L4 – Reaction turbines

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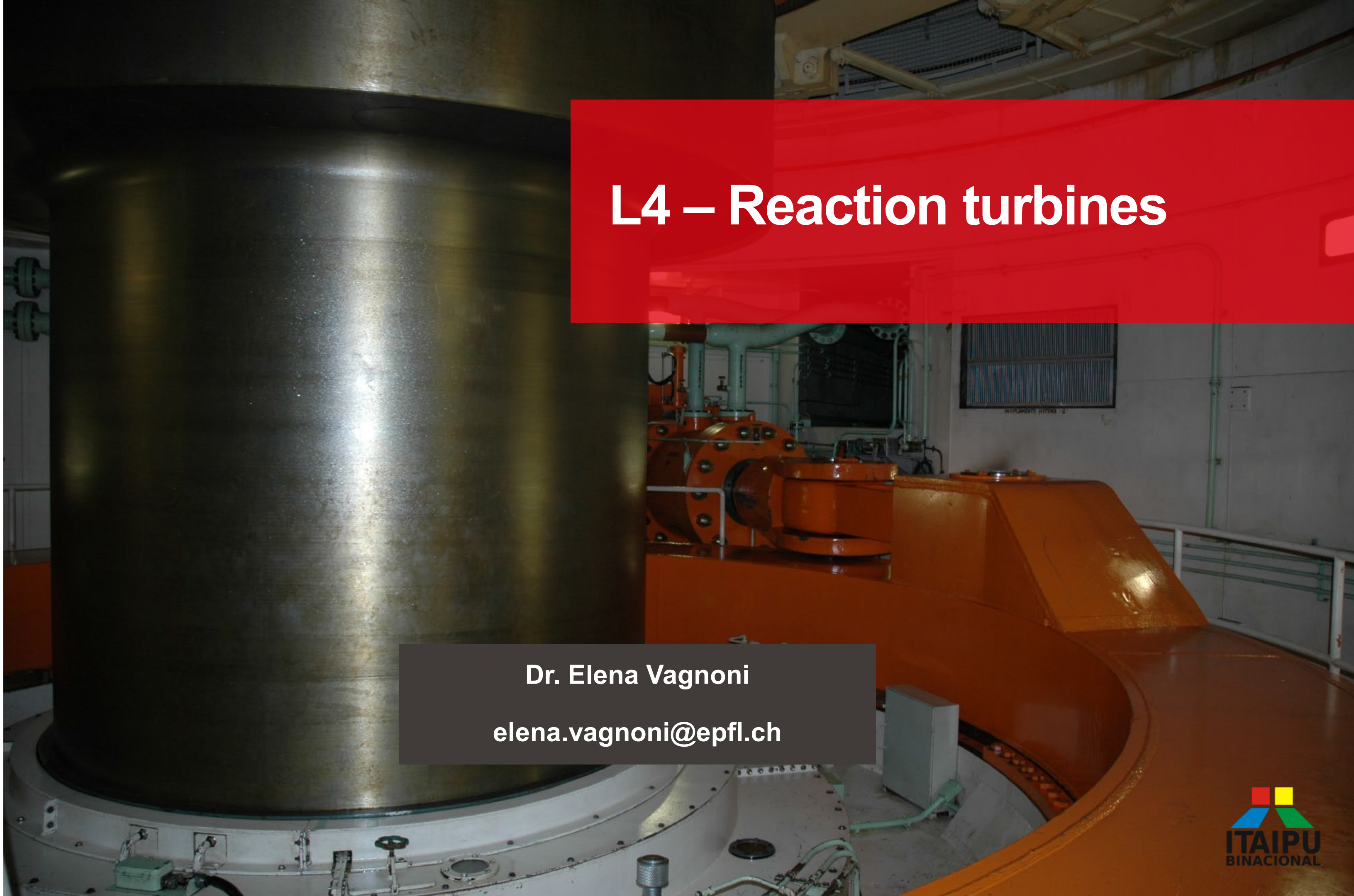

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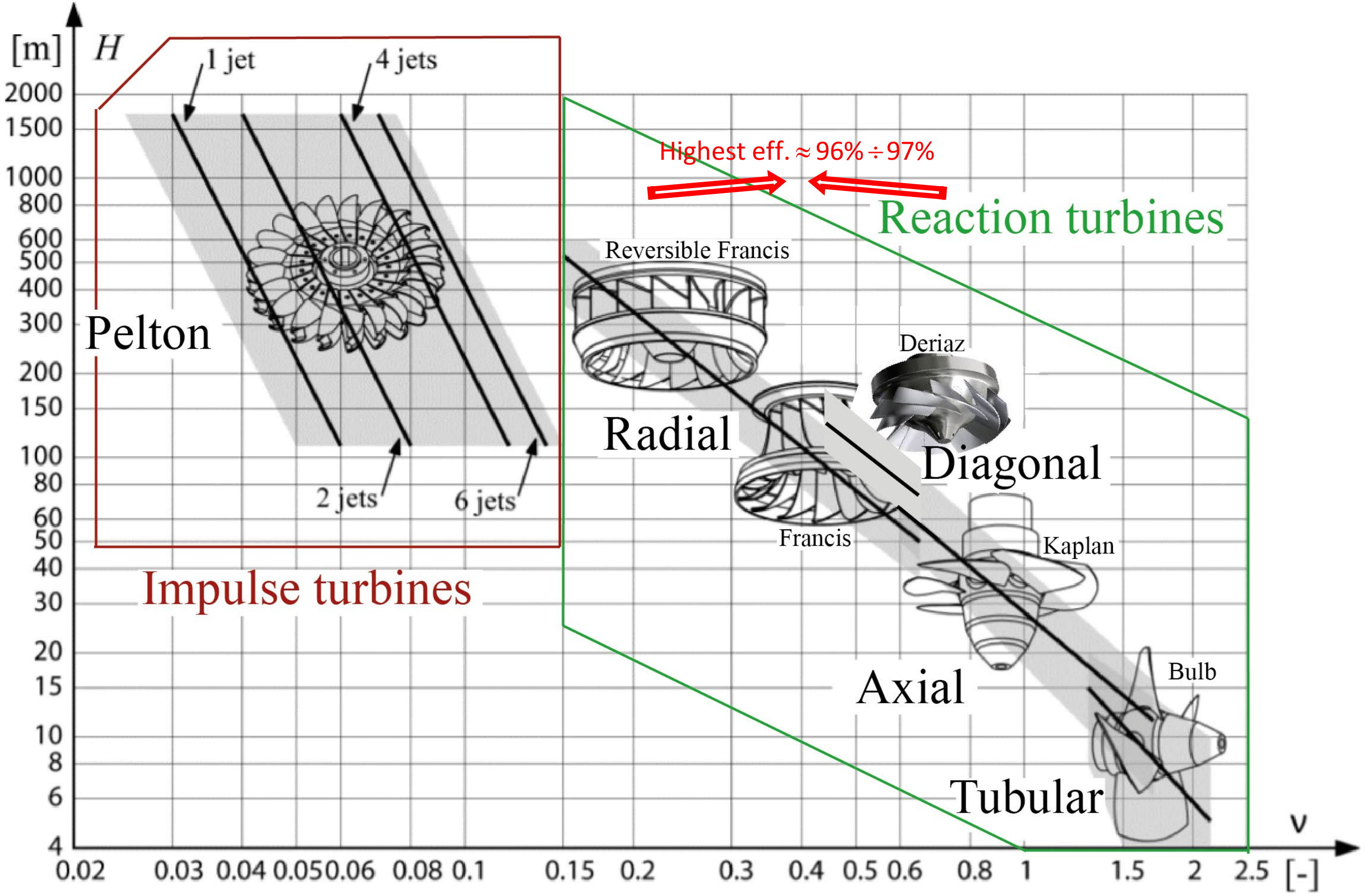
Topics of the lecture

Francis, Kaplan and Bulb turbines:

- Classification and geometrical proprieties
- Operating Principle
- Special Issues
- Real world examples

From L2: Classification of Hydraulic



Head $= H$ (m)

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

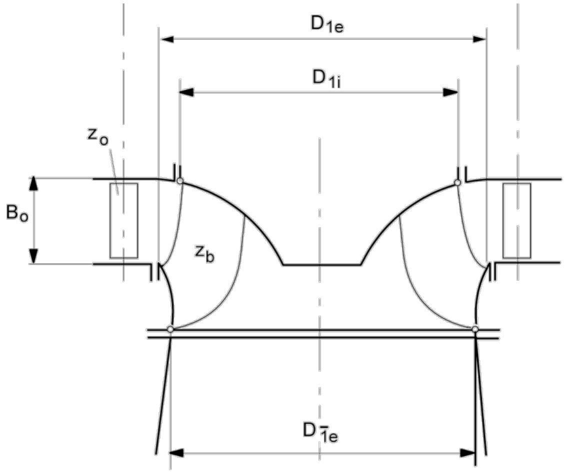
Speed $= N$ $(\mathrm{min^{-1}})$

$$\nu = 2^{\frac{1}{4}} \pi^{\frac{1}{2}} \times n \times \frac{Q^{\frac{1}{2}}}{E^{\frac{3}{4}}}$$

Classification of Hydraulic Runners

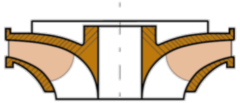
Francis Runners

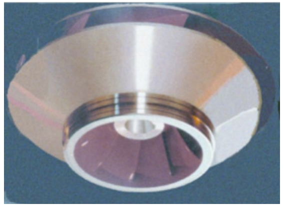
- Reaction machine
- Radial flow
- Medium Head



Low specific speed

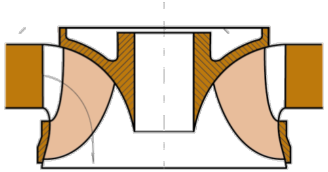
n_q = 12........35
ν = 0.10....0.22
n_{QE} = 0.04....0.10



