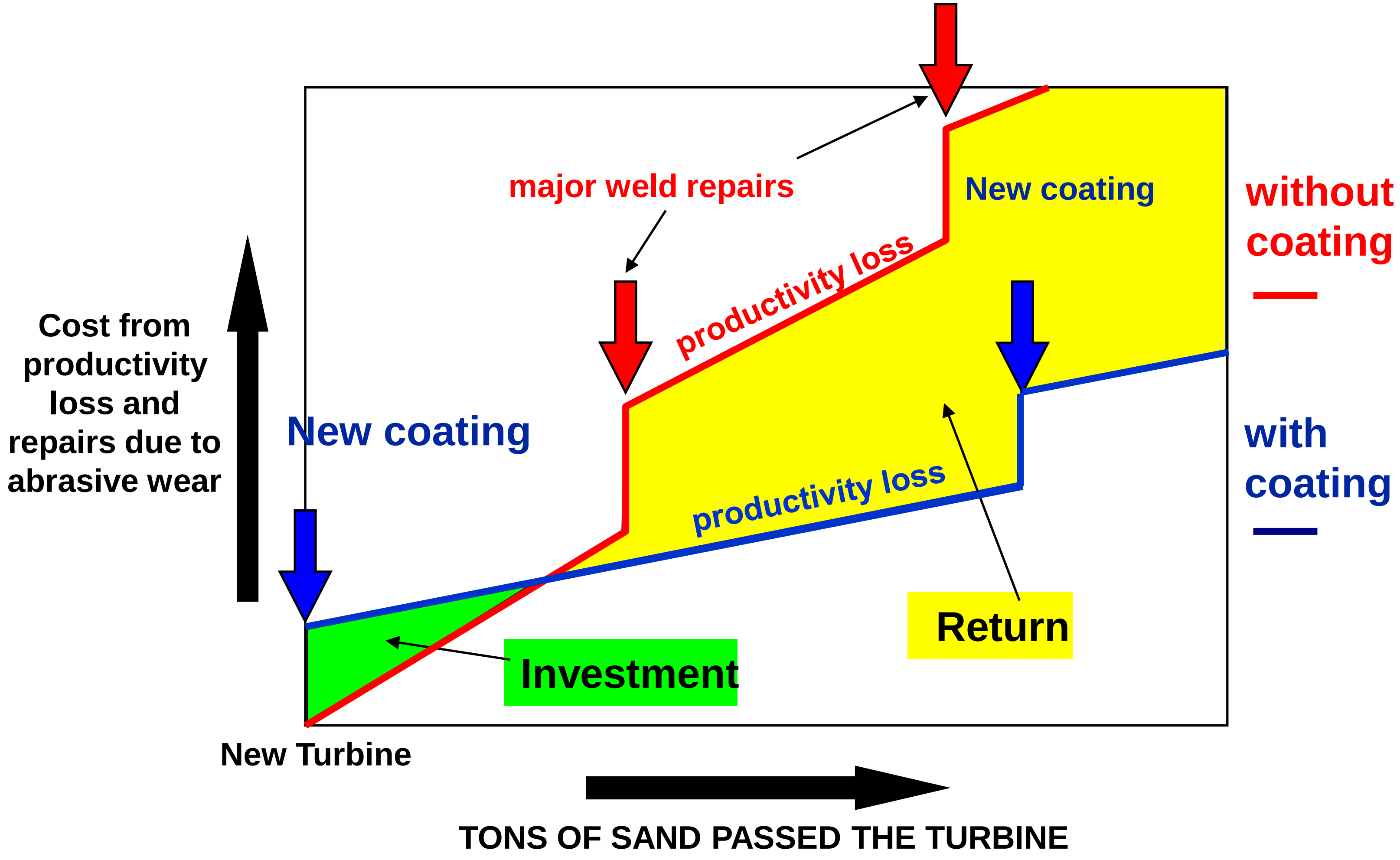
Nozzle tips: outside area.

Nozzle ring: inside area.



Nozzle housing: inside area.

