

The background of the slide is an aerial photograph of the Tucuruí Dam. The dam is a long, concrete structure with multiple spillways. Water is cascading over the spillways, creating a large plume of white spray at the base. The surrounding area is flat and appears to be a reservoir or a large body of water. A red semi-transparent banner is overlaid on the top right of the image.

L6 – Reaction Turbines

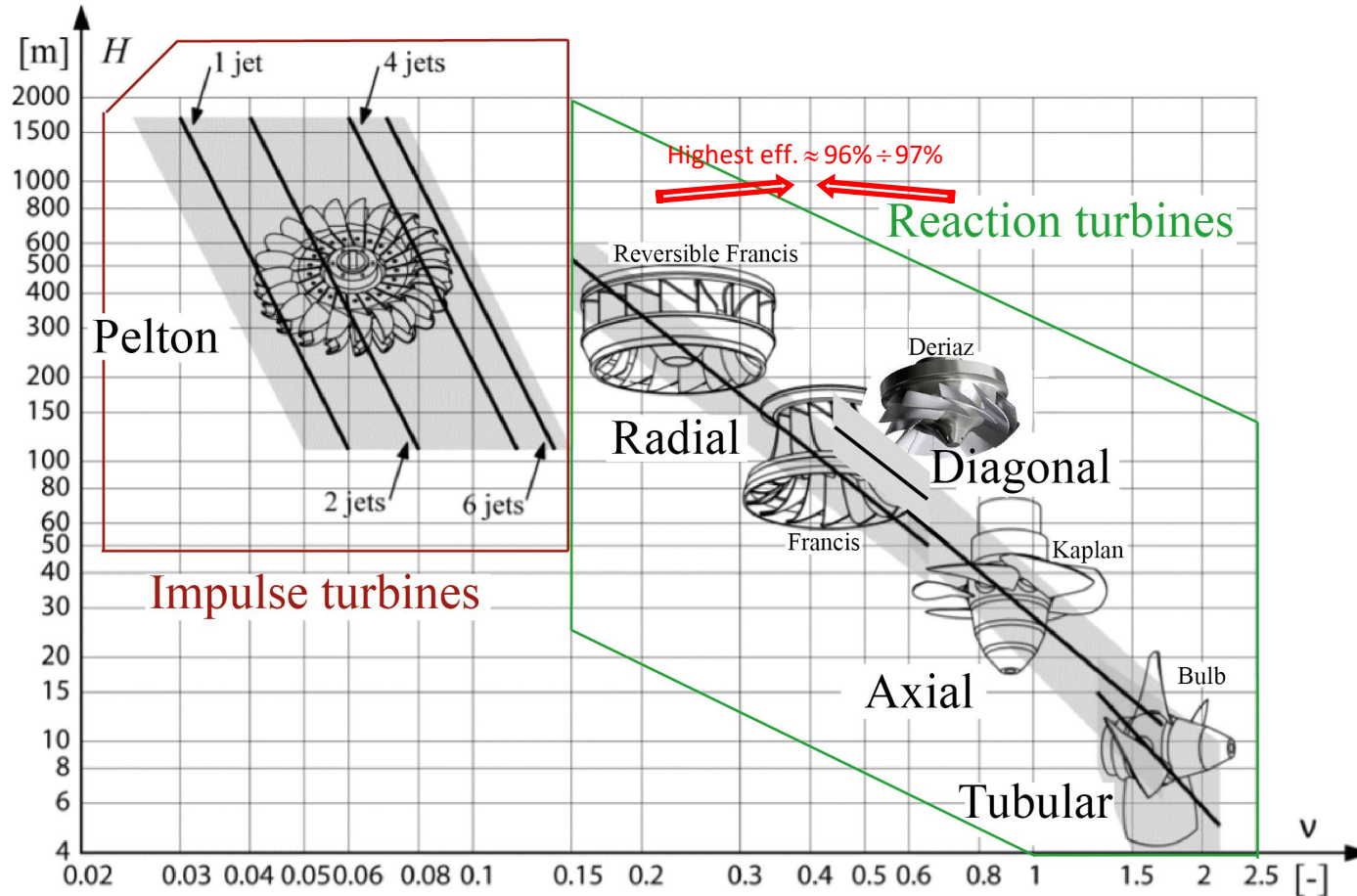
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EPFL Topics of the lecture

- Reaction turbines components
- Spiral case
- Guide vanes
- Runner parameters and velocity triangles
- Draft tube
- Main issues for Kaplan

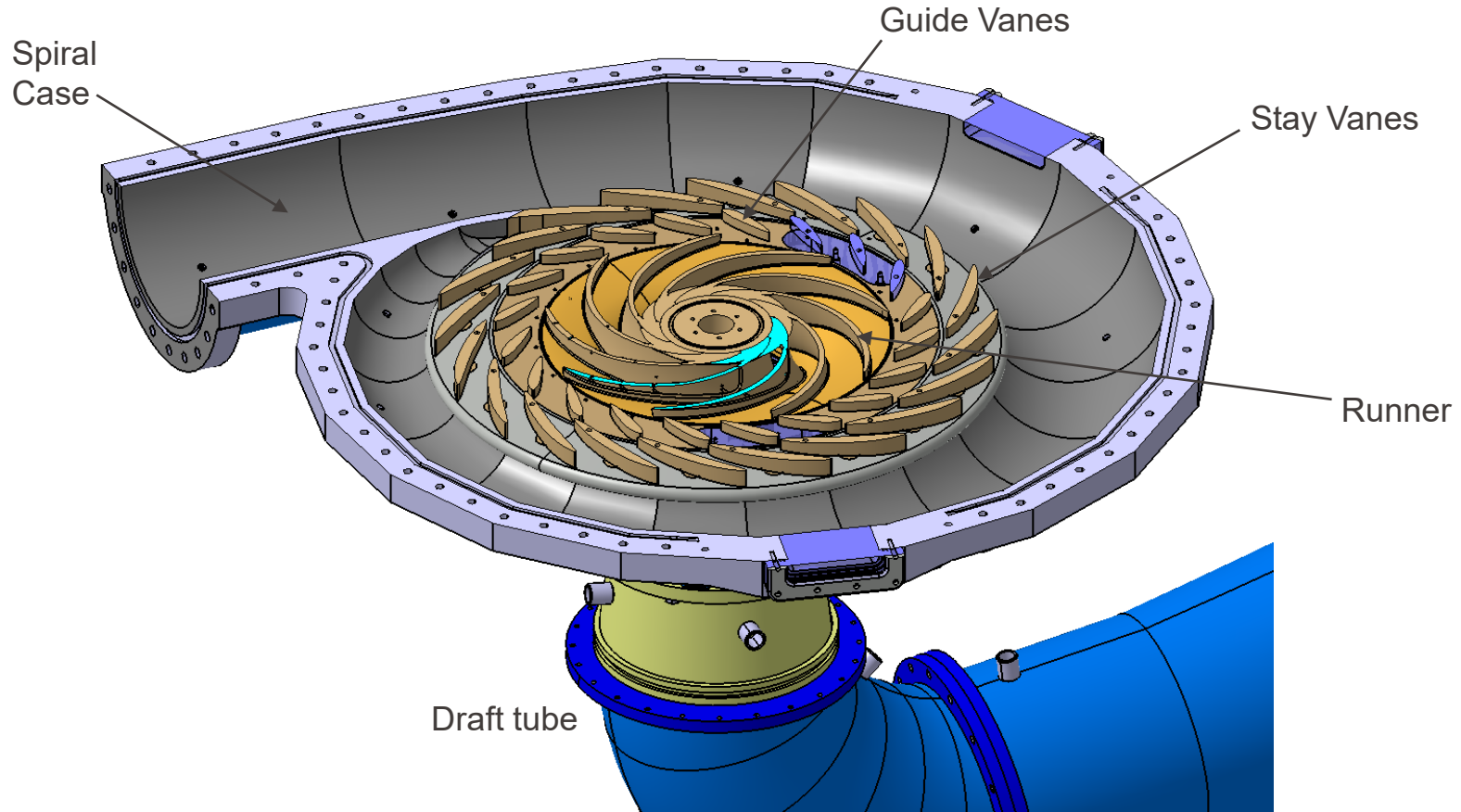
EPFL From L2: Classification of Hydraulic Runners



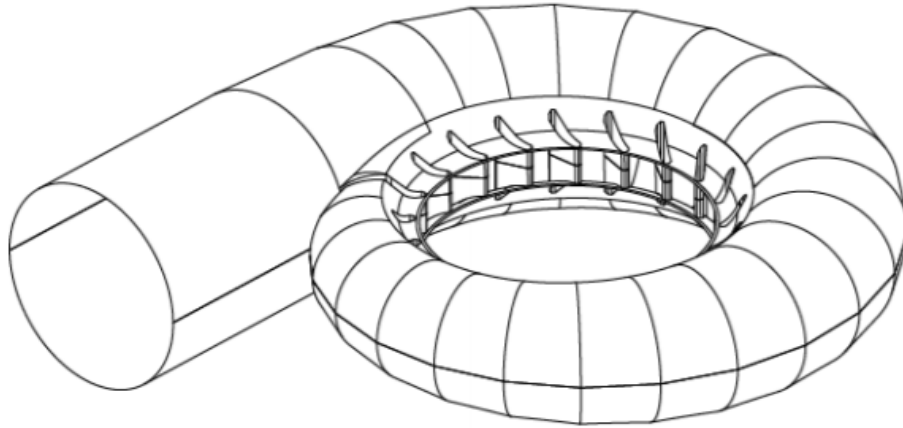
$$\begin{aligned} \text{Head} &= H \quad (\text{m}) \\ \text{Discharge} &= Q \quad (\text{m}^3 \cdot \text{s}^{-1}) \\ \text{Speed} &= N \quad (\text{min}^{-1}) \end{aligned}$$

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

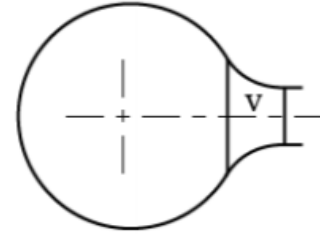
Classification and geometrical proprieties