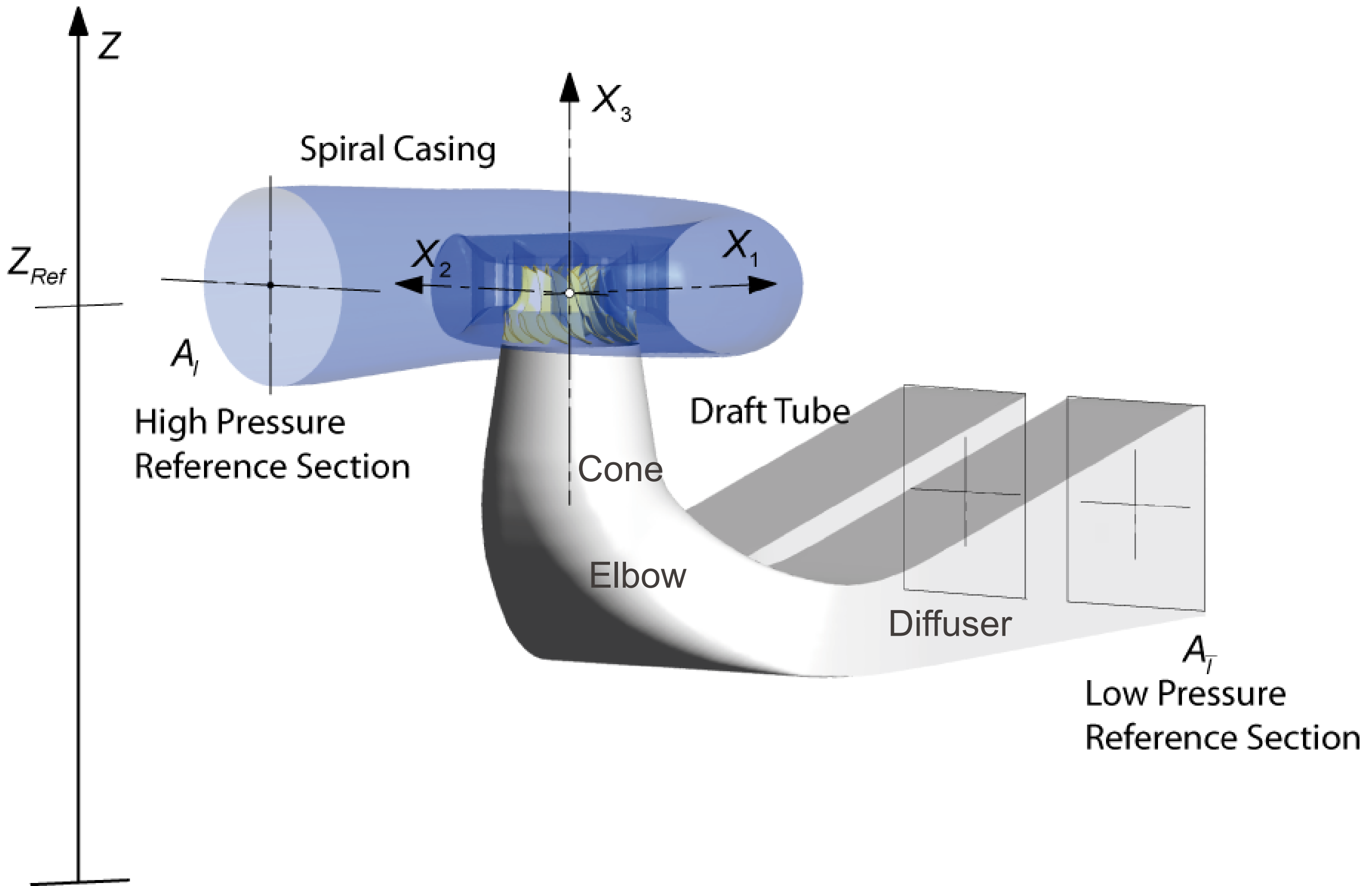


High specific speed

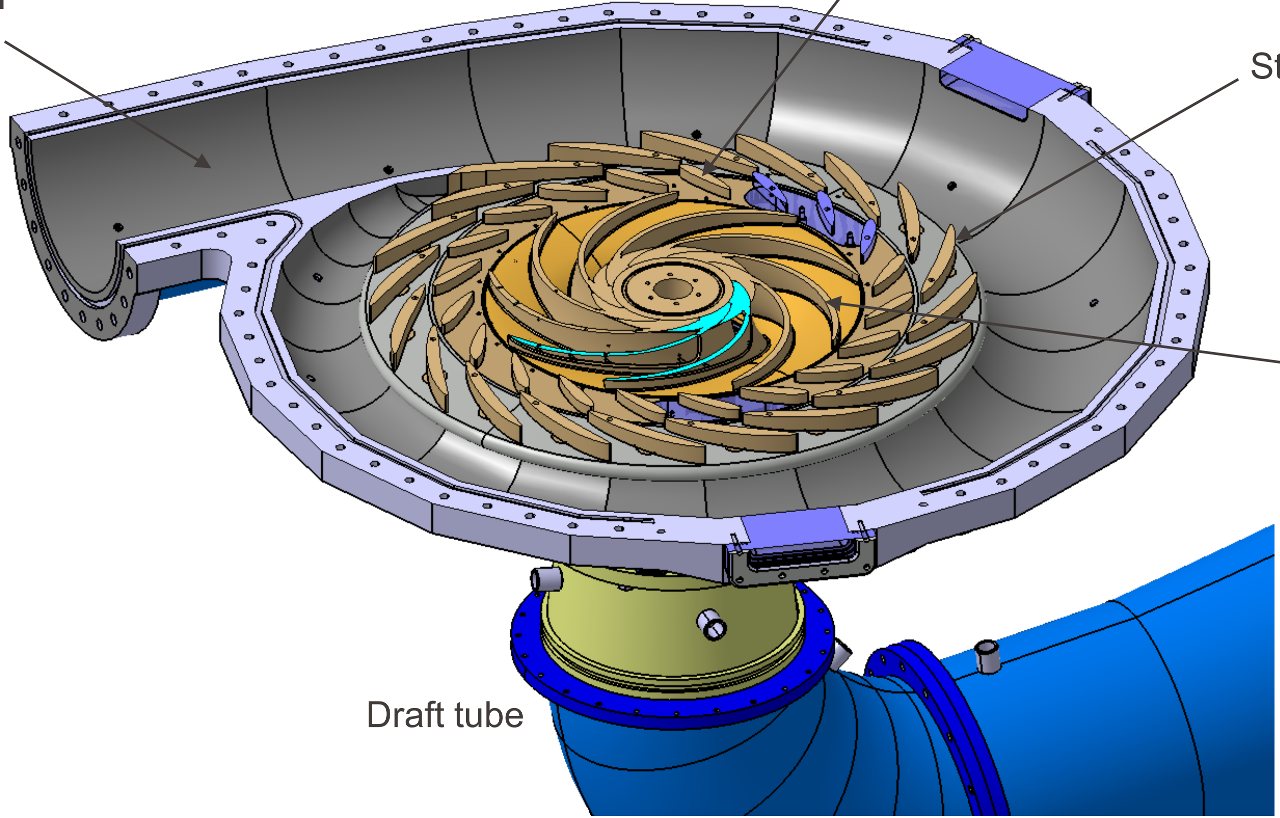
n_q = 35.......80
ν = 0.22....0.50
n_{QE} = 0.10....0.24