Coating Concept



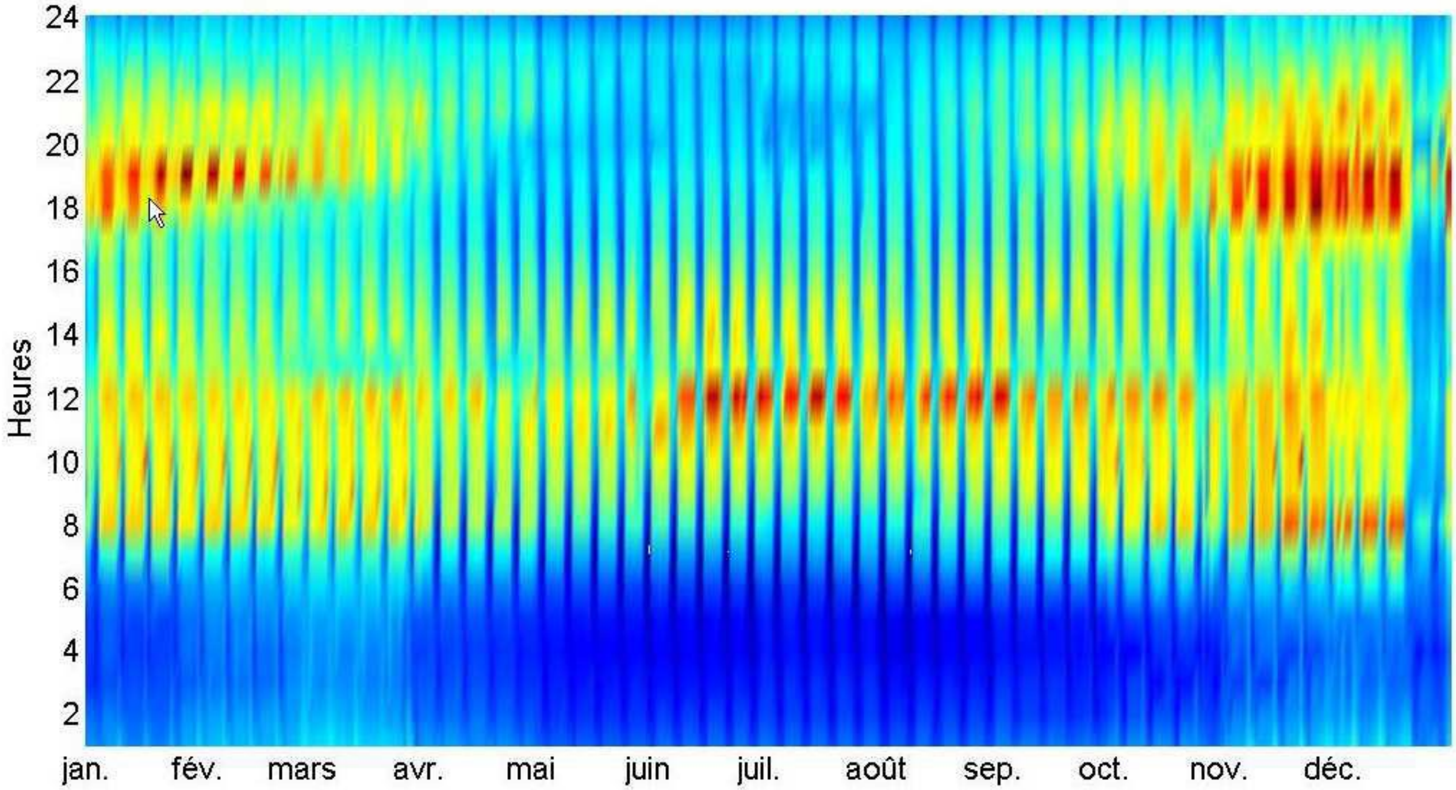
SXH™ Coatings

Successfully combating abrasive wear on hydraulic turbine parts since 20 years

after 4000h (uncoated)