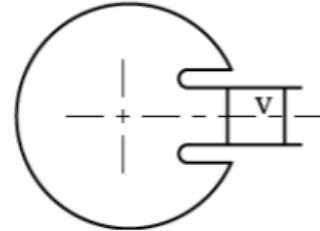
Types of Spiral Case



Double curvature



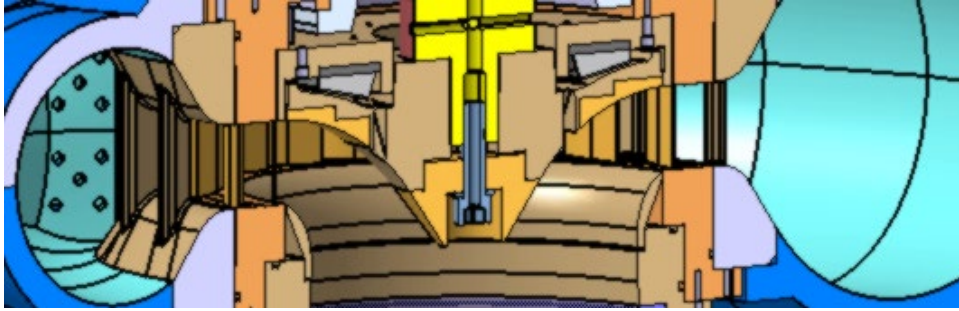
Piguet type



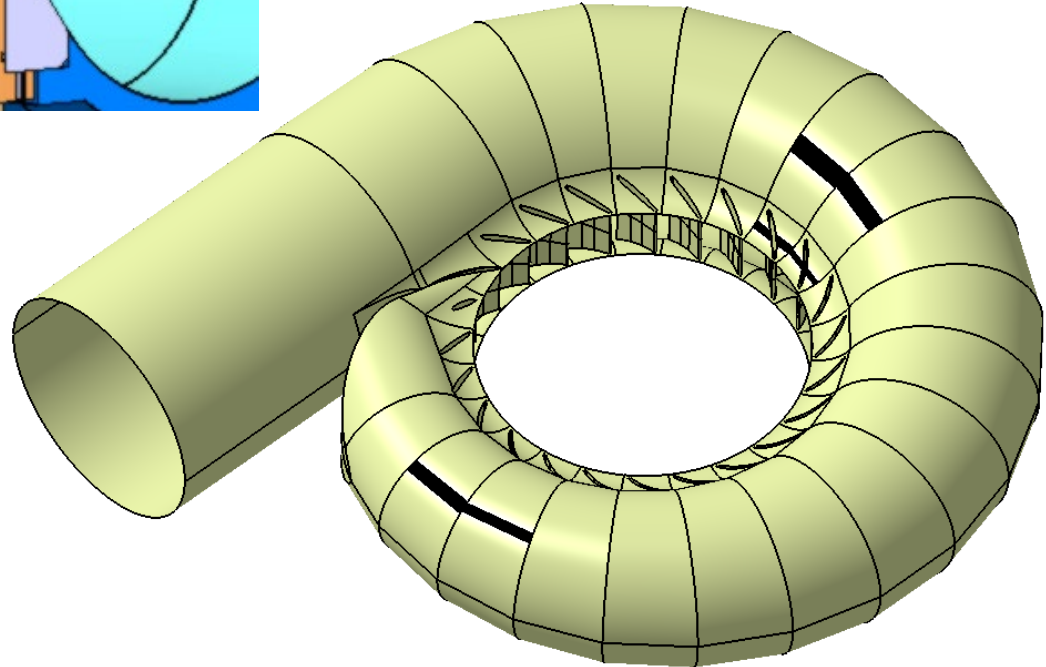
Spiral case: distributes uniformly the flow all around the runner

Stay vanes: addresses radially the flow at the inlet of the guide vanes to minimize losses and have maximum swirl; carry the axial forces in the spiral case

Double Curvature Spiral Case

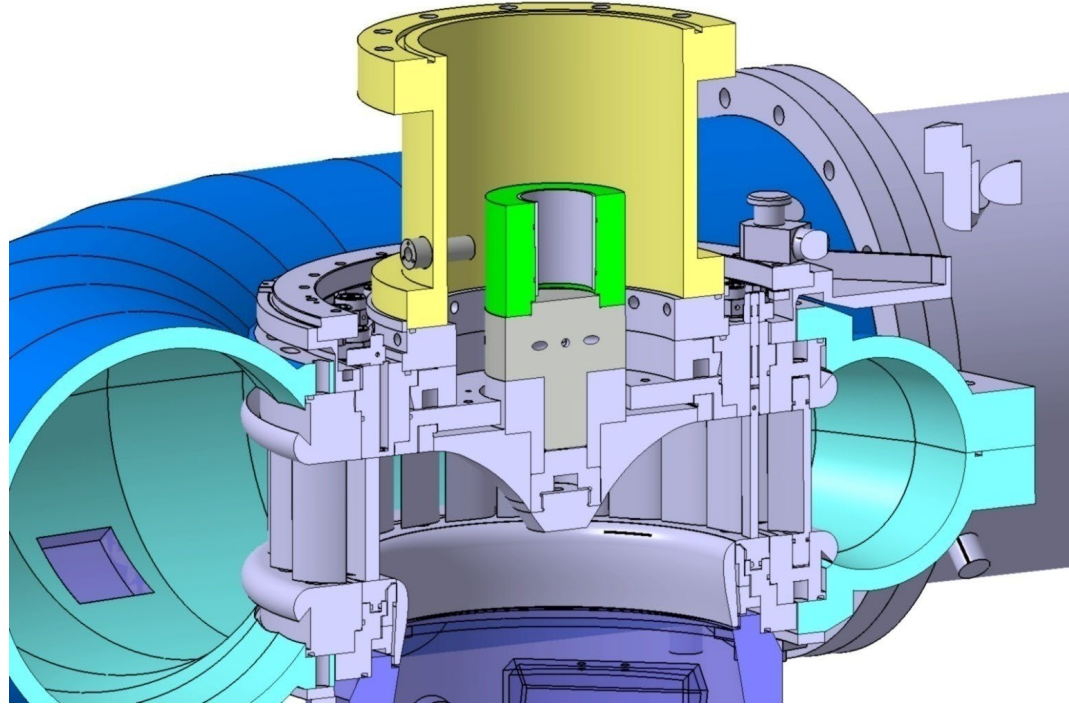


- Historical Casting Process
- Complex Distribution of Stresses
- Stay vanes are welded