Classification and geometrical proprieties

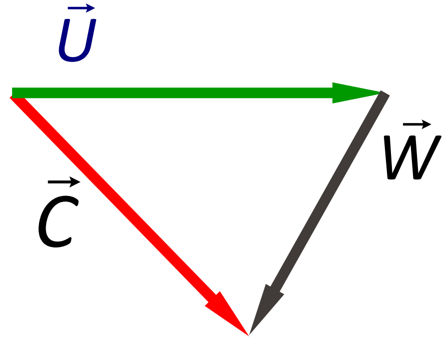


Classification and geometrical proprieties



Classification and geometrical proprieties

Rotating Frame



- Absolute Flow Velocity

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

- Rotating Velocity $\vec{U} = \vec{\omega} \times \vec{X}$

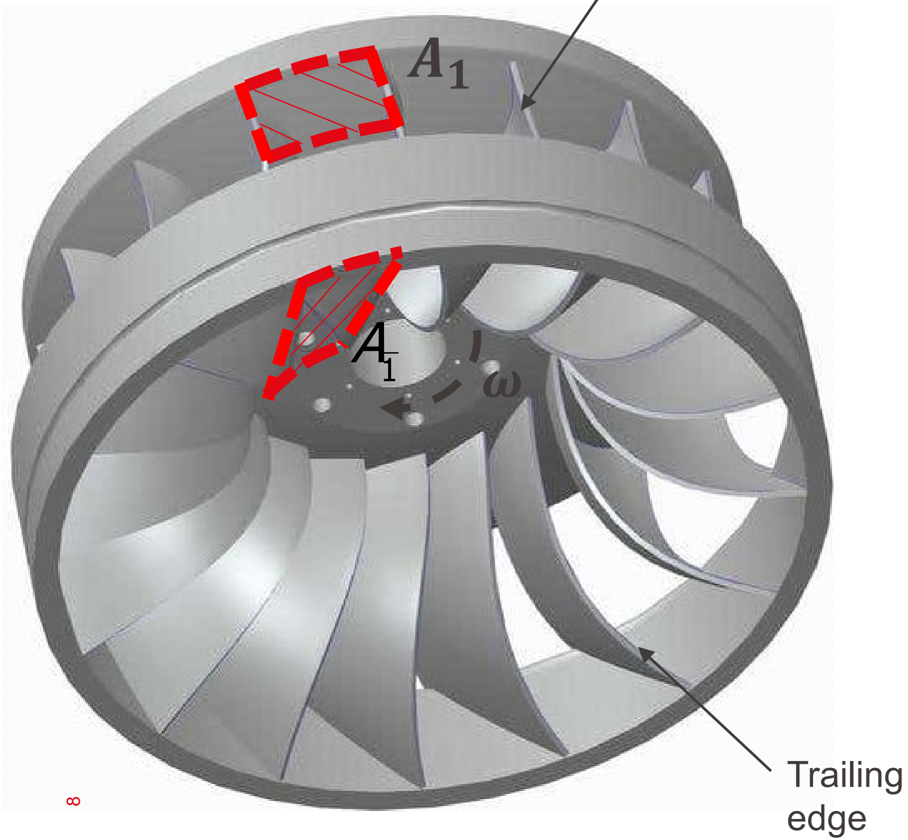
$$= \omega R$$

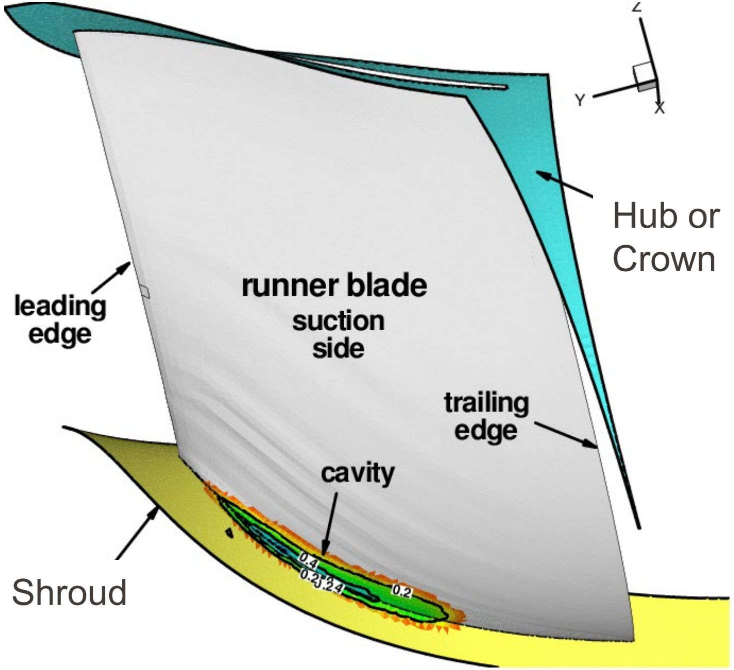
- Relative Flow Velocity

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

Classification and geometrical proprieties

Blade Shape

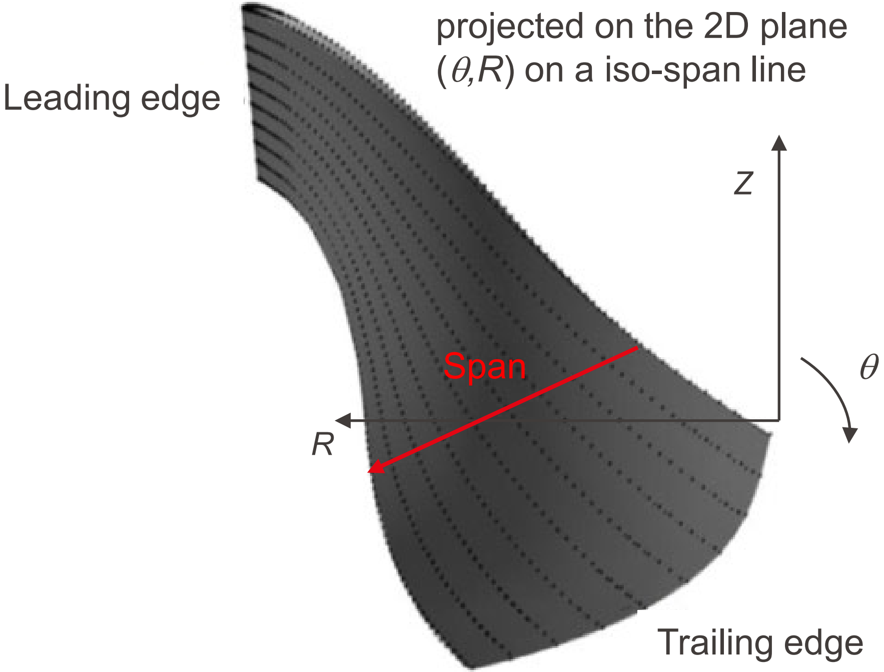


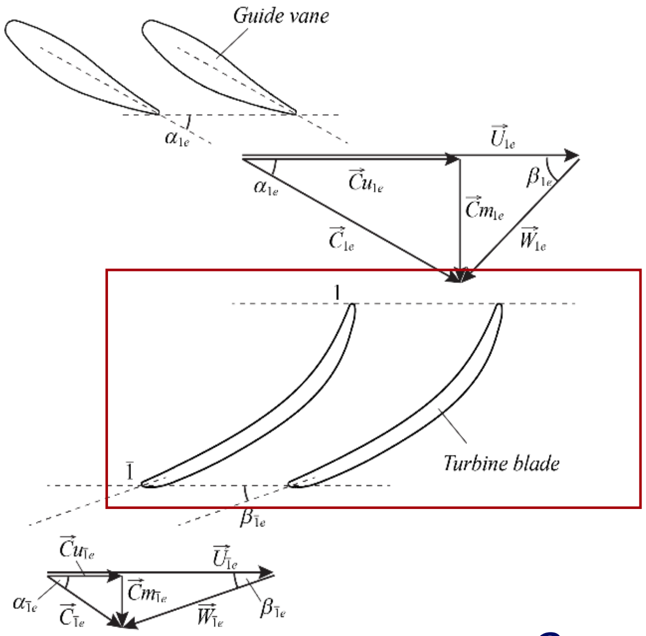


Classification and geometrical proprieties

Blade to Blade view

View of the blade channel projected on the 2D plane (θ,R) on a iso-span line





- Meridional Component $Cm = \dfrac{Q}{A}$
- Tangential Component $Cu = \dfrac{Cm}{tg\alpha} = U - \dfrac{Cm}{tg\beta}$

Blade to blade view

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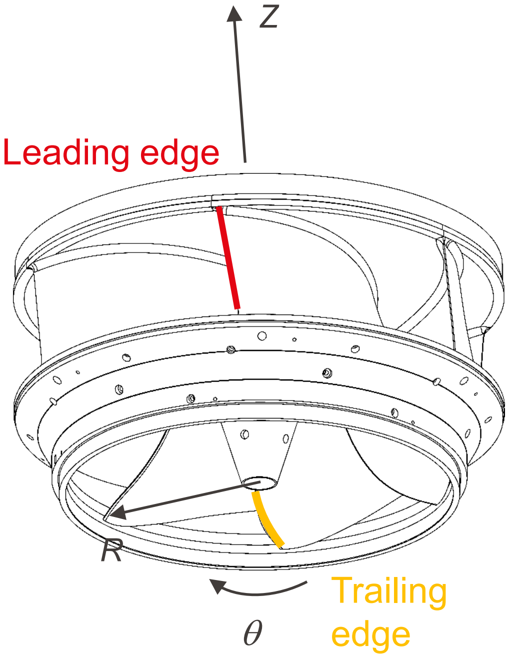
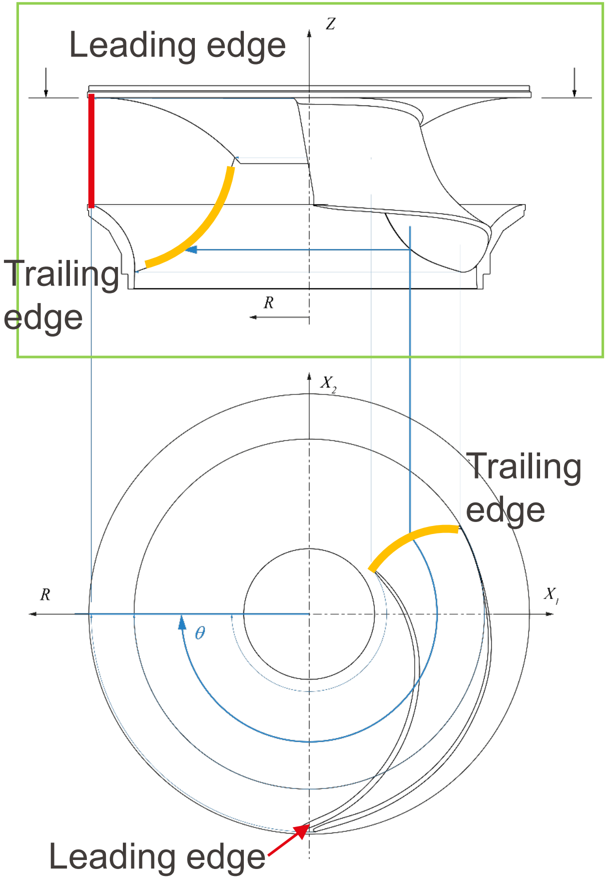
Classification and geometrical proprieties

Meridional view

View of the blade projected on the 2D plane (Z,R)

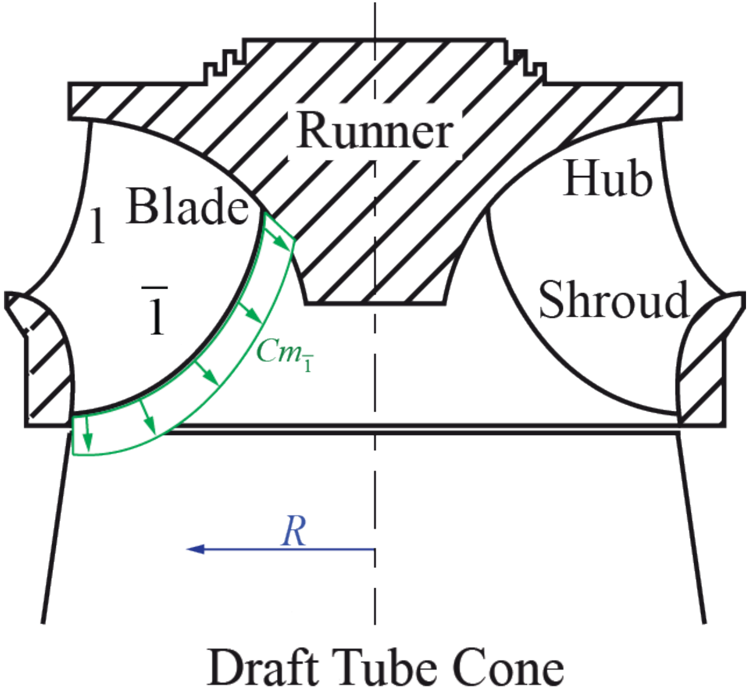




Meridional view

Classification and geometrical proprieties

Meridional view



From L2: Classification of Hydraulic Runners

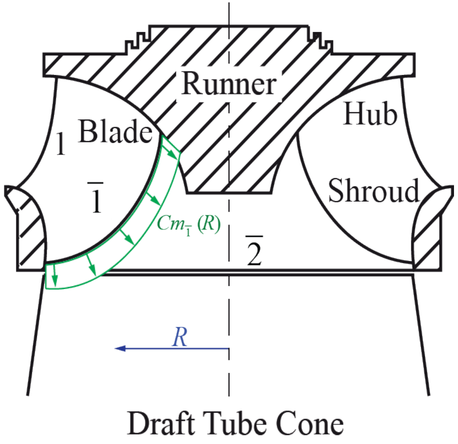
Runner/impeller specific energy transfer

- Transferred Specific Energy

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

- Specific Energy

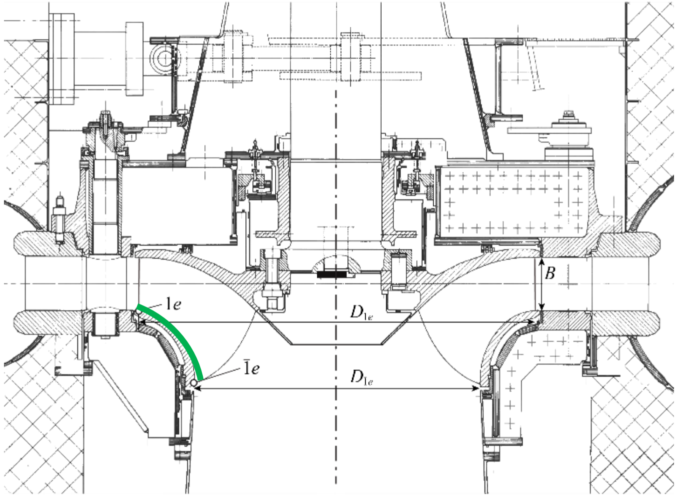
$$gH = \frac{p}{\rho} + gZ + \frac{C^2}{2} \quad \left(\mathrm{J \cdot kg^{-1}}\right)$$



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

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

Operational Properties
The Global Euler Equation



1D Equation: local form of the transferred energy by considering any particular streamline, for example, the transferred specific energy is defined by using the outer, external, streamline between the 2 points:

$$E_t = k_{C_{u1e}} \vec{C}_{1e} \cdot \vec{U}_{1e} - k_{C_{u\bar{1}e}} \vec{C}_{\bar{1}e} \cdot \vec{U}_{\bar{1}e}$$

- As the Euler equation is defined for the mean flow, the local form uses the following flow velocity distribution coefficients to take into account the influence of the spatial velocity distribution :

$$k_{C_{ux}} = \left| \frac{\int_{A_x} \left(\vec{C}\cdot\vec{U}\right) \vec{C}\cdot\vec{n}\, dA}{Q_t \left(\vec{C}_x \cdot \vec{U}_x\right)} \right|$$

- Turbine Flow: Uniform Inlet & Solid Body Rotation Outlet.