after 3000 h SXH70-coated

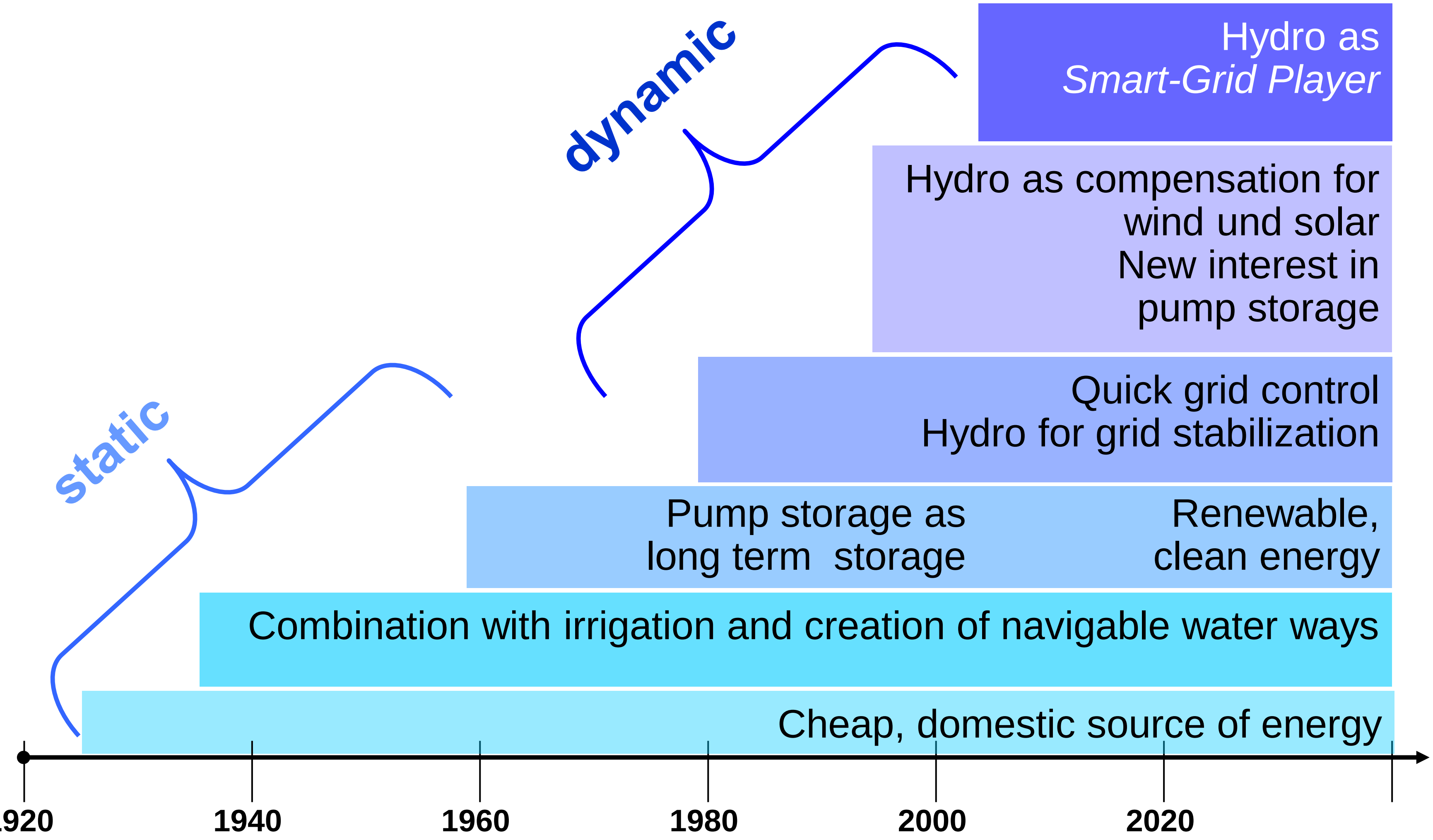
Operation



Heures
24
22
20
18
16
14
12
10
8
6
4
2
jan.
fév.
mars
avr.
mai
juin
juil.
août
sep.
oct.
nov.
déc.