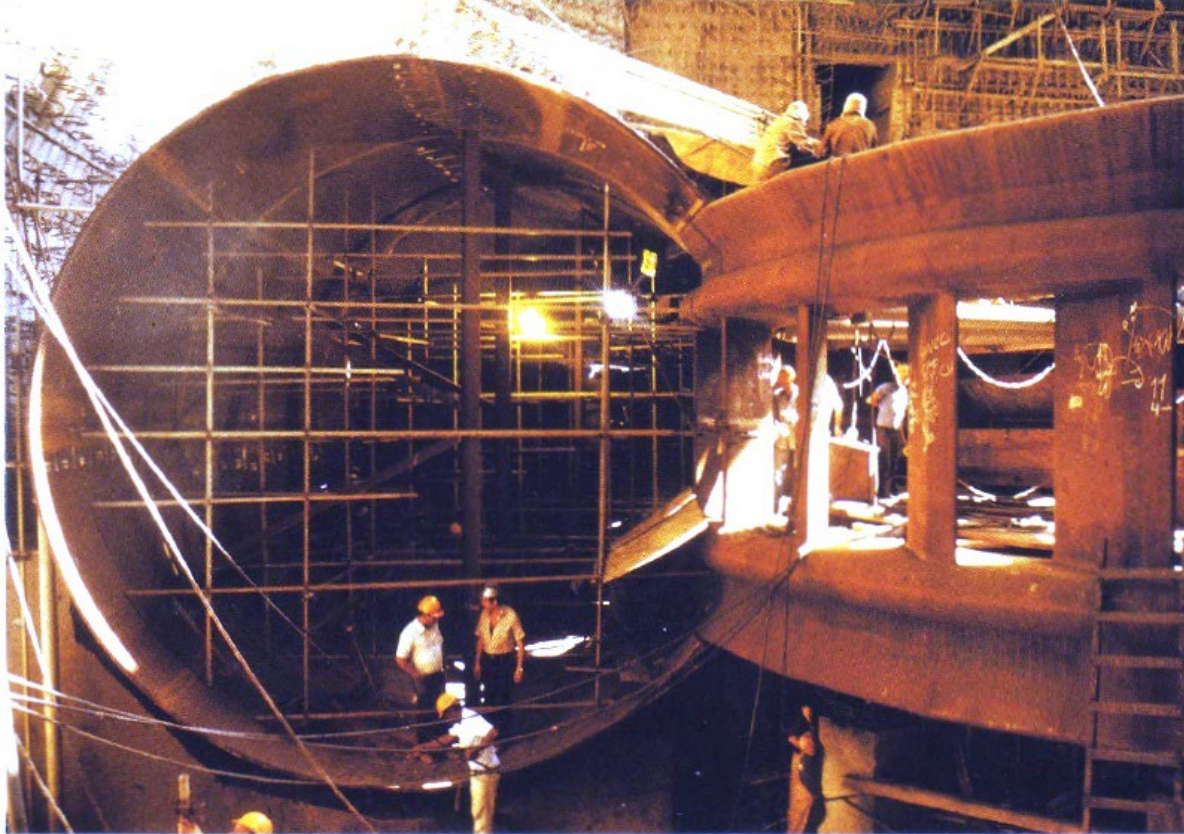


Spiral Case of Piguet Type

- Large Machines
- Welding Process
- Steel plates
- Stay ring with stay vanes



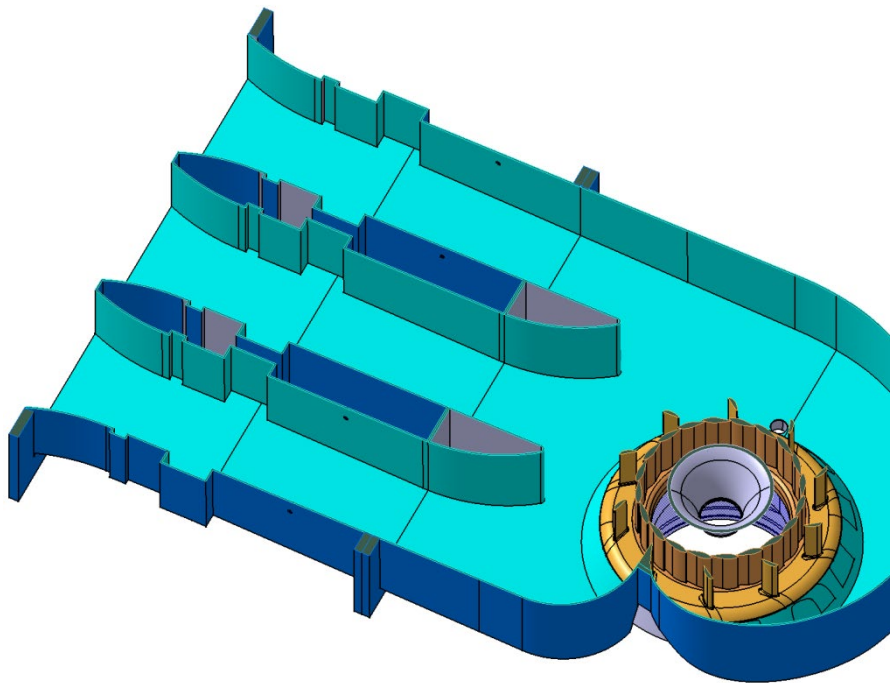
Spiral Case of Piguet Type Construction



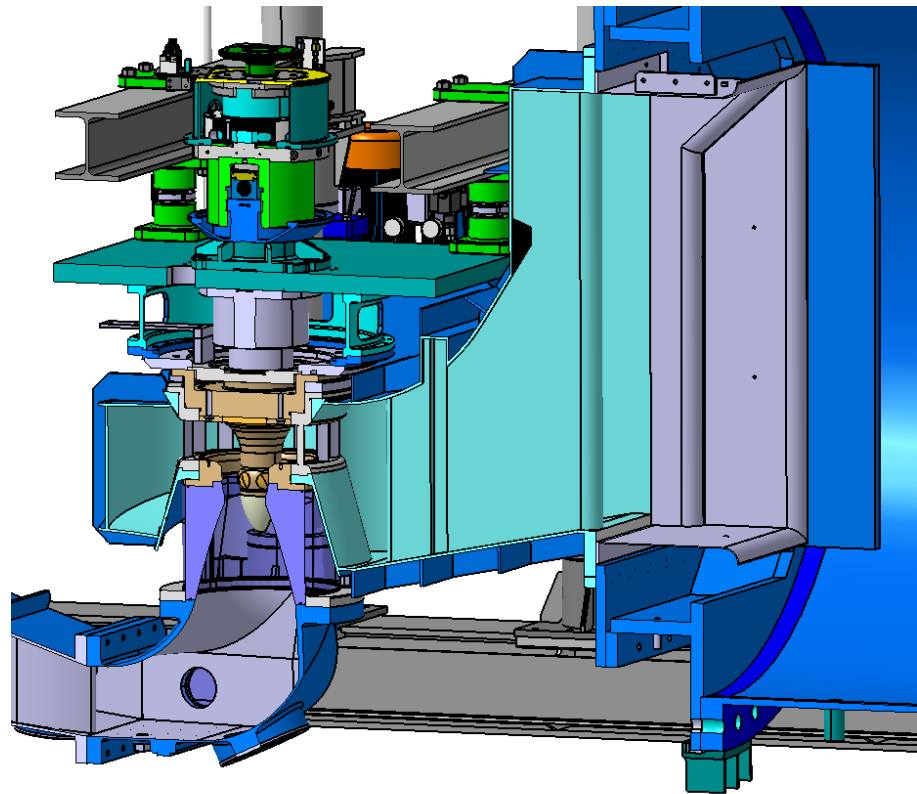
Construction of Itaipu Turbines

Semi Spiral Case

For low-head turbines

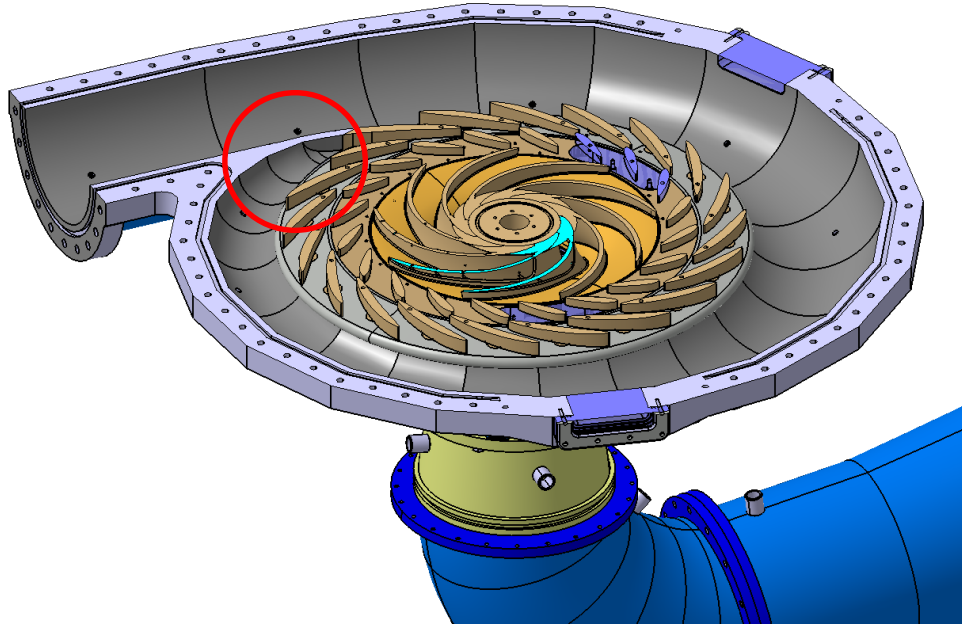


Made of concrete and included in civil works



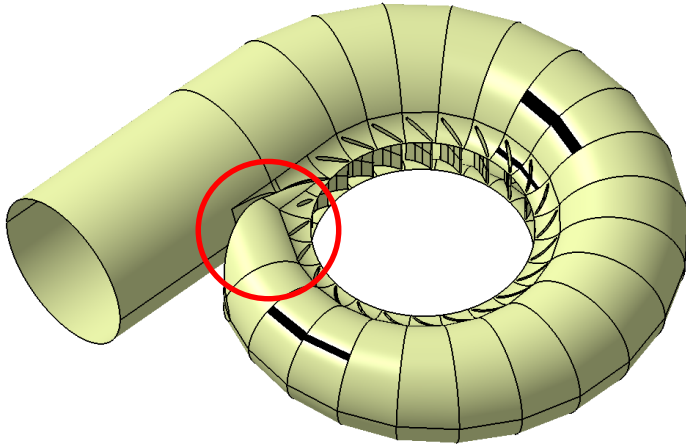
Spiral Case

Tongue or Nose vane

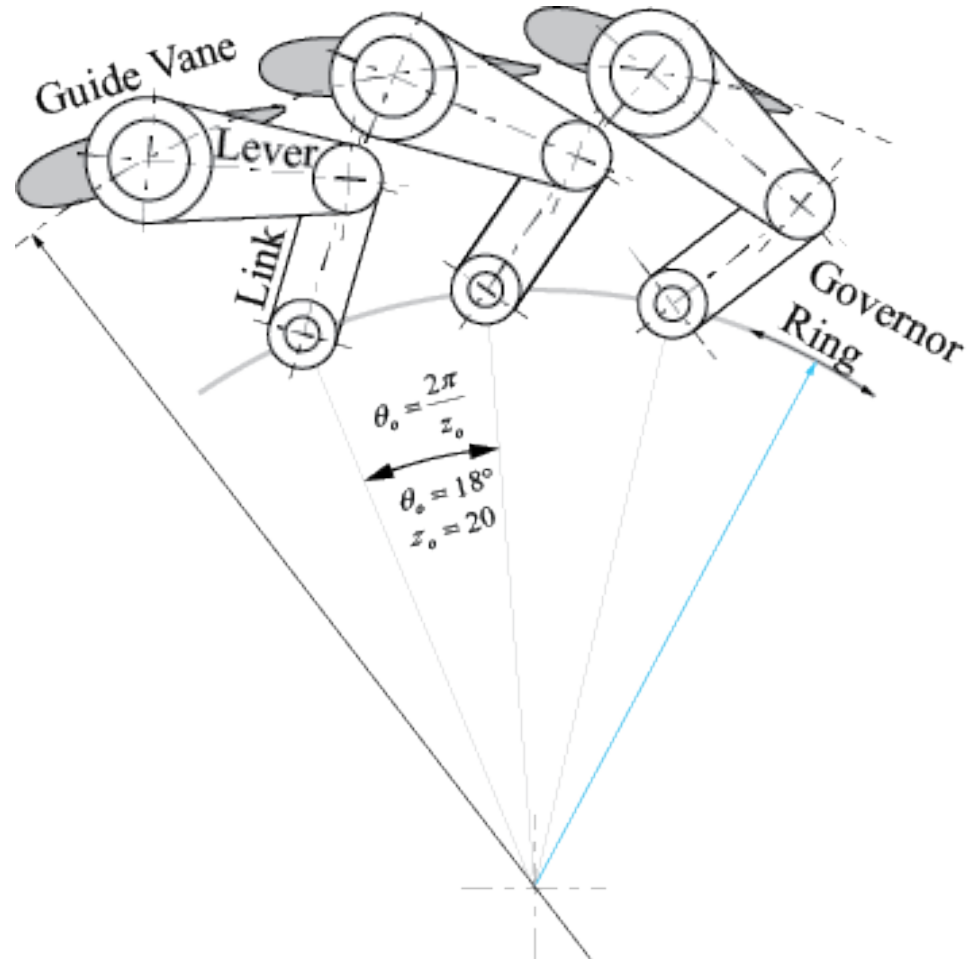


Spiral Case

Tongue or Nose vane

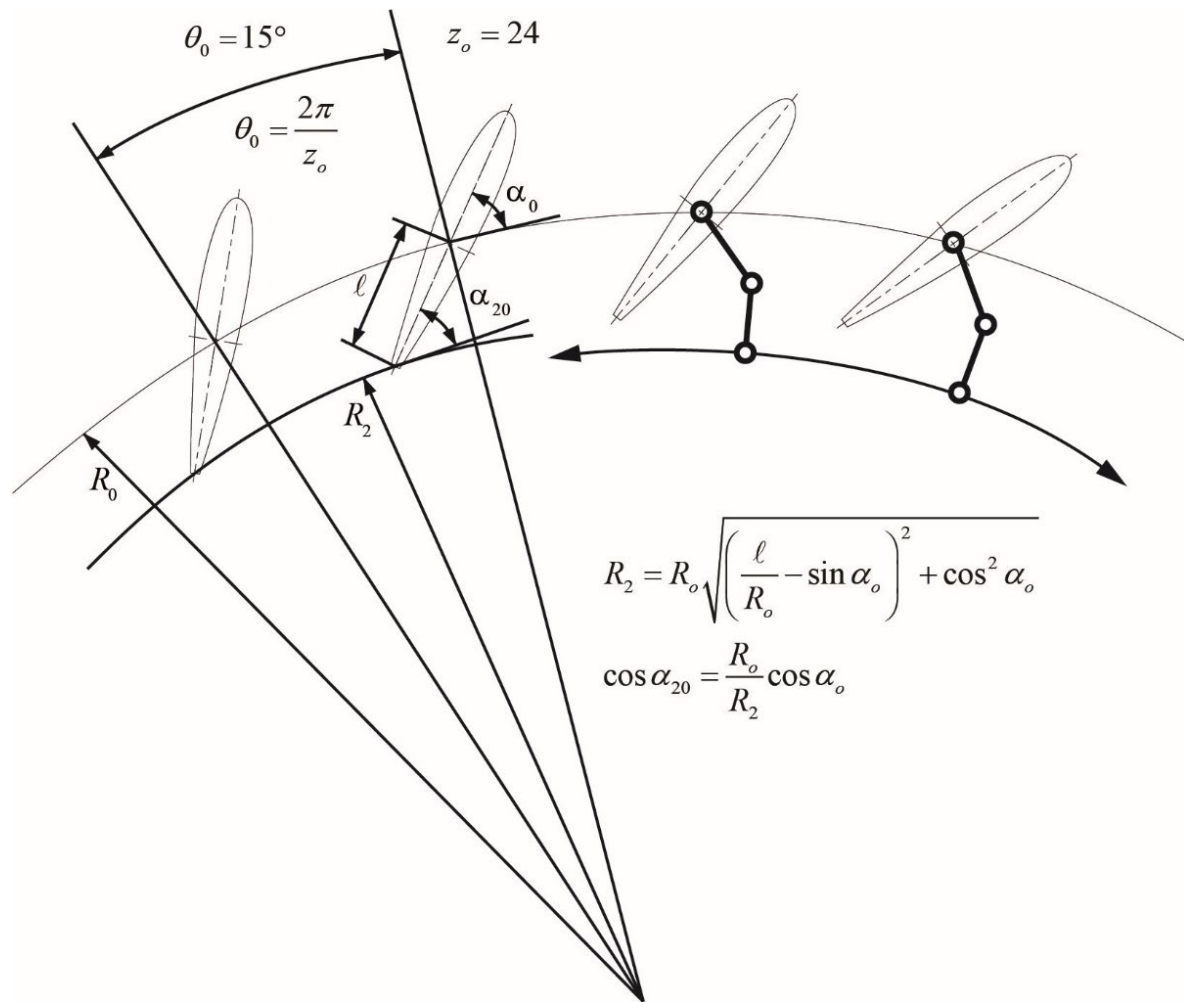


Guide Vanes



Guide Vanes

- Angular Momentum Control
- Sealed at Closed Position



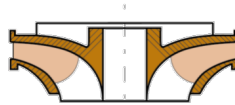
Classification of Hydraulic Runners

Francis Runners and Impellers

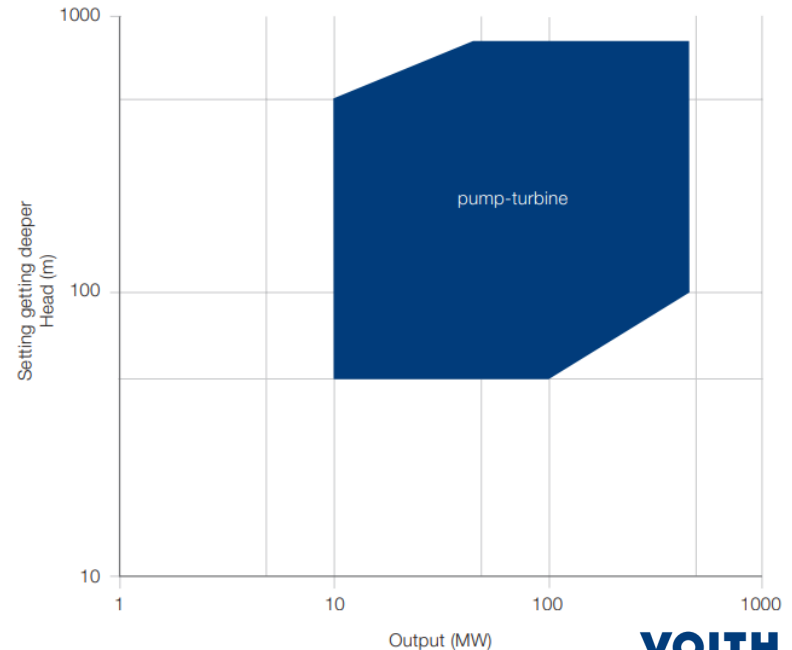
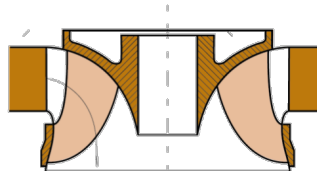
- Francis-type turbine and pump-turbine
 - Reaction machine
 - Radial flow
 - Medium Head