Operational Properties

The Global Euler Equation

Uniform flow at turbine inlet

$$k_{C_{uA_{1e}}} = \left| \frac{\int_{A_{1e}} \left(\vec{C} \cdot \vec{U} \right) \vec{C} \cdot \vec{n} \, dA}{Q_t \left(\vec{C}_{1e} \cdot \vec{U}_{1e} \right)} \right| = 1$$

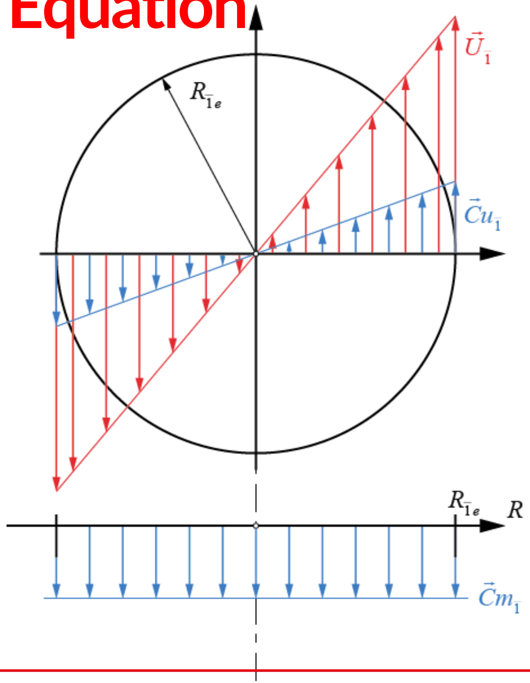
$$k_{C_{mA_{1e}}} = \left| \frac{\int_{A_{1e}} \vec{C} \cdot \vec{n} \, dA}{A_{1e} \, Cm_{1e}} \right| = 1$$

Operational Properties
The Global Euler Equation

Solid Body Rotation at turbine outlet

$$\frac{\vec{U}}{\vec{U}_{\bar{1}e}} = \frac{R}{R_{\bar{1}e}}$$

$$\frac{C_u}{C_{u\bar{1}e}} = \frac{R}{R_{\bar{1}e}}$$



$$k_{C_{uA\bar{1}e}} = \left| \frac{\int_{A_{\bar{1}e}} \left(\vec{C}\cdot\vec{U}\right) \vec{C}\cdot\vec{n}\, dA}{Q_t \left(\vec{C}_{\bar{1}e}\cdot\vec{U}_{\bar{1}e}\right)} \right|$$

$$k_{C_{mA\bar{1}e}} = \left| \frac{\int_{A_{\bar{1}e}} \vec{C}\cdot\vec{n}\, dA}{A_{\bar{1}e}\, Cm_{\bar{1}e}} \right| = 1$$

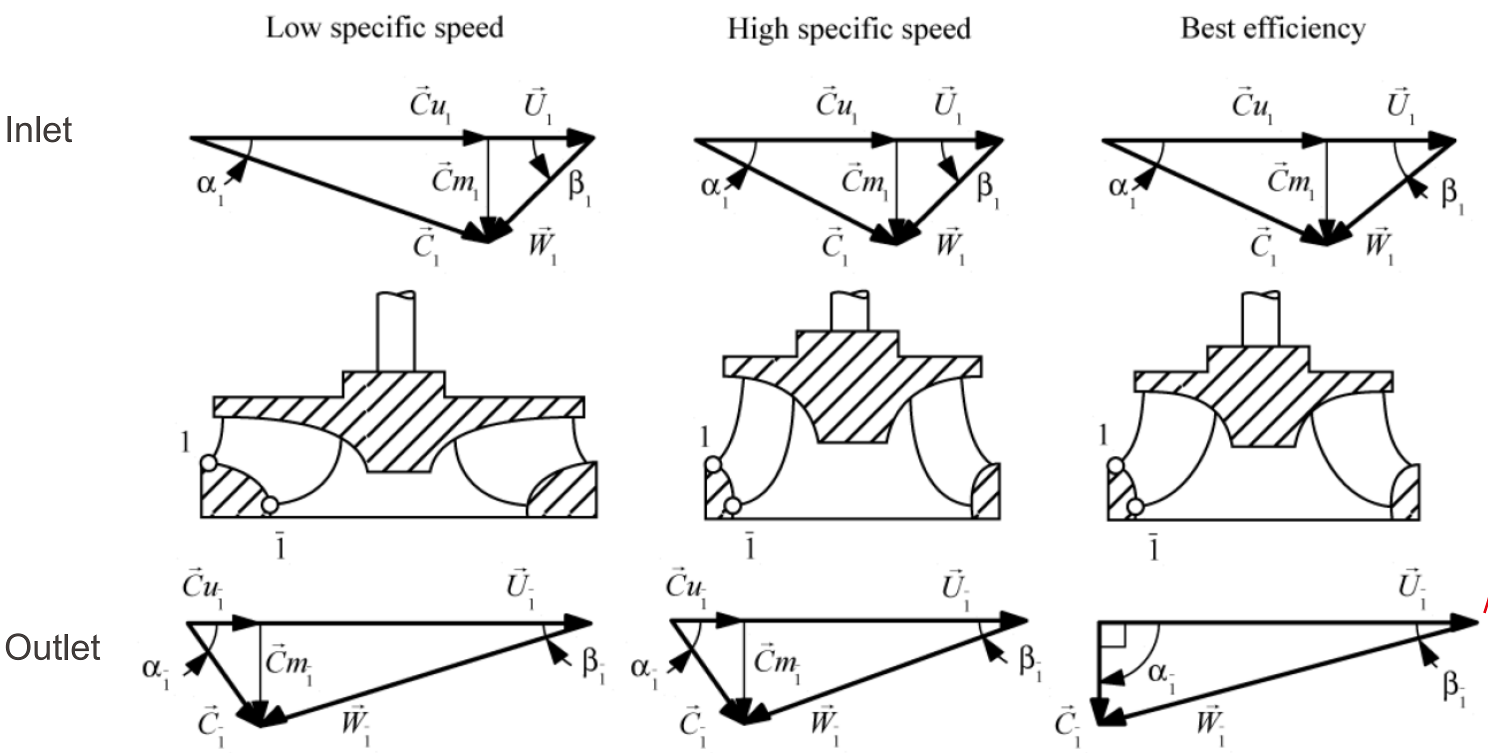
$$E_t = (1)\times\vec{C}_{1e}\cdot\vec{U}_{1e} - \left(\frac{1}{2}\right)\times\vec{C}_{\bar{1}e}\cdot\vec{U}_{\bar{1}e}$$

→ Depending on the velocity components the extracted energy will be different!

Operational Properties

Velocity triangles for Francis runners

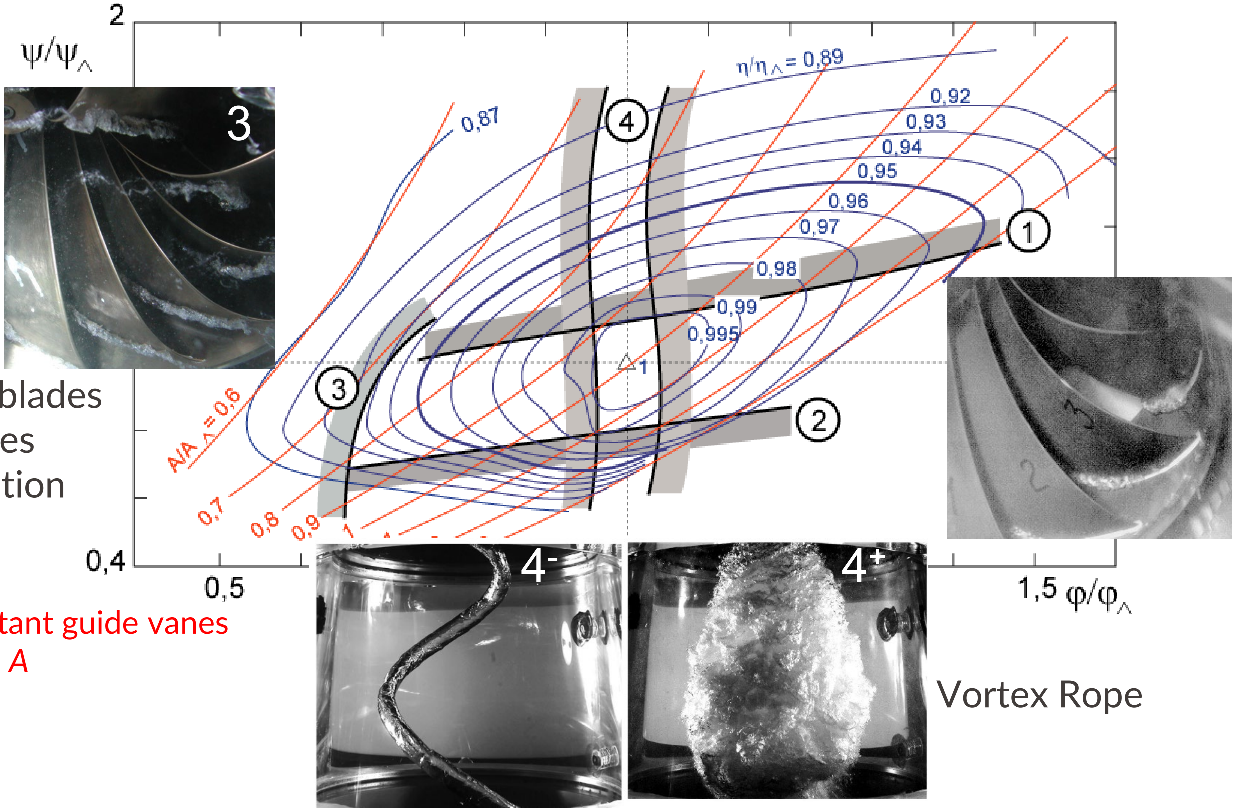
$$E_t = U_{1e} Cu_{1e} - k_{C_{u\bar{1}e}} U_{\bar{1}e} Cu_{\bar{1}e}$$



Axial outlet flow

$$Cu_{\bar{1}e} = 0$$

Operating issues
Performance degradation



Inter-blades vortices cavitation

Leading edge sheet cavitation

Vortex Rope

Constant guide vanes angle *A*

From L2: Classification of Hydraulic Runners

Machine setting level

Nomenclature:

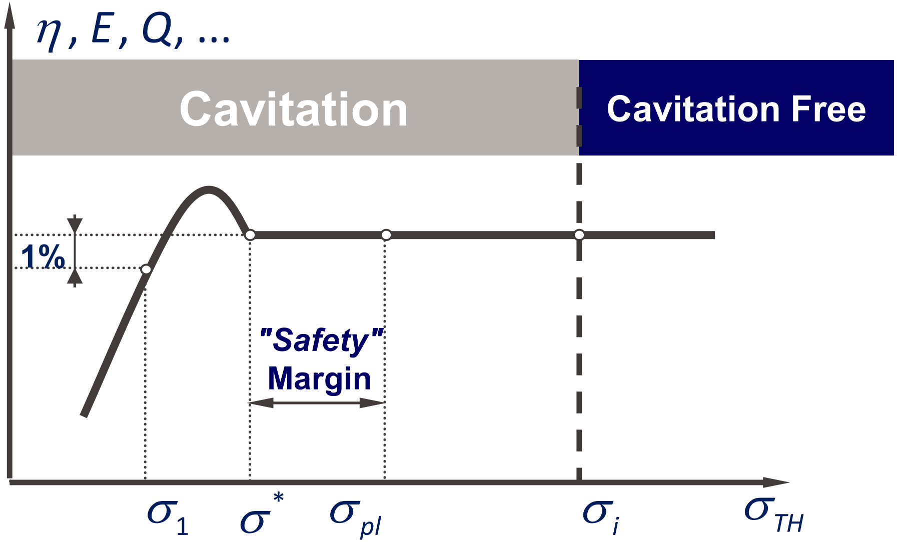
η (-) Efficiency

σ_i (-) Inception: 1st Cavity !