Market challenges are driving development

Moving from static to dynamic operation

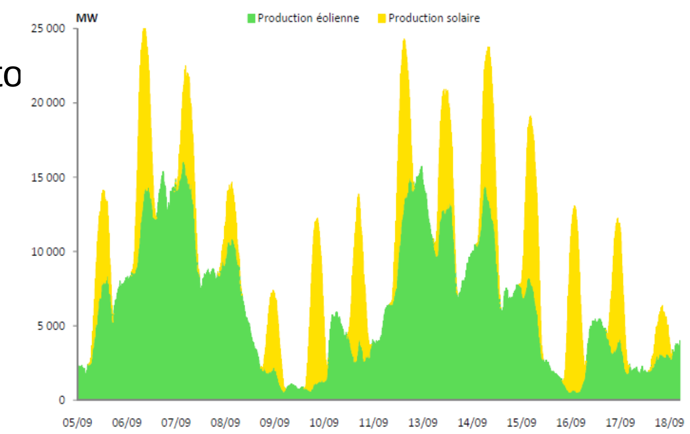


Hydro power as grid stabilizer

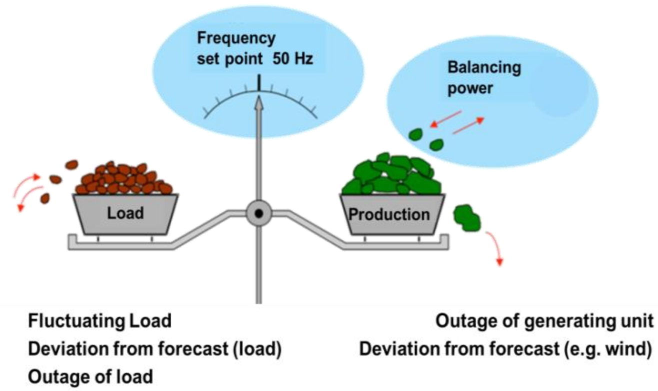
Moving from static to highly dynamic operation

- The electrical grid is changing rapidly
  - From coal, nuclear etc. to variable renewable energy sources
  - Hydro power technology integrates variable energy sources into the electrical grid
    - Fast to dispatch and control
    - Significant storage capacity and high power output (10 to 1000 MW)
- Innovation needed in hydro technology
  - From pure power production (MWh) to ancillary services (primary and secondary frequency control)
  - From hydraulic efficiency to operational flexibility
- Key technological challenges
  - Know-how from electrical and mechanical equipment to grid stability and ancillary services
  - Wide operating range from spinning reserve to full load
  - Fast and flexible pumped storage technology

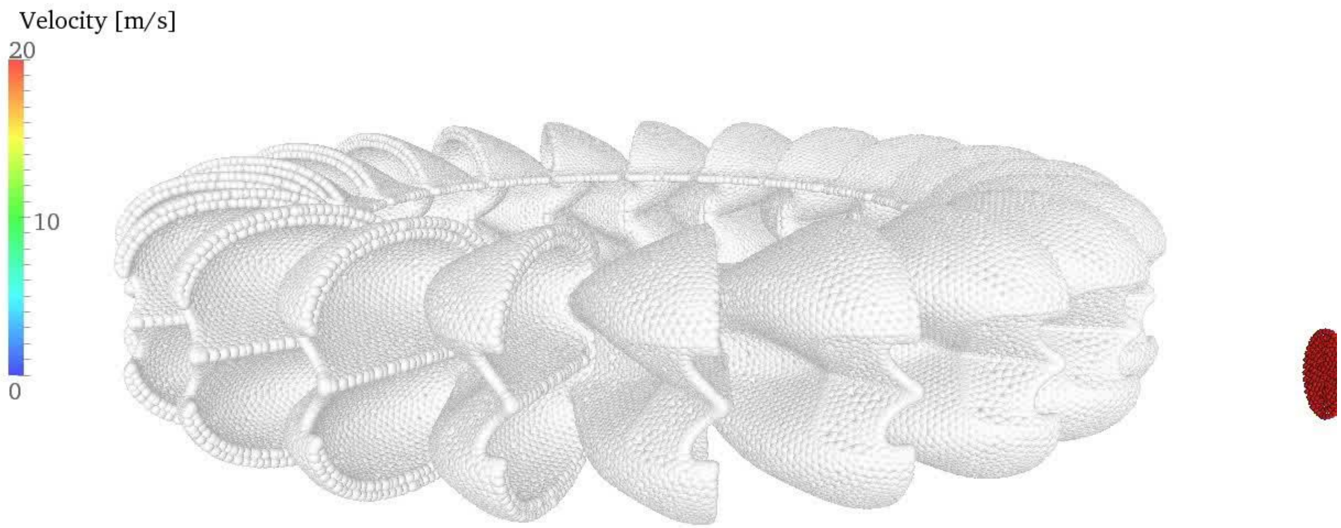
Germany, Sept. 2011
Electricity production from wind (green) and sun (yellow)