$n_q = 12 \dots 35$
 $v = 0.10 \dots 0.22$
 $\eta_{QE} = 0.04 \dots 0.10$



$n_q = 35 \dots 80$
 $v = 0.22 \dots 0.50$
 $\eta_{QE} = 0.10 \dots 0.24$



Low Specific Speed Francis Runner

Example: Alto Lindoso (Portugal)

$$E = 2'144 \text{ J} \cdot \text{kg}^{-1}$$

$$Q = 108.7 \text{ m}^3 \cdot \text{s}^{-1}$$

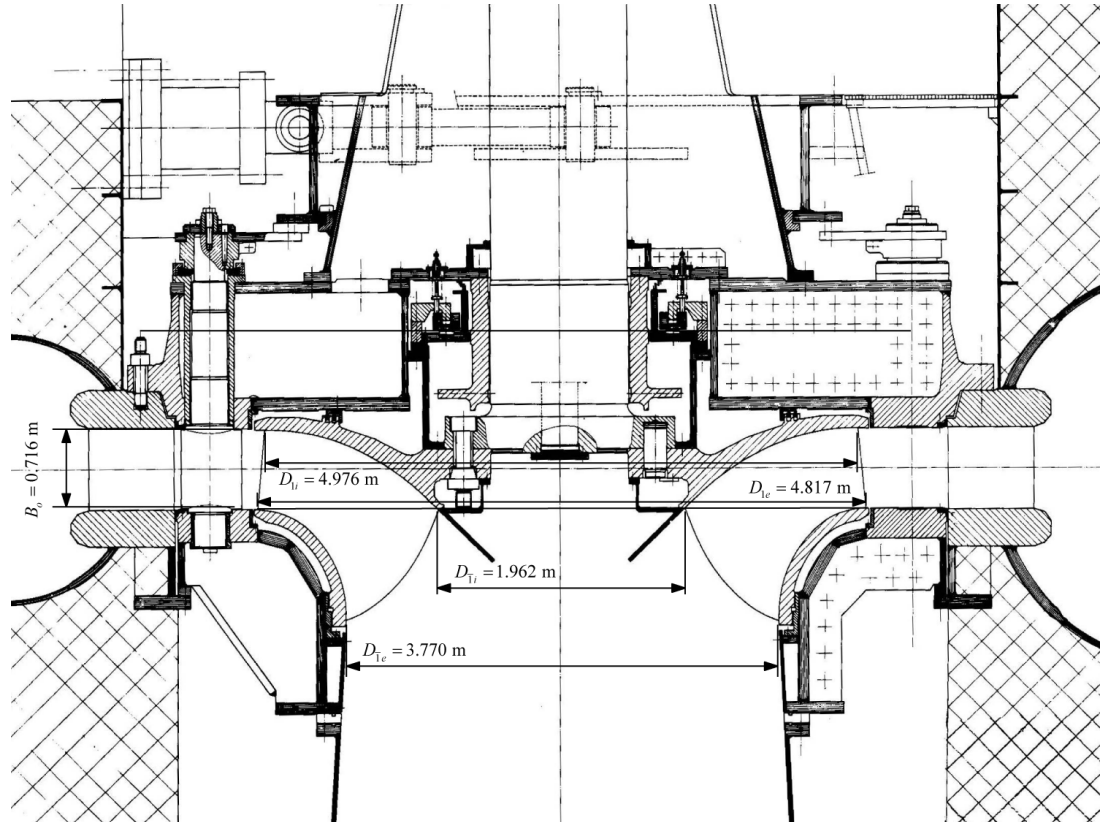
$$P = 317.0 \text{ MW}$$

$$N = 214 \text{ min}^{-1}$$

$$D_{1e} = 3.770 \text{ m}$$

$$D_{1i} = 4.976 \text{ m}$$

$$B_o = 0.716 \text{ m}$$



High Specific Speed Francis Runner

Example: Tucuruí (Brazil)

$$E = 596 \text{ J} \cdot \text{kg}^{-1}$$

$$Q = 574 \text{ m}^3 \cdot \text{s}^{-1}$$

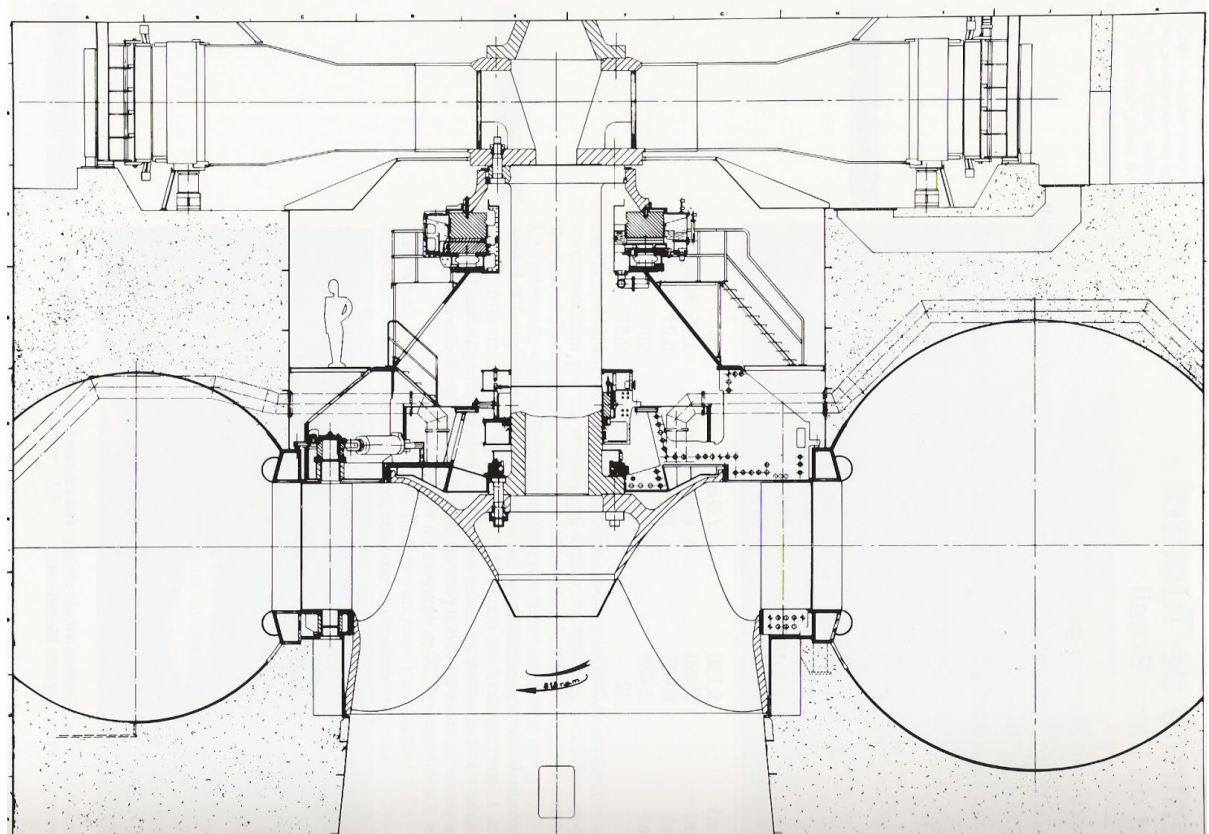
$$P = 320 \text{ MW}$$

$$N = 81.8 \text{ min}^{-1}$$

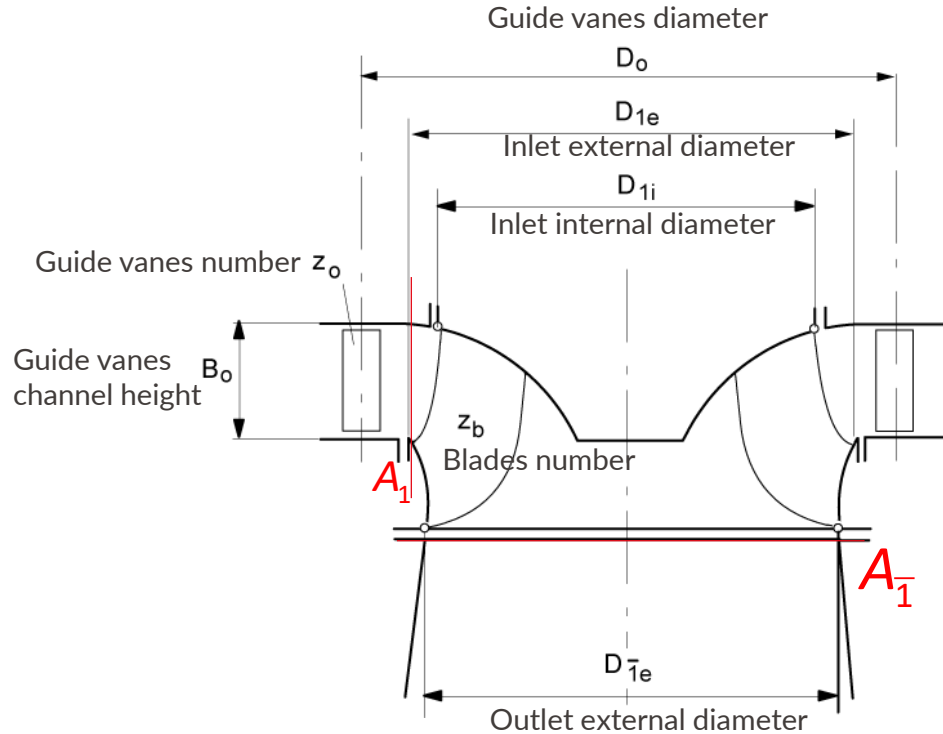
$$D_{1e} = 8.150 \text{ m}$$

$$D_{1i} = 5.480 \text{ m}$$

$$B_o = 2.475 \text{ m}$$



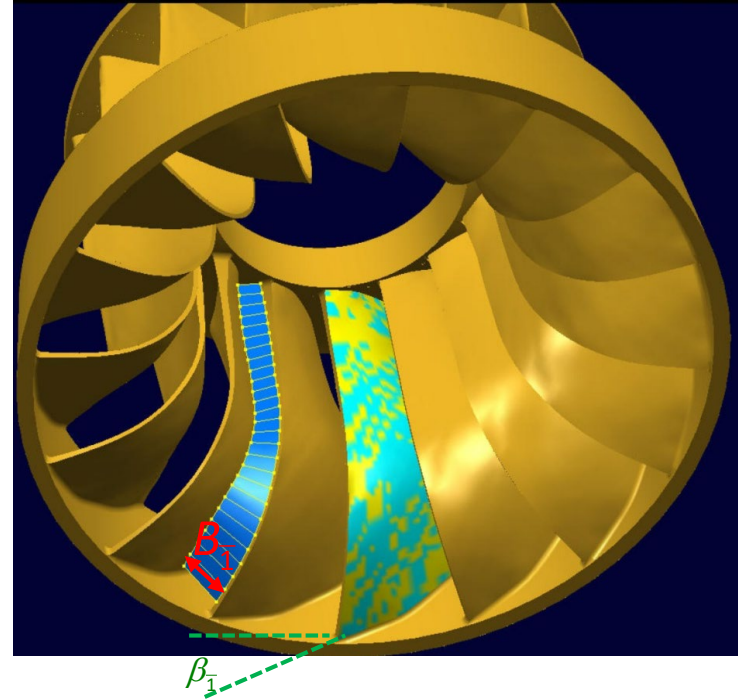
EPFL Main Geometrical Data of a Francis runner