σ_{pl} (-) Plant Value

σ_* (-) 1st Efficiency Change

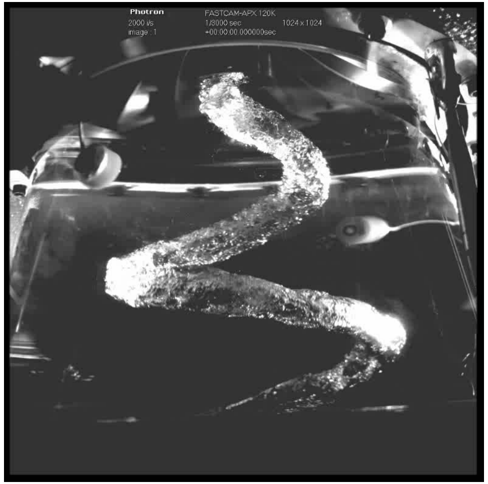
σ_1 (-) 1% Efficiency Drop



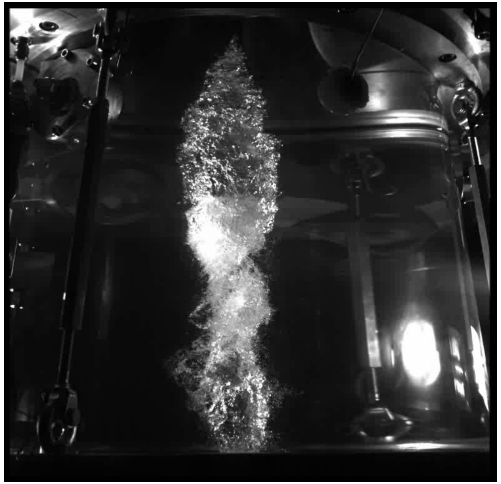
Operating issues

Unsteady Flow in Francis Draft Tube

Precession vortex rope



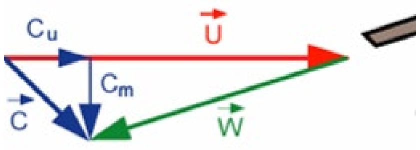
Axisymmetric vortex rope

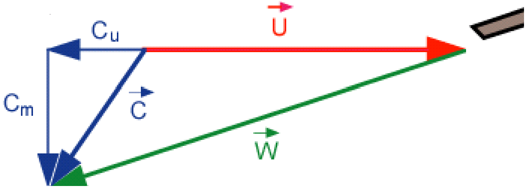


Partial Load: $Q < Q_{BEP}$

Full Load: $Q > Q_{BEP}$

Velocity Triangle at the runner outlet

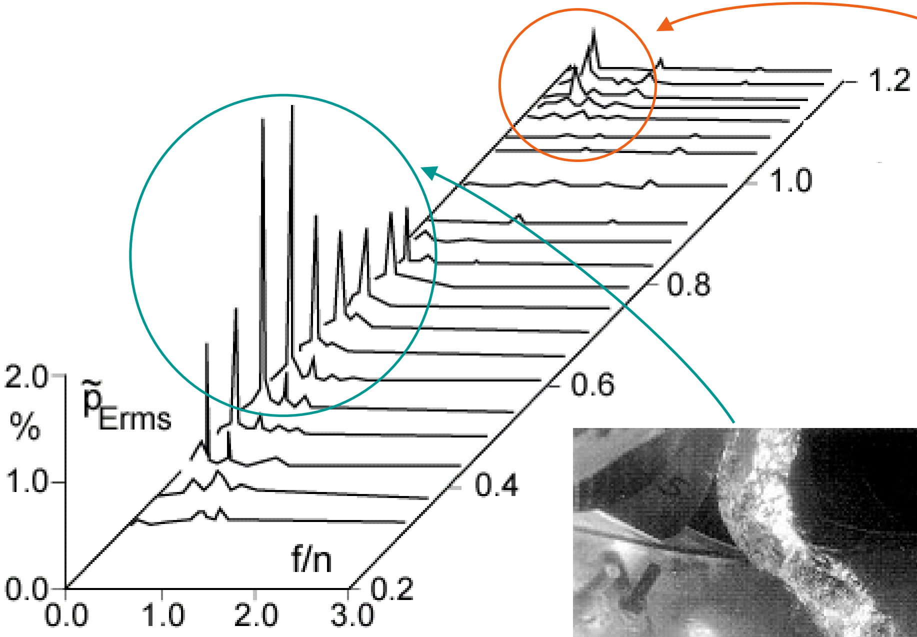


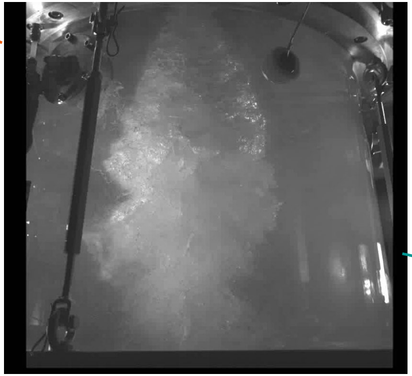


Driving Parameters Discharge and Thoma number

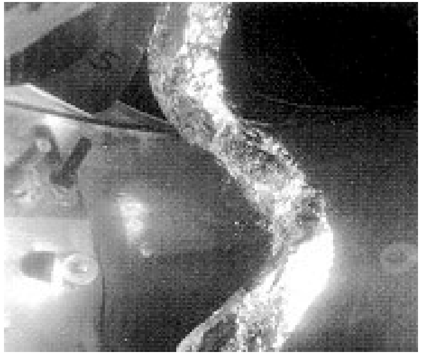
Operating issues

Pressure fluctuations → Power surge and vibrations

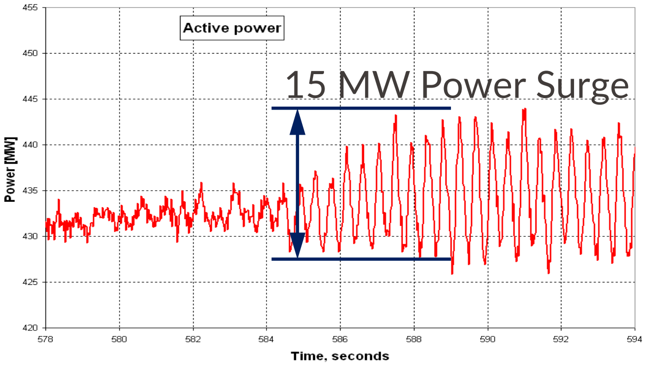




Full Load: $Q > Q_{BEP}$



Partial Load: $Q < Q_{BEP}$



Operating issues
Summary

- Noise, Vibration
- Cavitation Erosion
- Operation Instability
- Performance Alteration
  - Efficiency
  - Characteristic curves

Major Hydroelectric Power Stations are Francis Powered

Hydropower Plant	Country	Capacity (MW)	Energy (TWh)	EPFL Model Testing	Type
Three Gorges	China	22'500	98.5	○	Storage
Itaipú	Brazil-Paraguay	14'000	98.3	✓	Storage
Belo Monte	Brazil	11'233	-	✓	Run-of-River
Guri (Raúl Leoni)	Venezuela	8'850	53.4	✓	Storage
Tucurui	Brazil	8'370	41.4	✓	Storage
Grand Coulee	USA	6'809	20.0	✓	Storage
Longtan	China	6'426	18.7	○	Storage
Krasnoyarsk	Russia	6'000	20.4	○	Storage
Robert Bourassa (LG2)	Canada	5'616	26.5	✓	Storage
Churchill Falls	Canada	5'428	35.0	○	Storage

Xiangjiaba Power Station (Jinsha River, Yunnan)

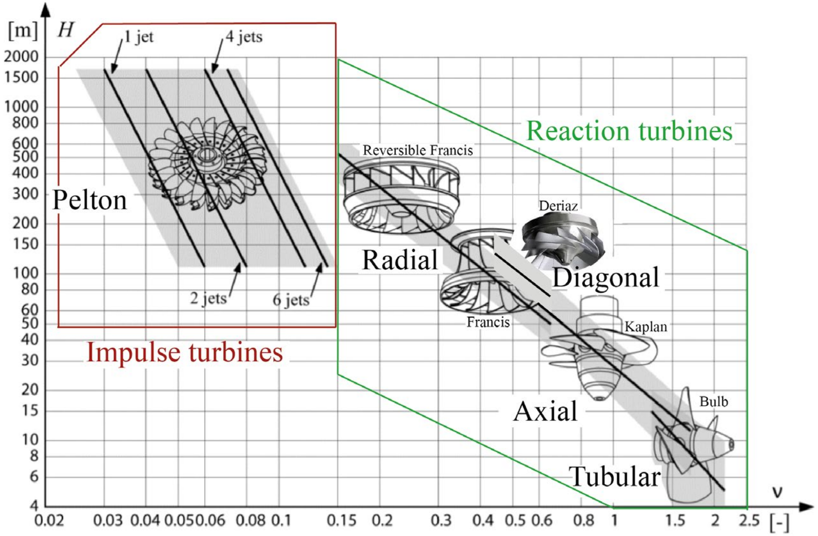
- 8 Francis Turbines
- 825 MW Max. Power
- 10.5 m Diameter
- ~ 406 000 kg

Toward 1 GW Unit Capacity?

Classification of Hydraulic Runners

Kaplan Runners

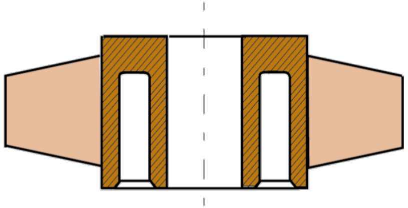
- Kaplan Turbine
  - Reaction machine
  - Axial flow
  - Low head