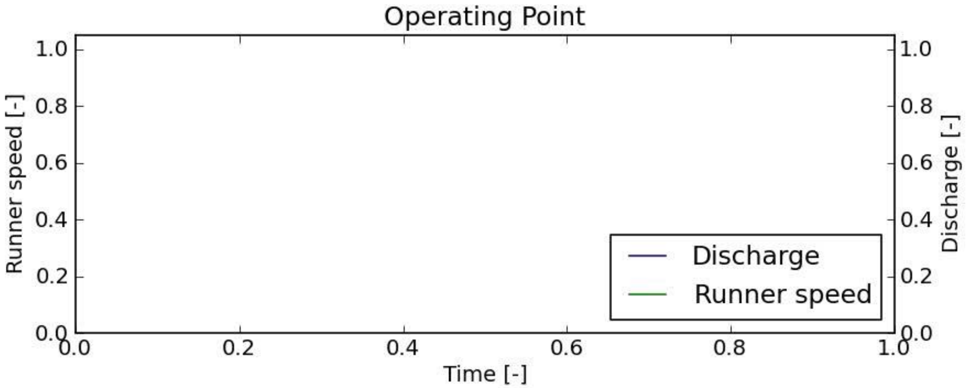


Balance of the electrical grid: stable frequency



Operation is more and more “dynamic”





Bieudron