$$A_1 = \pi D_{1e} B_o$$

$$A_{\bar{1}} = \pi \frac{D_{\bar{1}e}^2}{4}$$

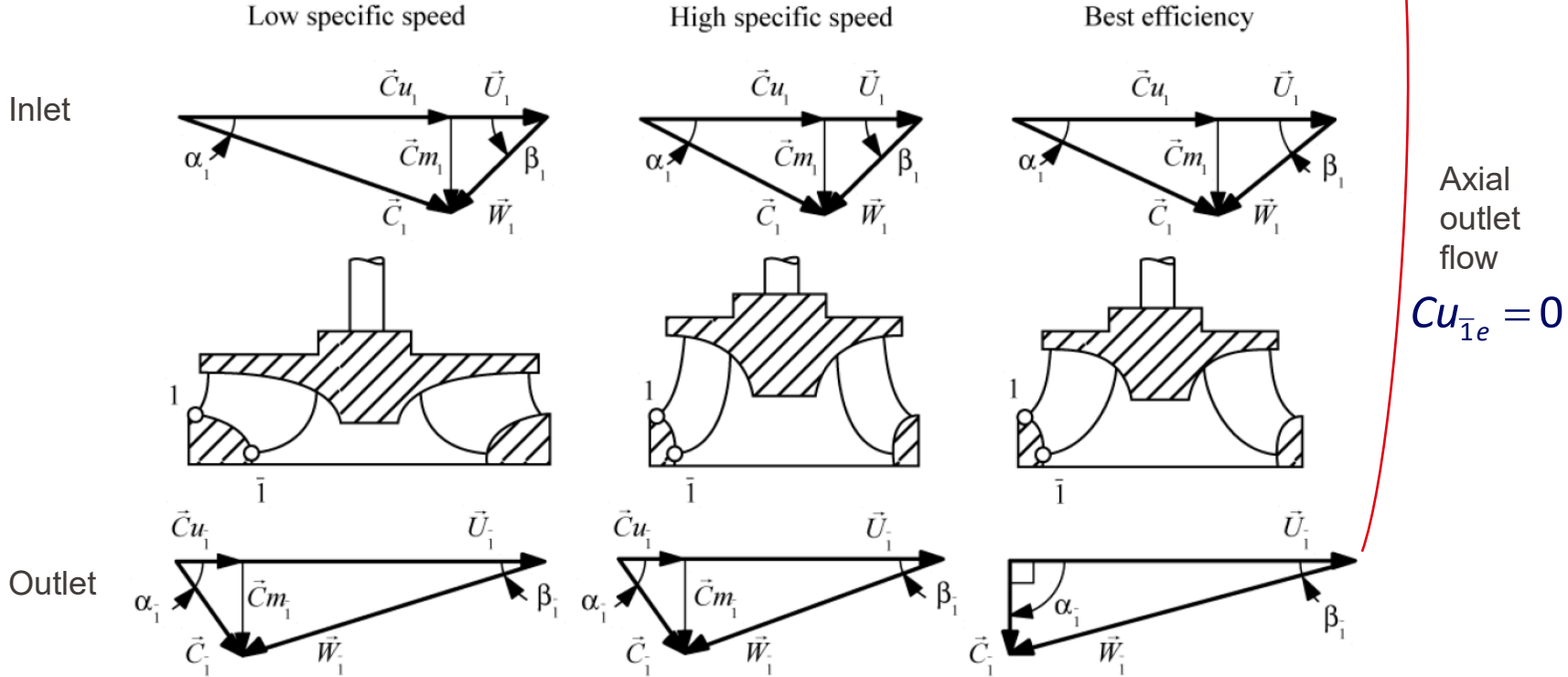
Vent Opening (Flow passage section)



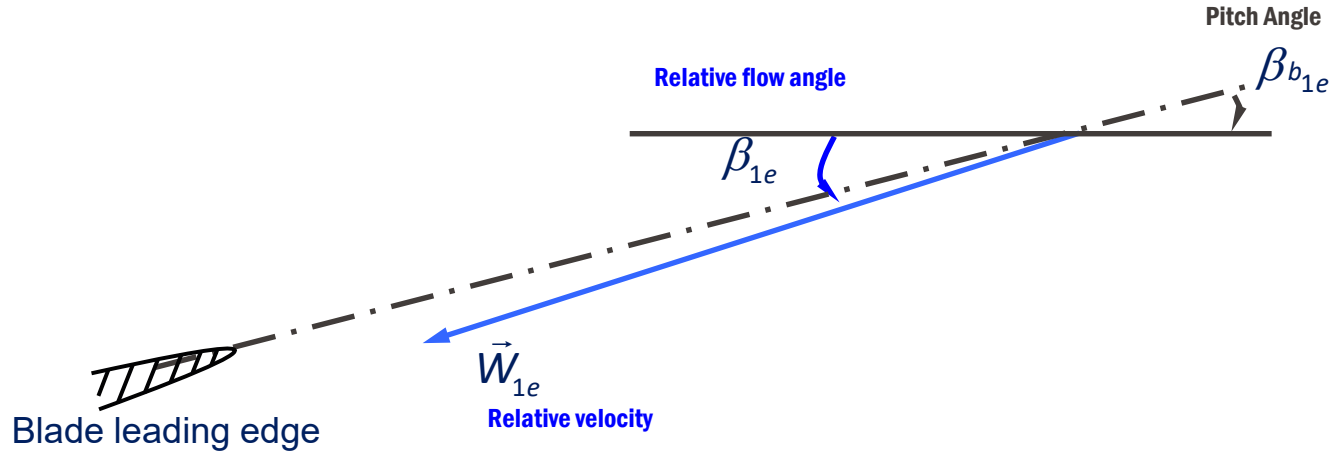
$$\sin \beta_1 = \frac{z_b B_1}{2\pi R_1}$$