n_q = 200.....400

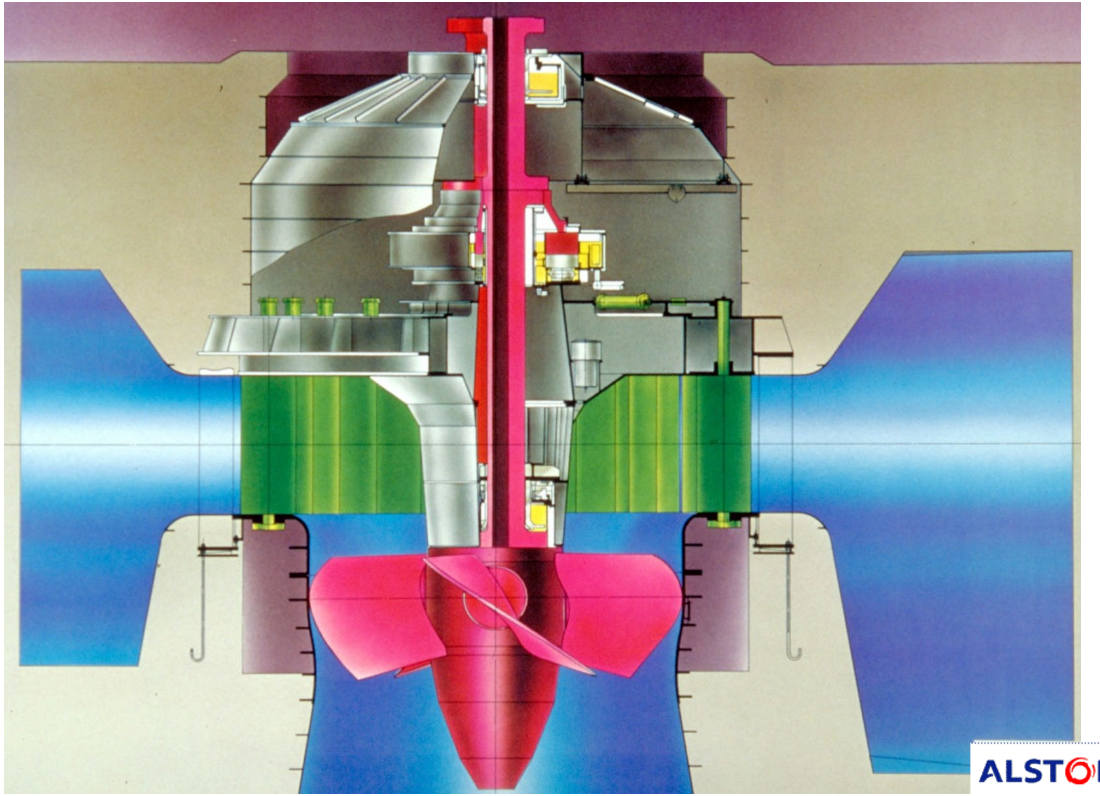
ν = 1.25....2.50

n_{QE} = 0.50...1.20



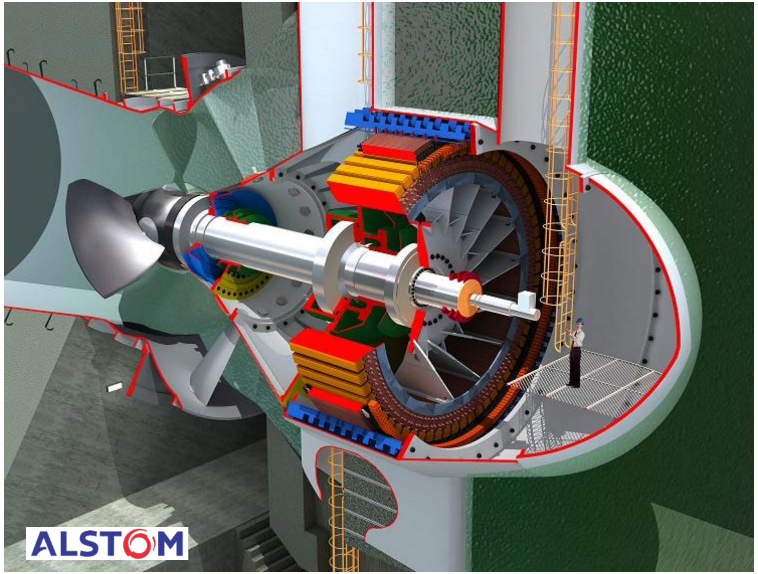
Classification of Hydraulic Runners

Kaplan Runners

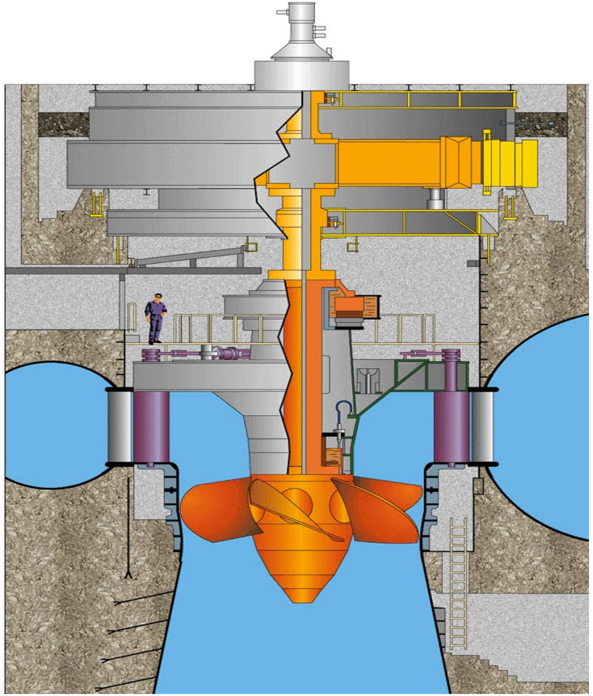


Bulb VS Kaplan

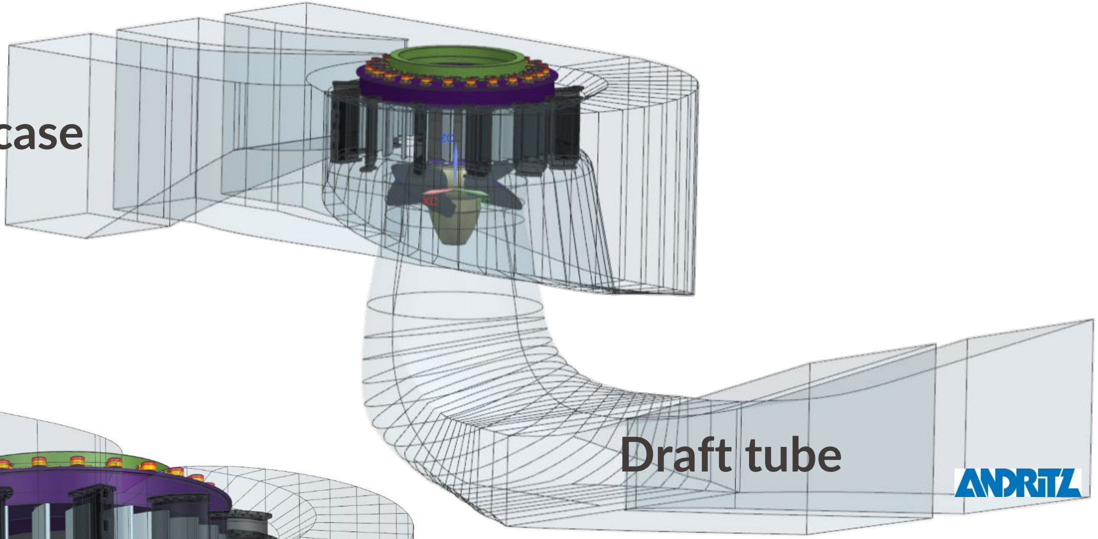
Bulb: fully axial or mixed flow

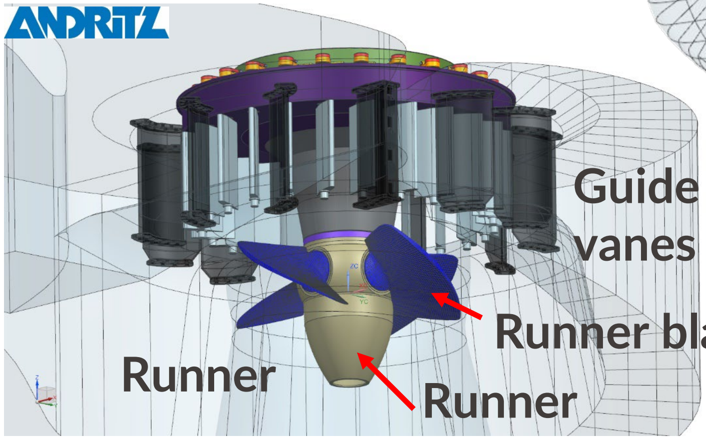


Kaplan: radial guide vanes and axial runner flow

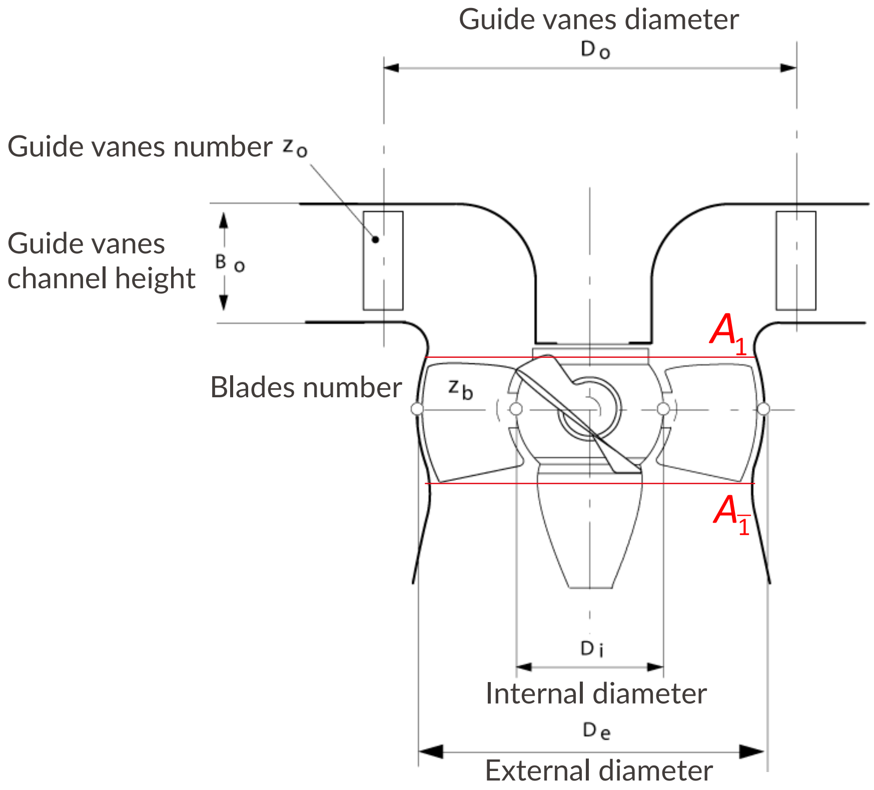


Main Geometrical Data of a Kaplan turbine





Main Geometrical Data of a Kaplan runner



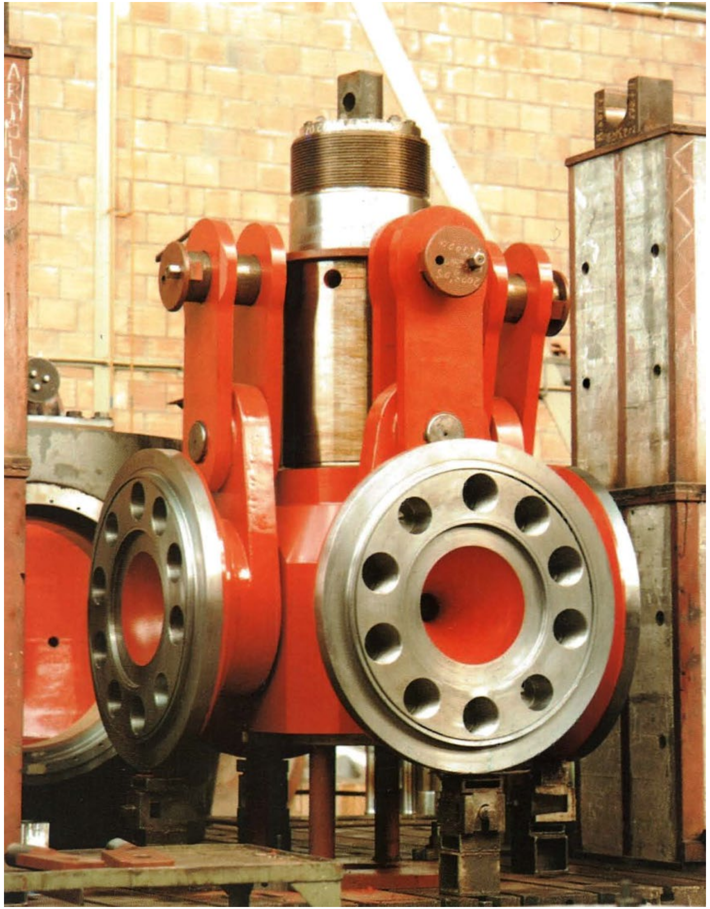
$$A_1 = \pi \frac{D^2_{1e} - D^2_{1i}}{4}$$