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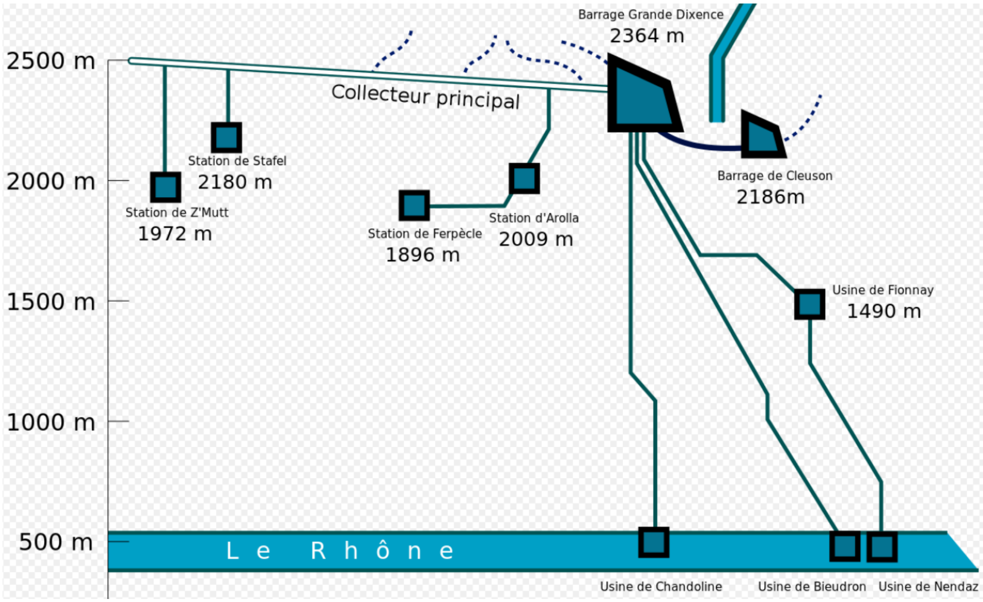
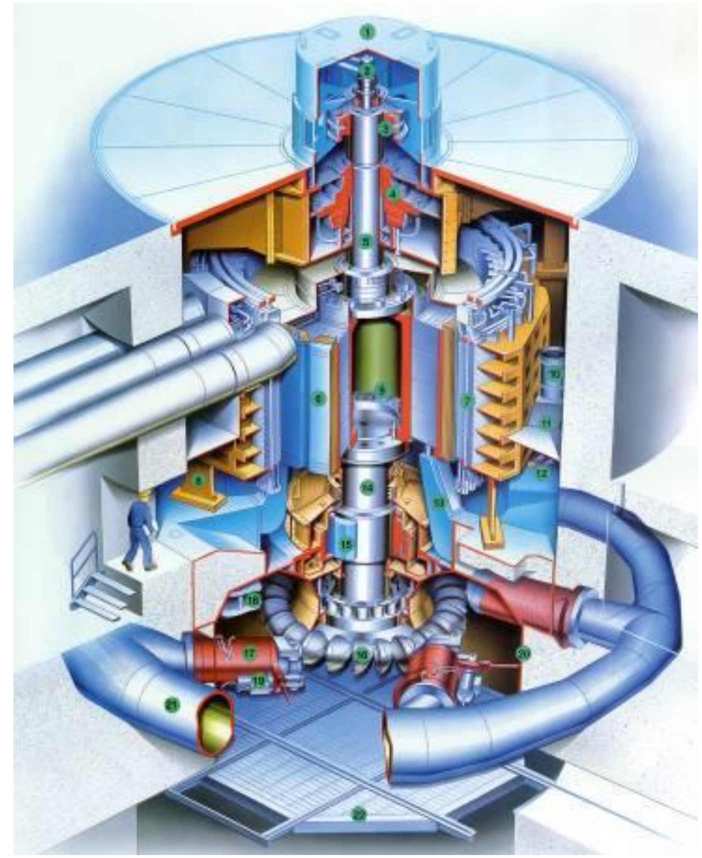
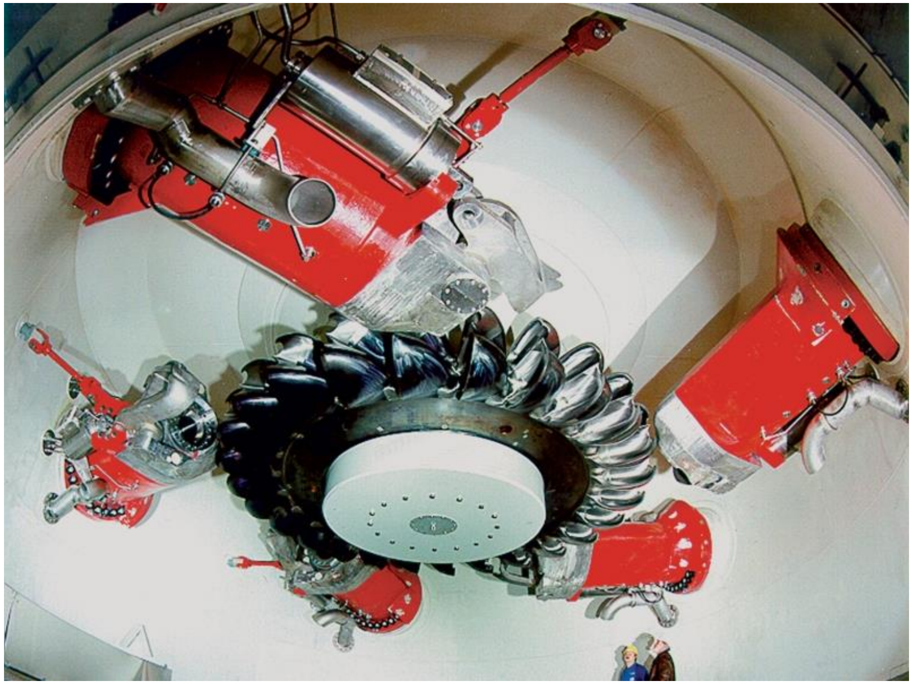