Turbine Runner Velocity Triangles

~~$$E_t = U_{1e} C u_{1e} - k_{C u_{1e}} U_{1e} C u_{1e}$$~~



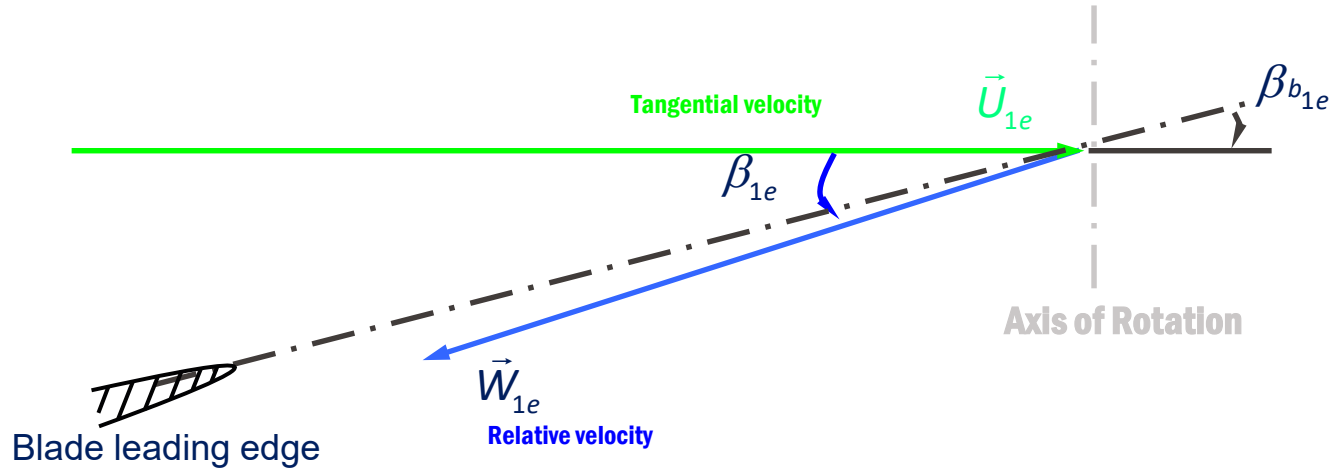
Flow Velocity Diagram



- Relative Flow Incidence

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

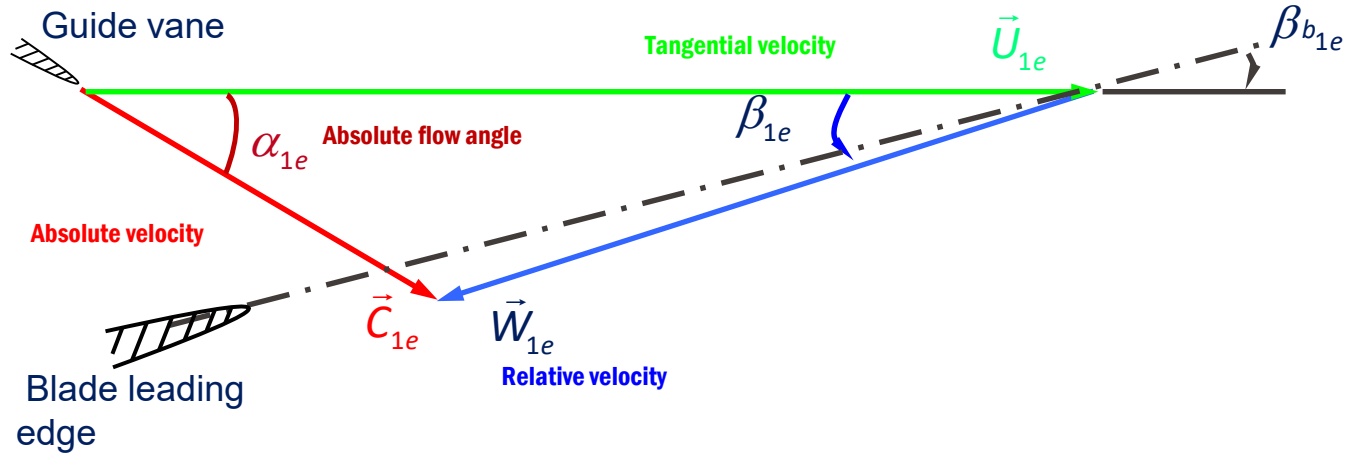
Flow Velocity Diagram



- Relative Flow Incidence

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

Flow Velocity Diagram



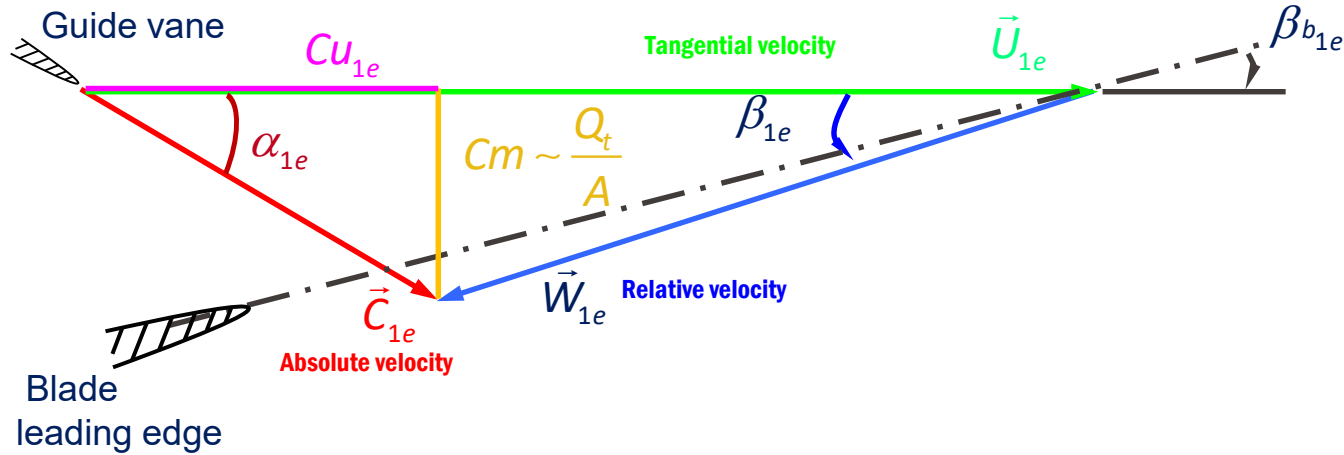
Absolute velocity

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

- Relative Flow Incidence

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

Flow Velocity Diagram

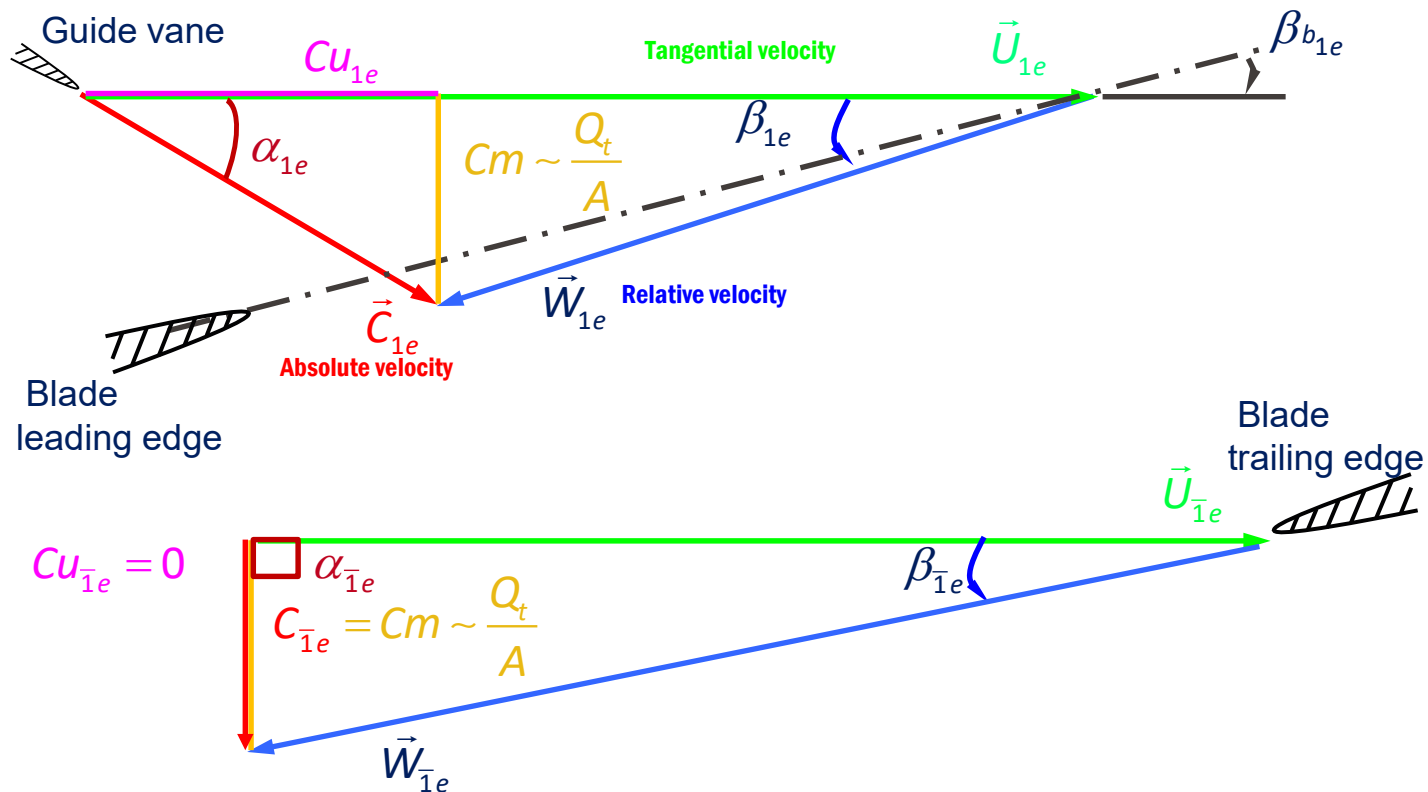


Meridional component of the absolute velocity

Tangential component of the absolute velocity

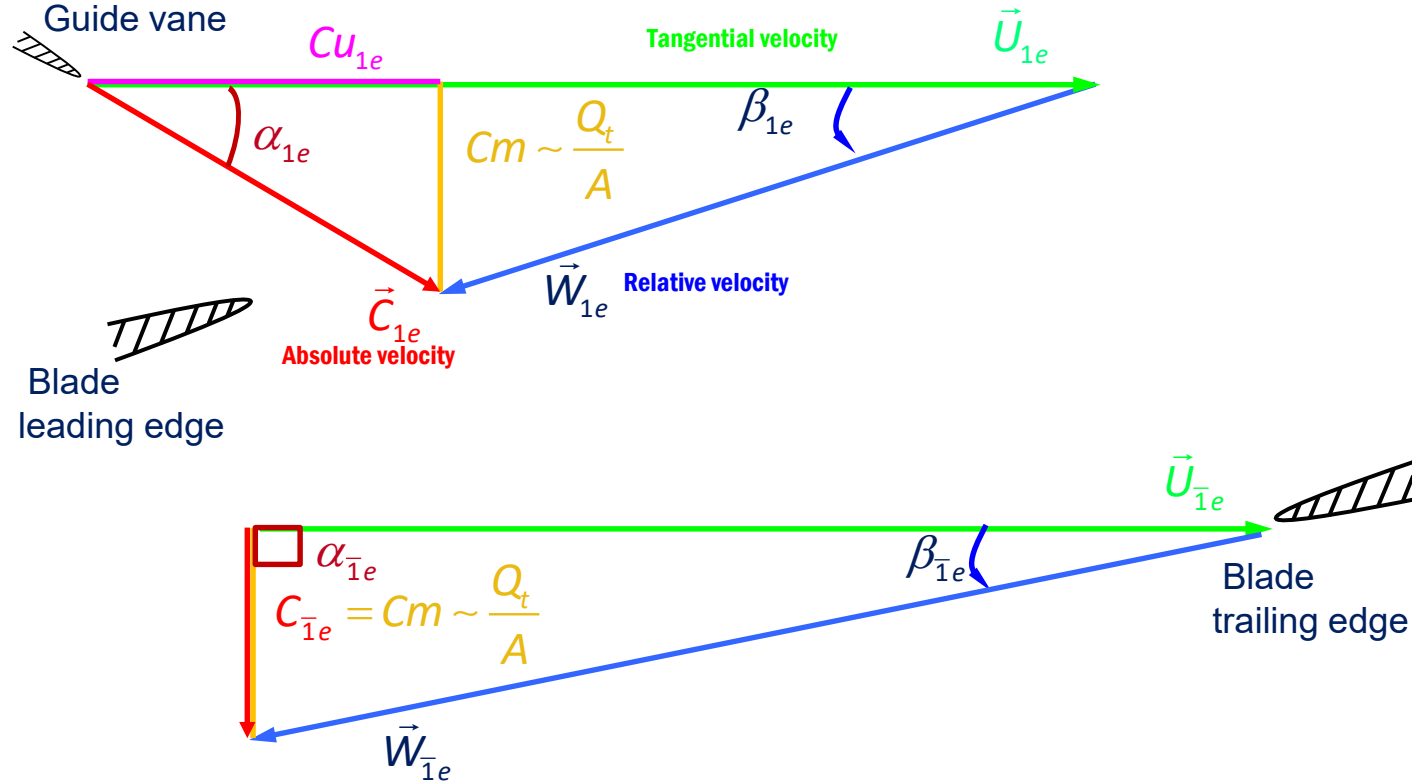
$$C_u = \frac{C_m}{\tan \alpha} = U - \frac{C_m}{\tan \beta}$$