$$A_{\bar{1}} = \pi \frac{D^2_{\bar{1}e} - D^2_{\bar{1}i}}{4}$$

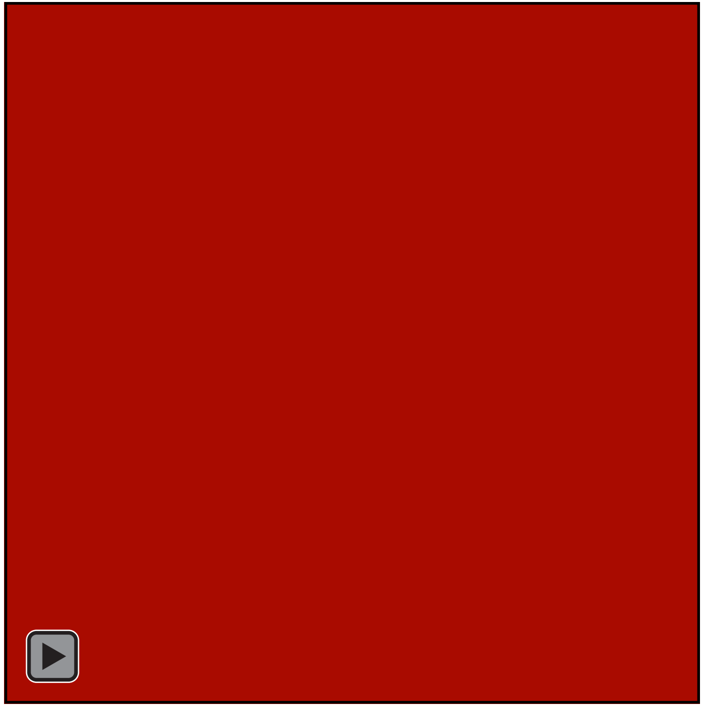
$$A_1 = A_{\bar{1}}$$

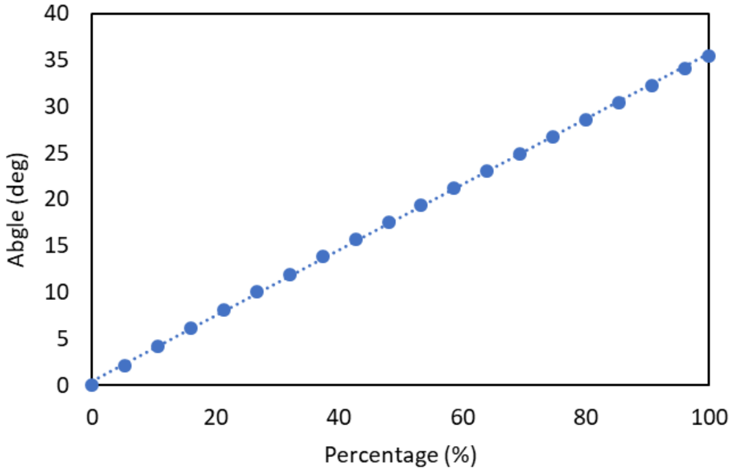
Controllable Pitch Kaplan Runner

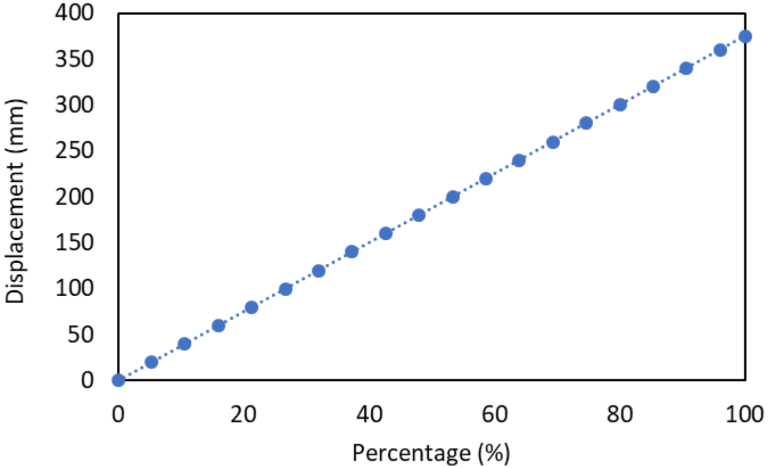
- Blade Base Plates
- Levers
- Connecting Rods
- Piston