Three world records:

- ✓ Highest **net head**
- ✓ Highest **output for a Pelton turbine**
- ✓ Highest **output per generator pole**

Bieudron



100 tons effort
5 times / rotation
35 times / second

$$\begin{cases} H = 1870\ m \\ D_1 = 3.993\ m \\ N = 428.6\ rpm\ (7.14\ rps) \\ P_1 = \dfrac{423}{5} \cdot 10^6\ W\ (5\ injectors) \end{cases}$$

$$\Rightarrow F_{1j} = \frac{P_1}{\omega \cdot \frac{D_1}{2}} = \frac{423 \cdot 10^6}{5 \cdot \frac{\pi \cdot 428.6}{30} \cdot \frac{3.993}{2}} = 944\ kN$$

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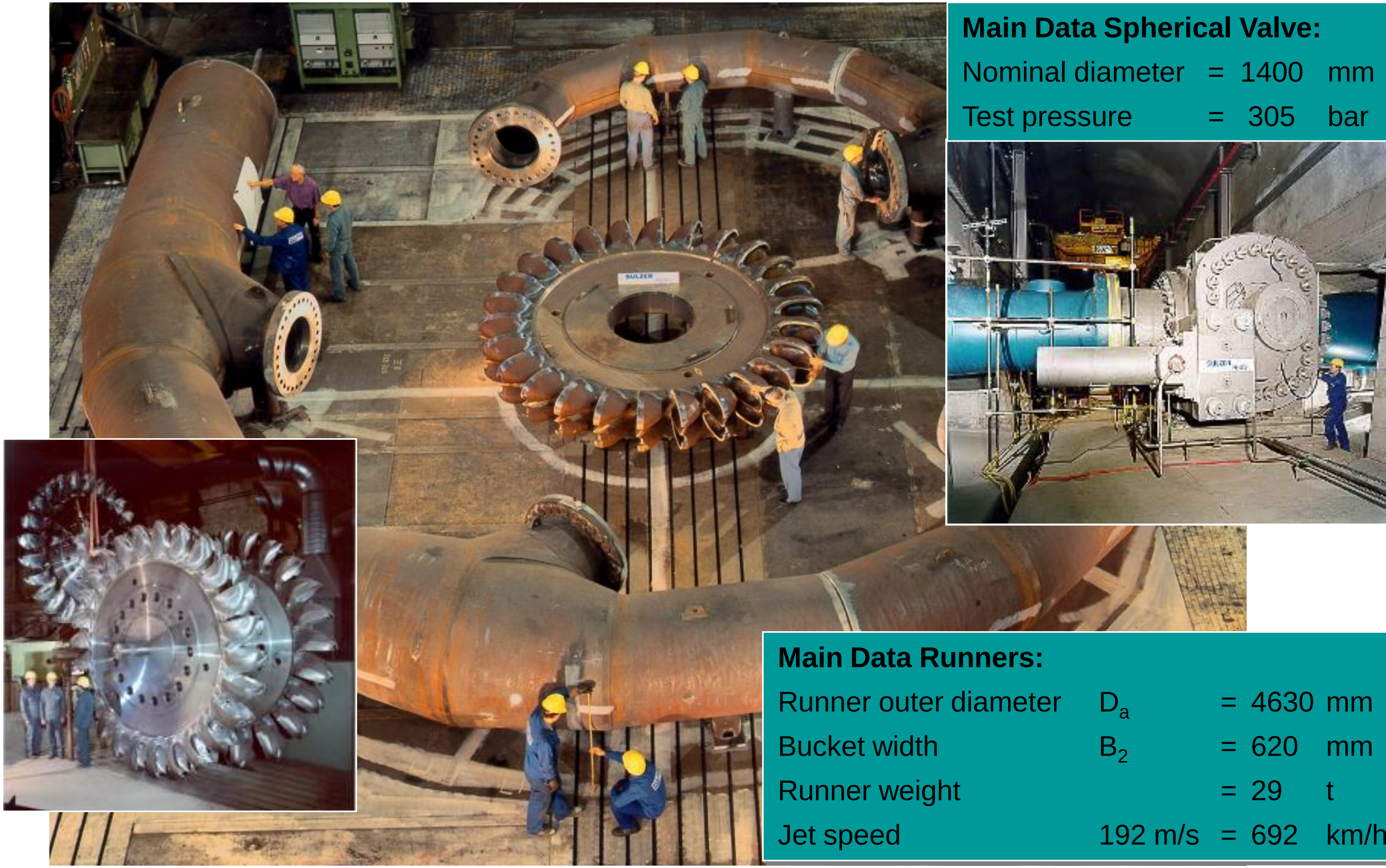
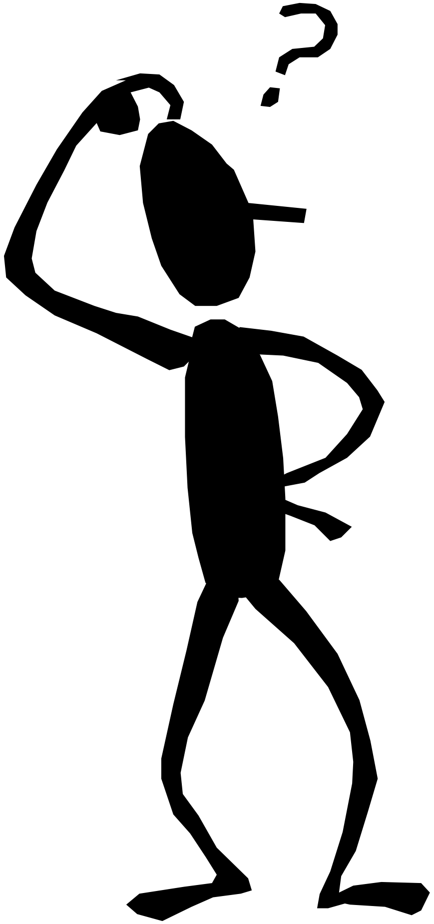


Main Data Spherical Valve:			
Nominal diameter	=	1400	mm
Test pressure	=	305	bar

Main Data Runners:				
Runner outer diameter	D_a	=	4630	mm
Bucket width	B_2	=	620	mm
Runner weight		=	29	t
Jet speed	192 m/s	=	692	km/h

Questions?



Many thanks for your attention!