Flow Velocity Diagram



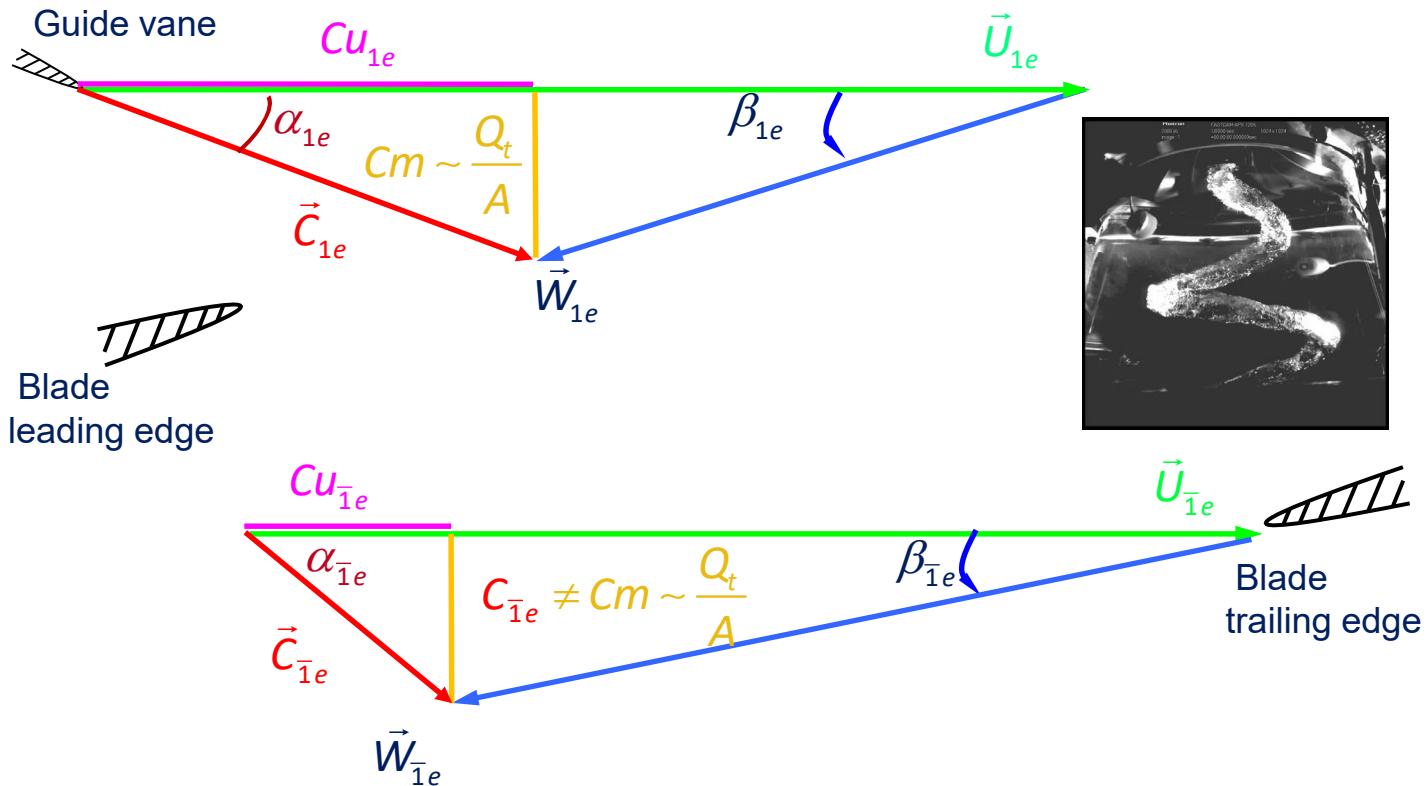
Flow Velocity Diagram

Let's imagine the discharge decreases



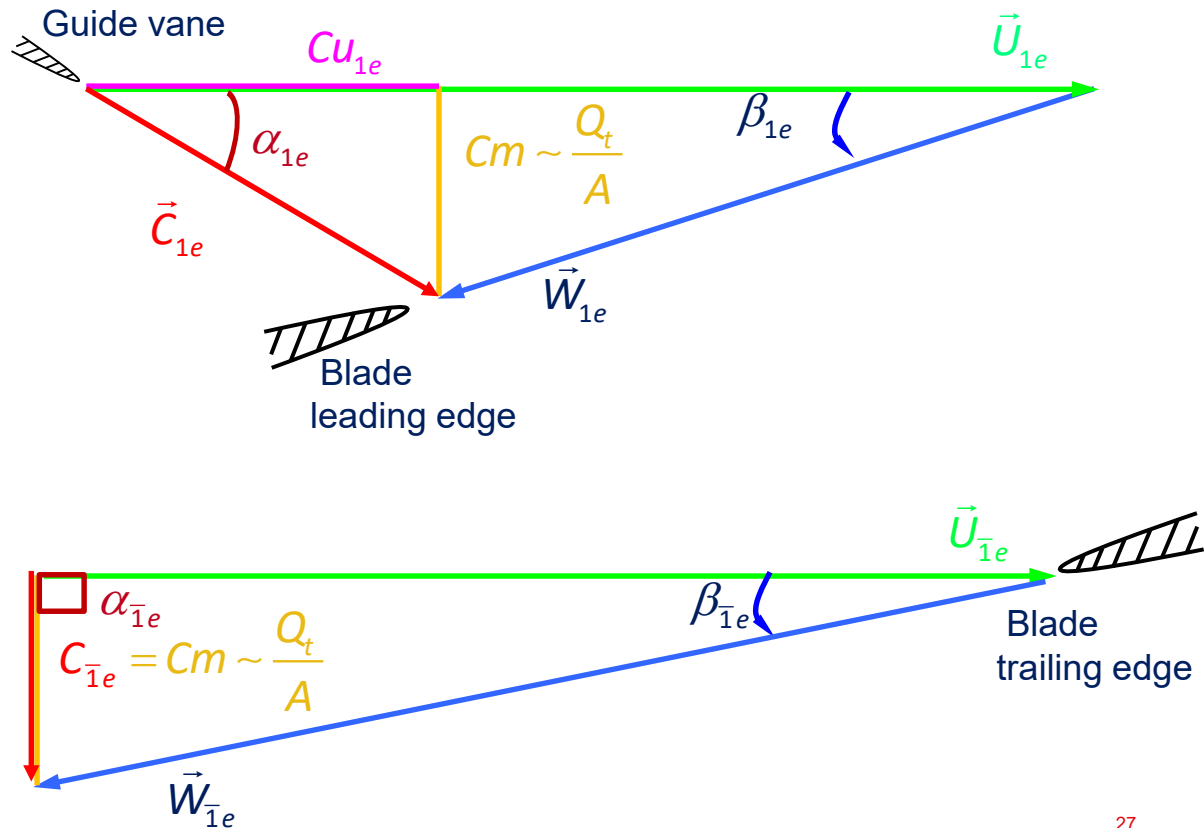
Flow Velocity Diagram

Let's imagine the discharge decreases: Part load condition



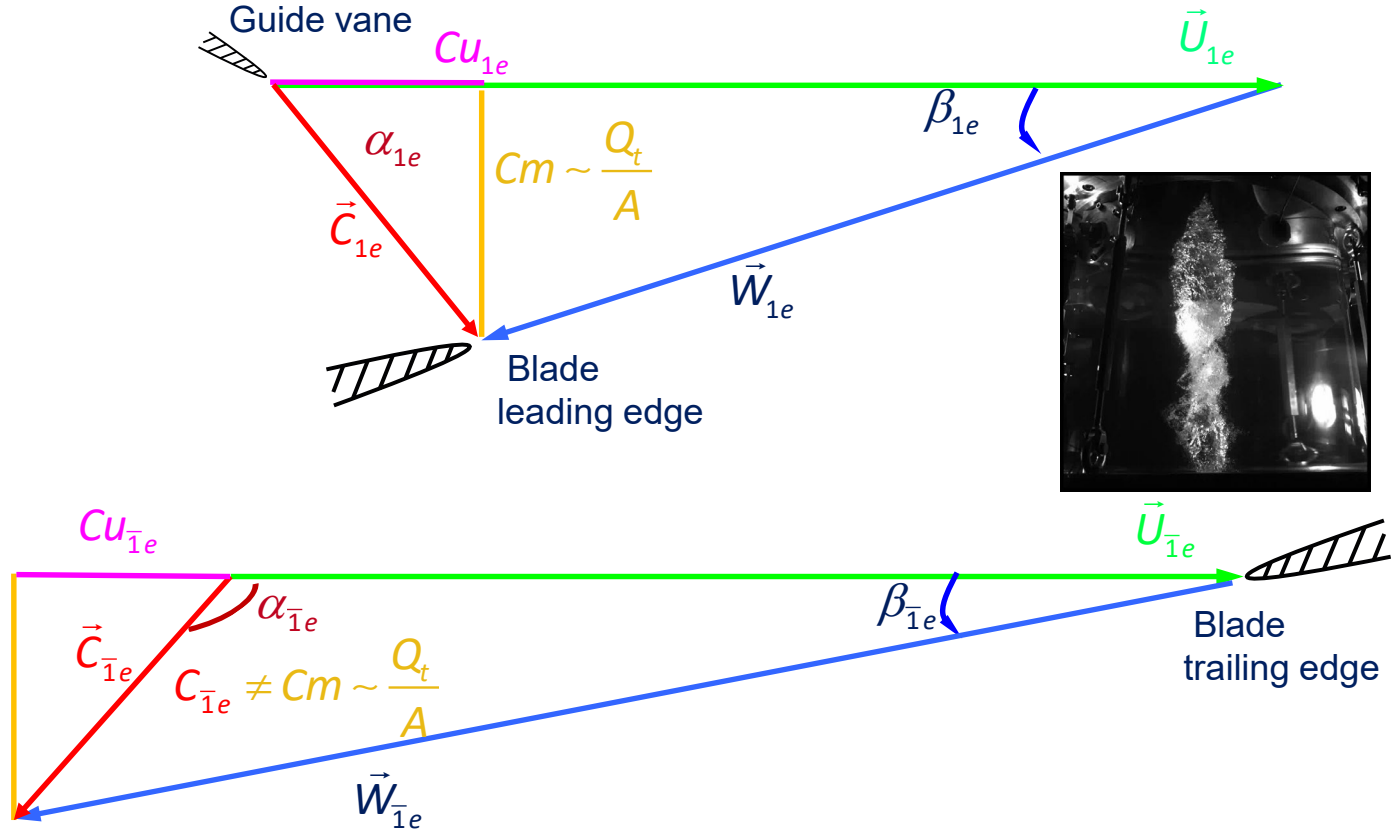
Flow Velocity Diagram

Let's imagine the discharge increases



Flow Velocity Diagram

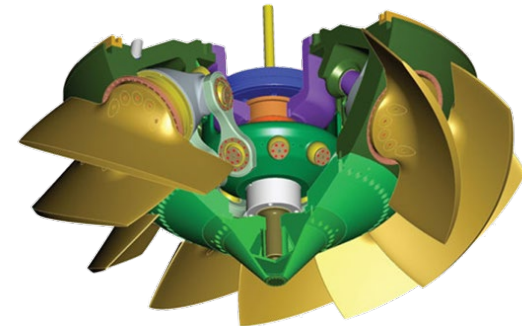
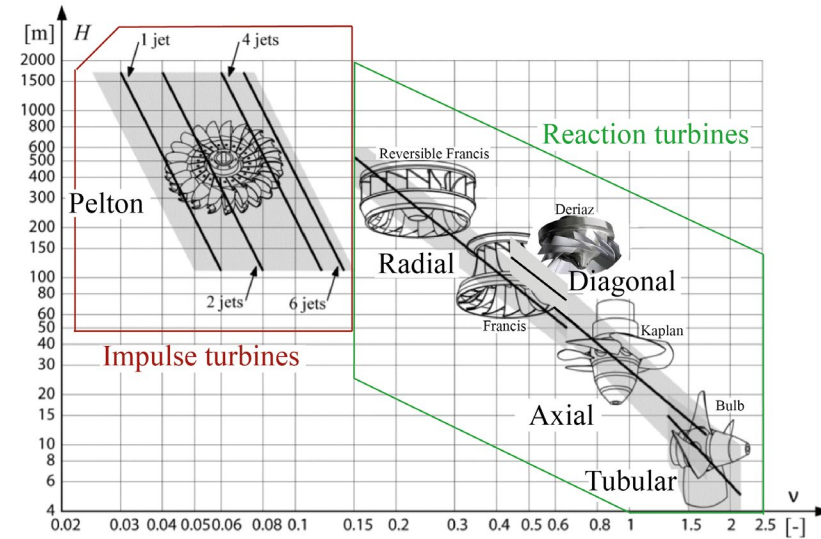
Let's imagine the discharge increases: Full load condition



Classification of Hydraulic Runners

Deriaz turbines

- Mixed flow hydraulic turbomachine
- Reversible
- Adjustable runner blades



Classification of Hydraulic Runners

Deriaz Turbines

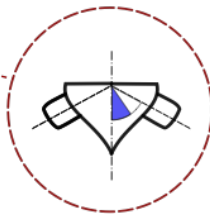
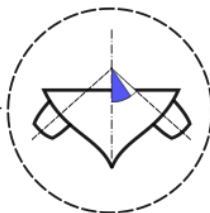
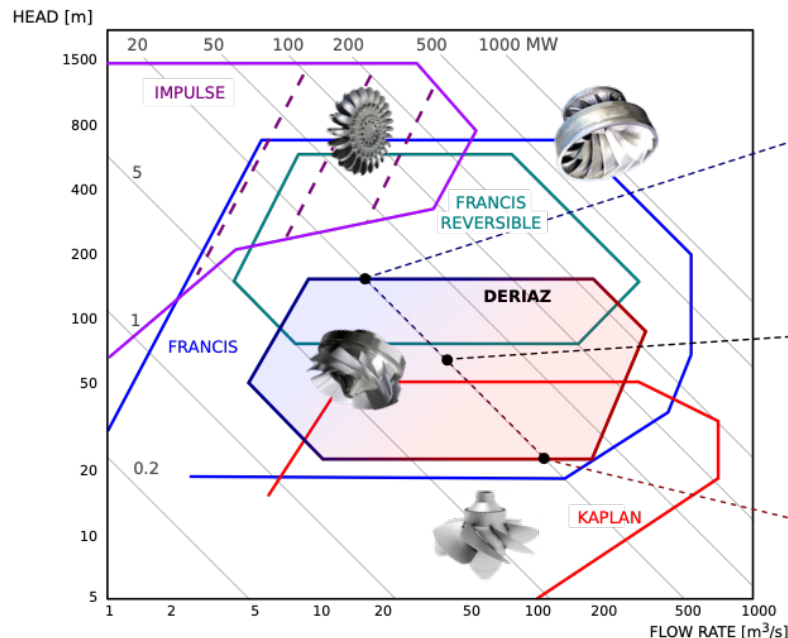


Table 1

Pumped storage plants using Deriaz pump-turbine.