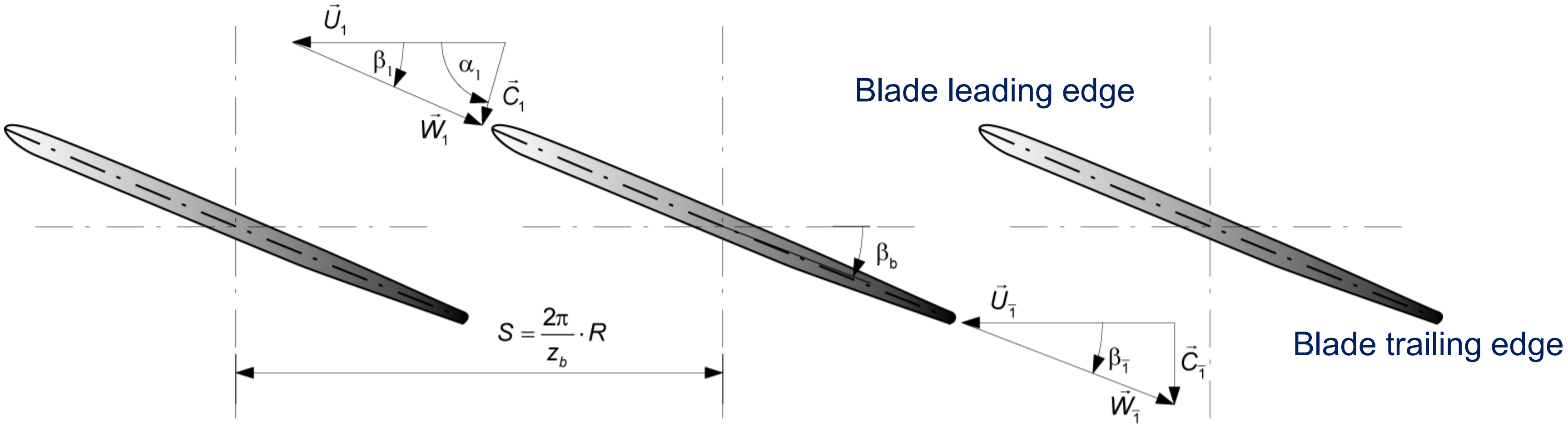
Controllable Pitch Kaplan Runner

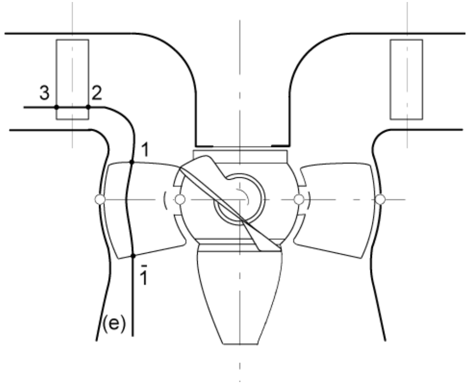




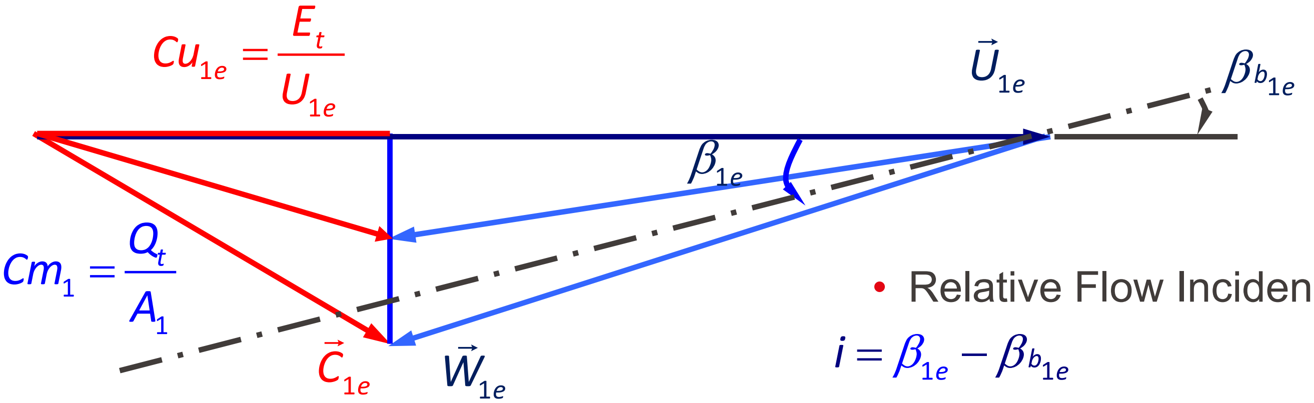


Controllable Pitch Kaplan Runner



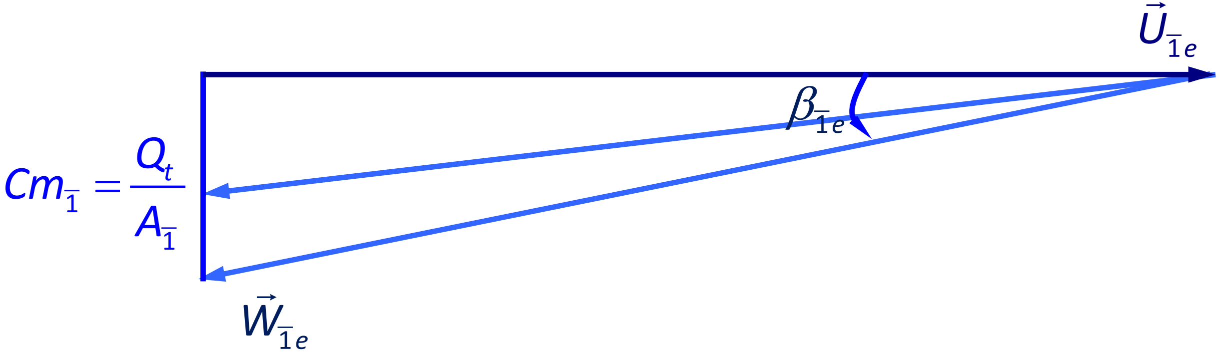


Flow Velocity Diagram

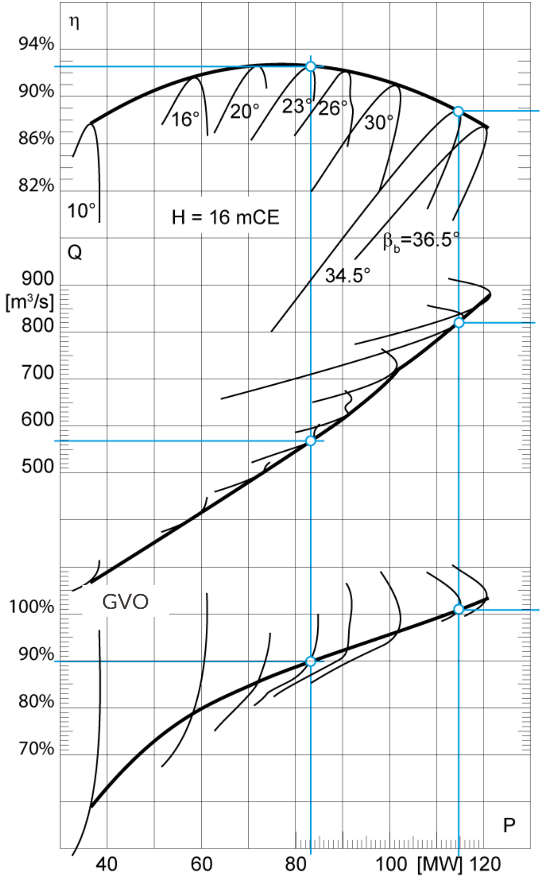


- Relative Flow Incidence

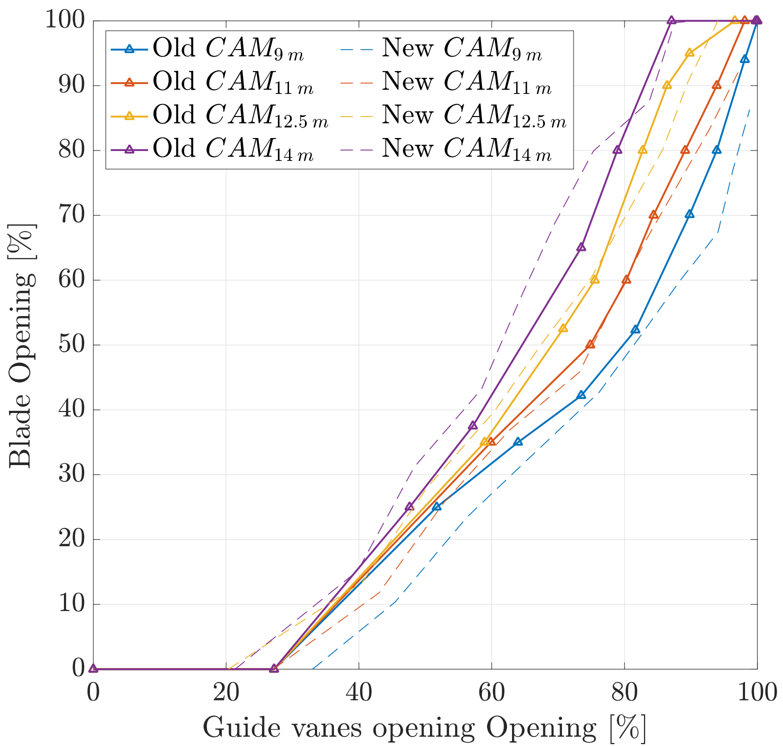
$$i = \beta_{1e} - \beta_{b_{1e}}$$



Hydraulic characteristics and on-cam curve



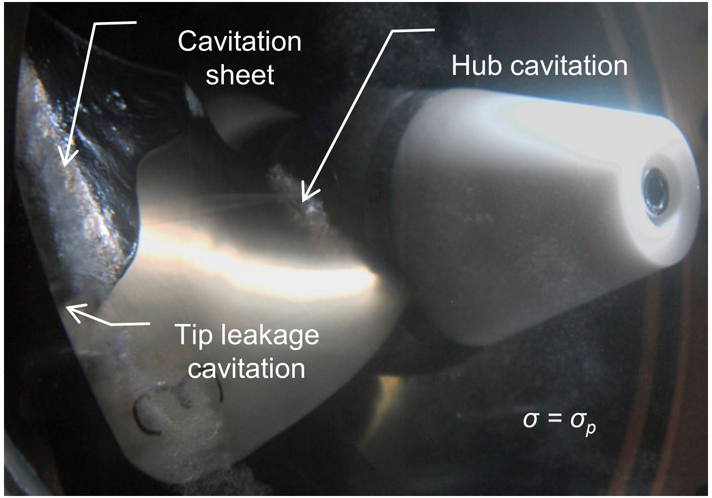
Yacyreta Power Plant

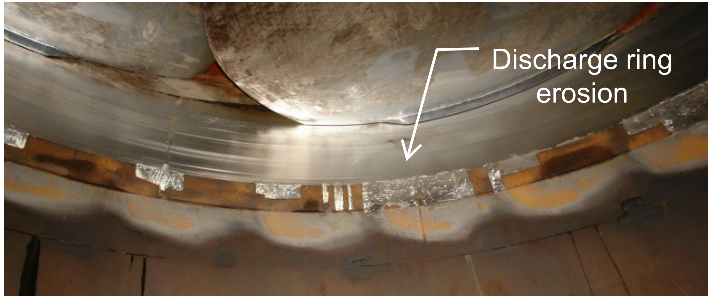


Vogelgrun Power Plant

Kaplan & Bulb Turbines: Main Issues

- Erosion Risk
  - Leading Edge Cavitation
  - Tip Vortex
  - Discharge ring erosion
  - Guide Vane Wakes-Blades interactions
- Efficiency Alteration
  - Hub Cavitation
  - Wear and tear

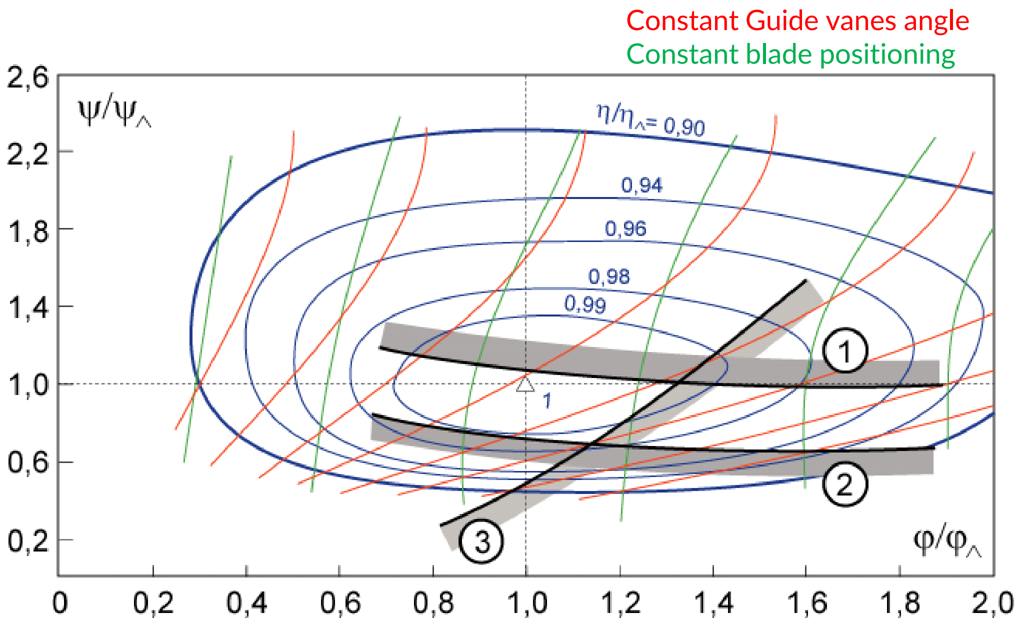




Kaplan Turbine Cavitation mapping

Specific Energy Coefficient

$$\psi = \frac{2}{\pi^2}\frac{E}{n^2 D^2}$$



Tip leakage Cavitation

- 1- Leading Edge Suction Side
- 2- Leading Edge Pressure Side
- 3- Hub Cavitation
- Tip leakage Cavitation

Discharge Coefficient

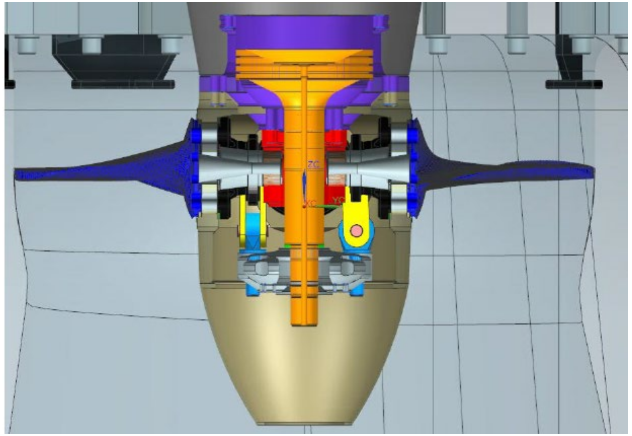
$$\varphi = \frac{4}{\pi^2}\frac{Q}{nD^3}$$

Nomenclature:

η_Δ (-) Efficiency at Best Efficiency Point (BEP)

Wear and Tear

- Fast dynamics (e.g. Frequency containment reserve)
- Number of guide vanes and blades movements
- Mileage



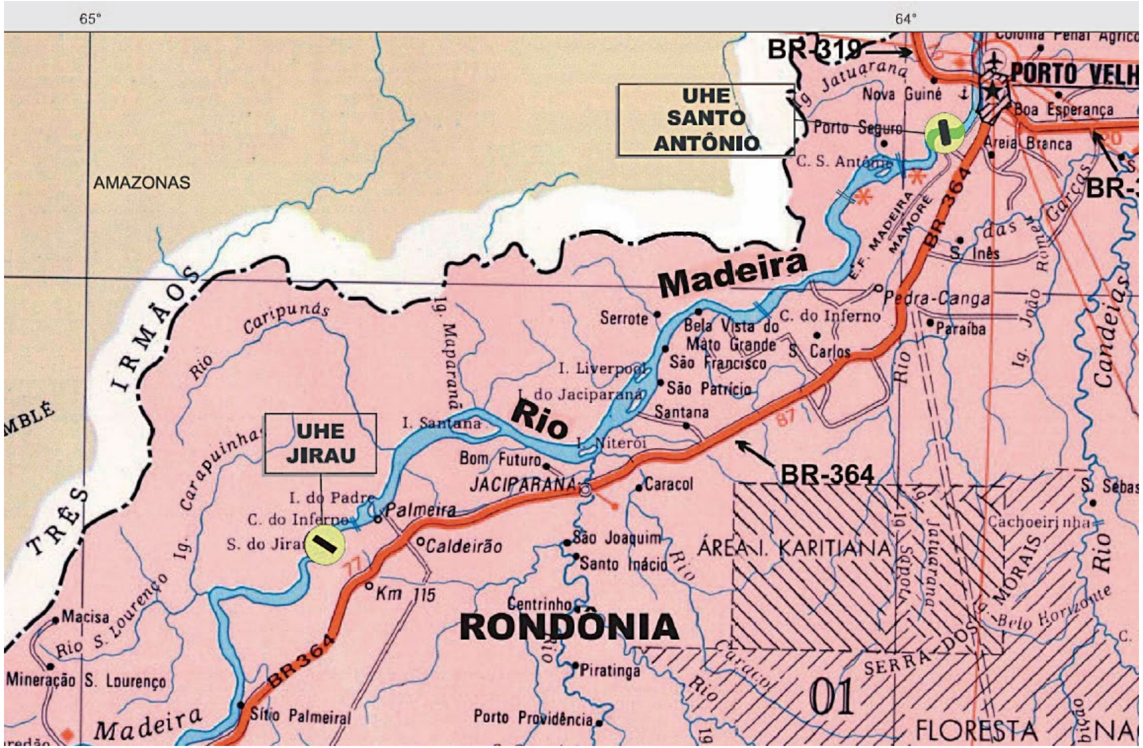
VOGELGRUN , France

- Four vertical Kaplan turbines
- Battery Hybrid

P = 35 MW, H = 12 m, Q = 325 m^3/s

Jirau Hydropower Project (Madeira River) Energia Sustentável do Brasil S.A.

- Run-of-river hydroelectric station
- 31 km² to 108 km² flooded area
- 83 m to 90 m a.s.l. headwater
- 74 m tailwater level
- 1'150 m long, 62 m high rock filled dam



Jirau Hydropower Project (Madeira River) Energia Sustentável do Brasil S.A.

Spillway
18 x 20 m wide radial gates

Spillway
18 x 20 m wide radial gates

Construction right bank power house

Right Bank Power Station
Draft Tube Construction

Right Bank Power Station
Draft Tube Construction

Right Bank Power Station
Draft Tube Construction

EPFL

Kaplan Runner and Regulating Ring