Power station	Size [MW]	Year	Country ^a	Nr unit
[19] Adam Beck	29	1954	CA	6
[23] Gangnan	11	1968	CN	1
[23] Miyun	22	1975	CN	2
Sesquile	100	1964	CO	2
[24] Valdecana	75	1964	ES	3
[25] Nassauc	3	1995	FR	1
[20] Culligran	17	1966	GB	1
[26] Kadana	61	1977	IN	4
[27] Maharashtra	52	2012	IN	2
Ananaigawa	13	1964	JP	1
Kagedaira	46	1968	JP	1
[22] Kuromata II	18	1963	JP	1
Masegawa I	144	1976	JP	2
[28] Niikappu	100	1973	JP	2
[28] Takami	103	1983	JP	2
Takane I	88	1969	JP	4
[29] Niedzica	92	1997	PL	2
[30] Czorstyn	42	1990	PL	2
[31] Liptovsk	97	1975	SK	2
[32] Dos Amigos	18	1963	US	3

^a Country code adopted by the two-letter Standard ISO 3166-1.

Classification of Hydraulic Runners

Deriaz turbines

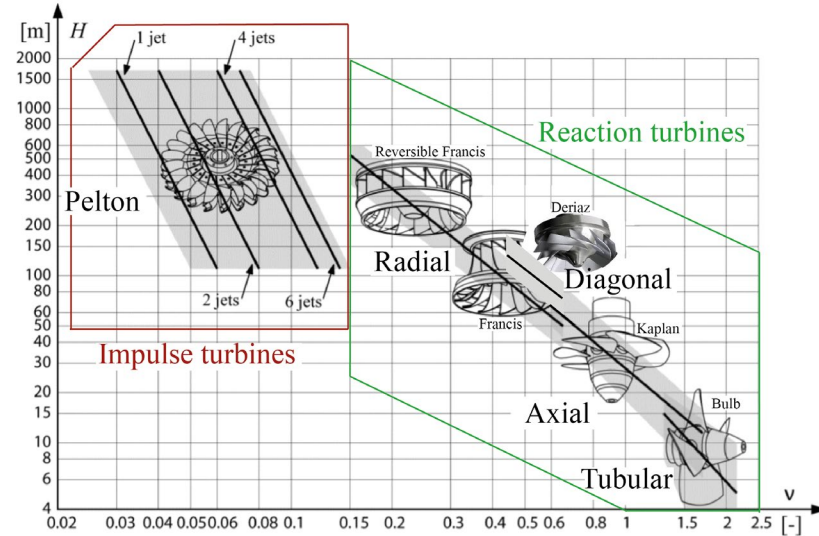
- Deriaz pump-turbine is a valid solution to the high incidence of part-load operation and high flexibility.
- The downsized units can conserve versatility over a wide range of partial loads and provide feasible options in micro systems as well.
- Until recent days its application might have been considered not affordable, especially in micro scale. However, further techno-economic assessment would be necessary for future energy market.



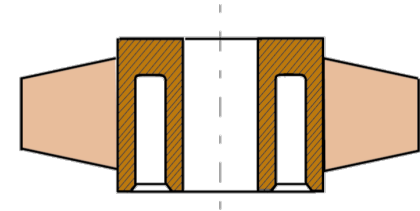
Classification of Hydraulic Runners

Kaplan Runners

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

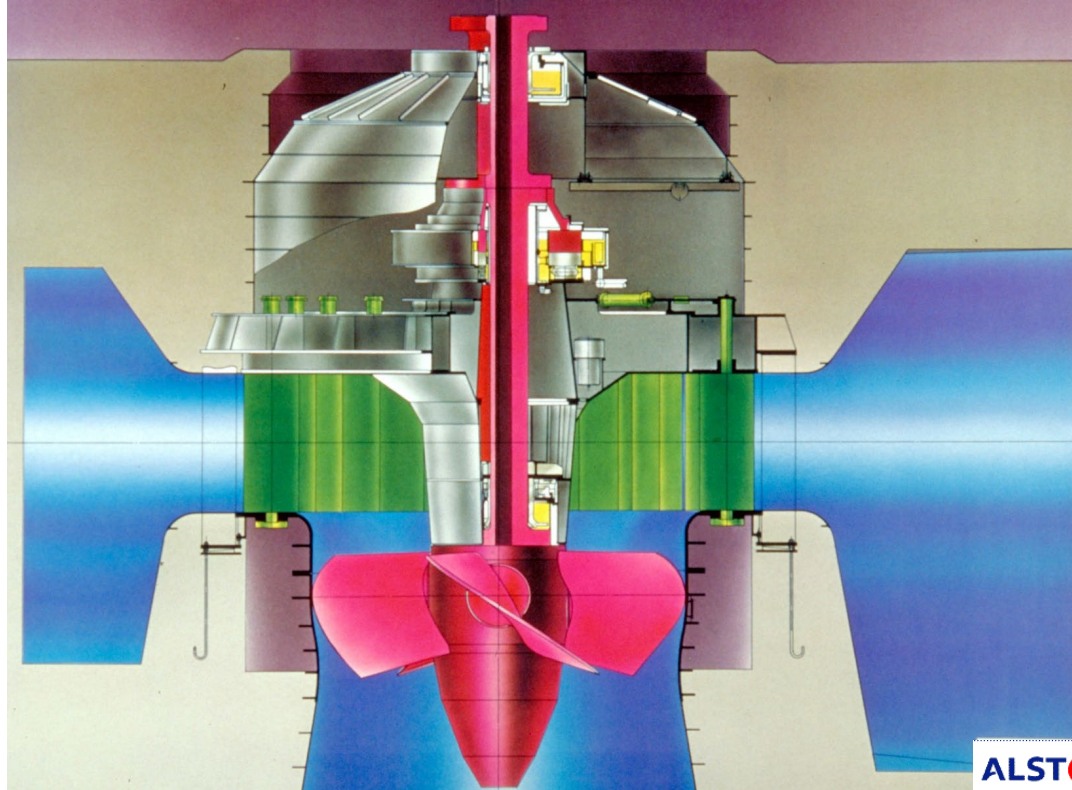


$$\begin{aligned}
 n_q &= 200 \dots 400 \\
 v &= 1.25 \dots 2.50 \\
 n_{QE} &= 0.50 \dots 1.20
 \end{aligned}$$



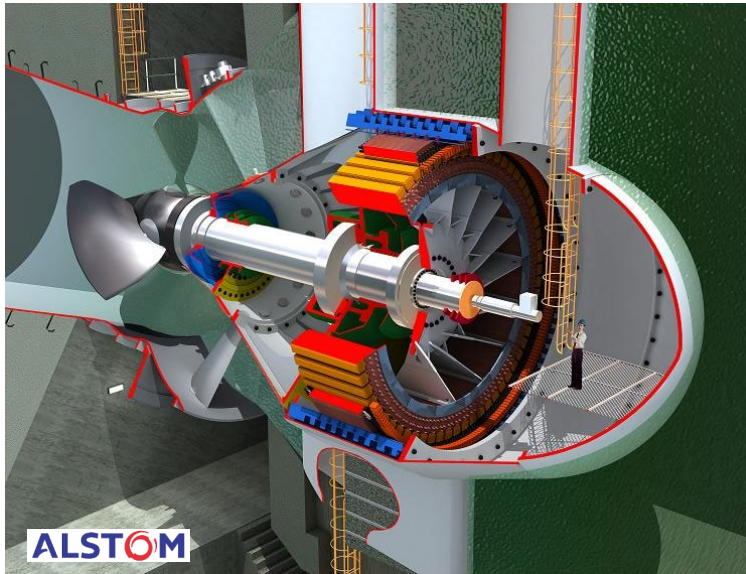
Classification of Hydraulic Runners

Kaplan Runners

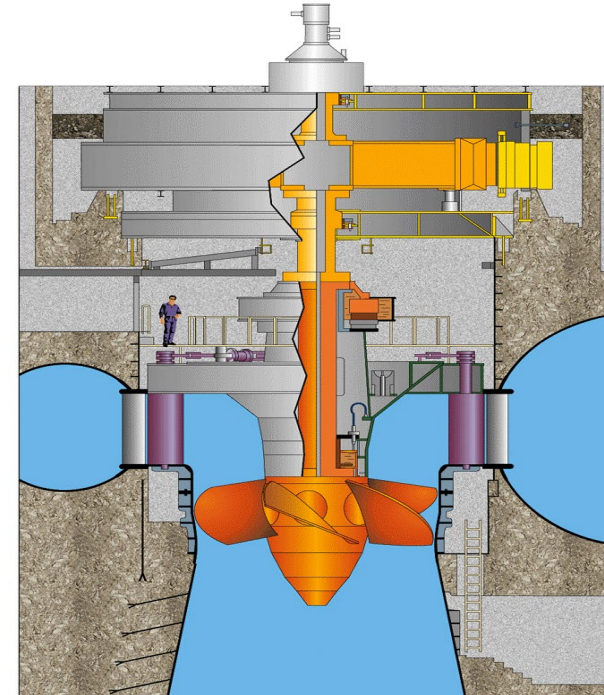


Bulb VS Kaplan

Bulb: fully axial or mixed flow



Kaplan: radial guide vanes and axial runner flow



Kaplan runner

Example: Verbois (Switzerland)

$$E = 178.5 \text{ J} \cdot \text{kg}^{-1}$$

$$Q = 155 \text{ m}^3 \cdot \text{s}^{-1}$$

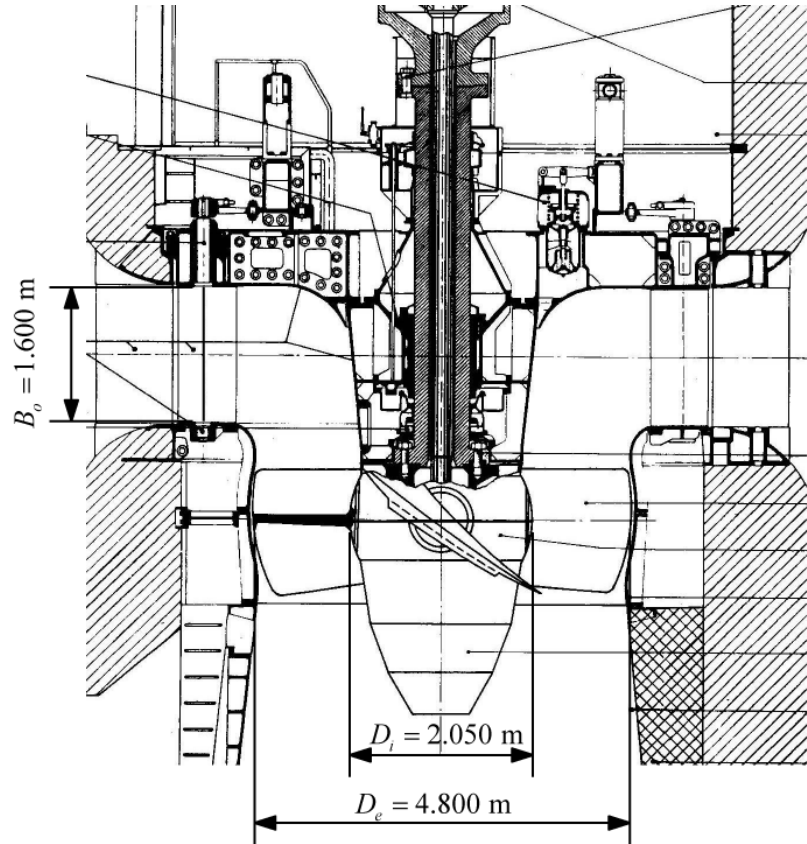
$$P = 25.3 \text{ MW}$$

$$N = 136.4 \text{ min}^{-1}$$

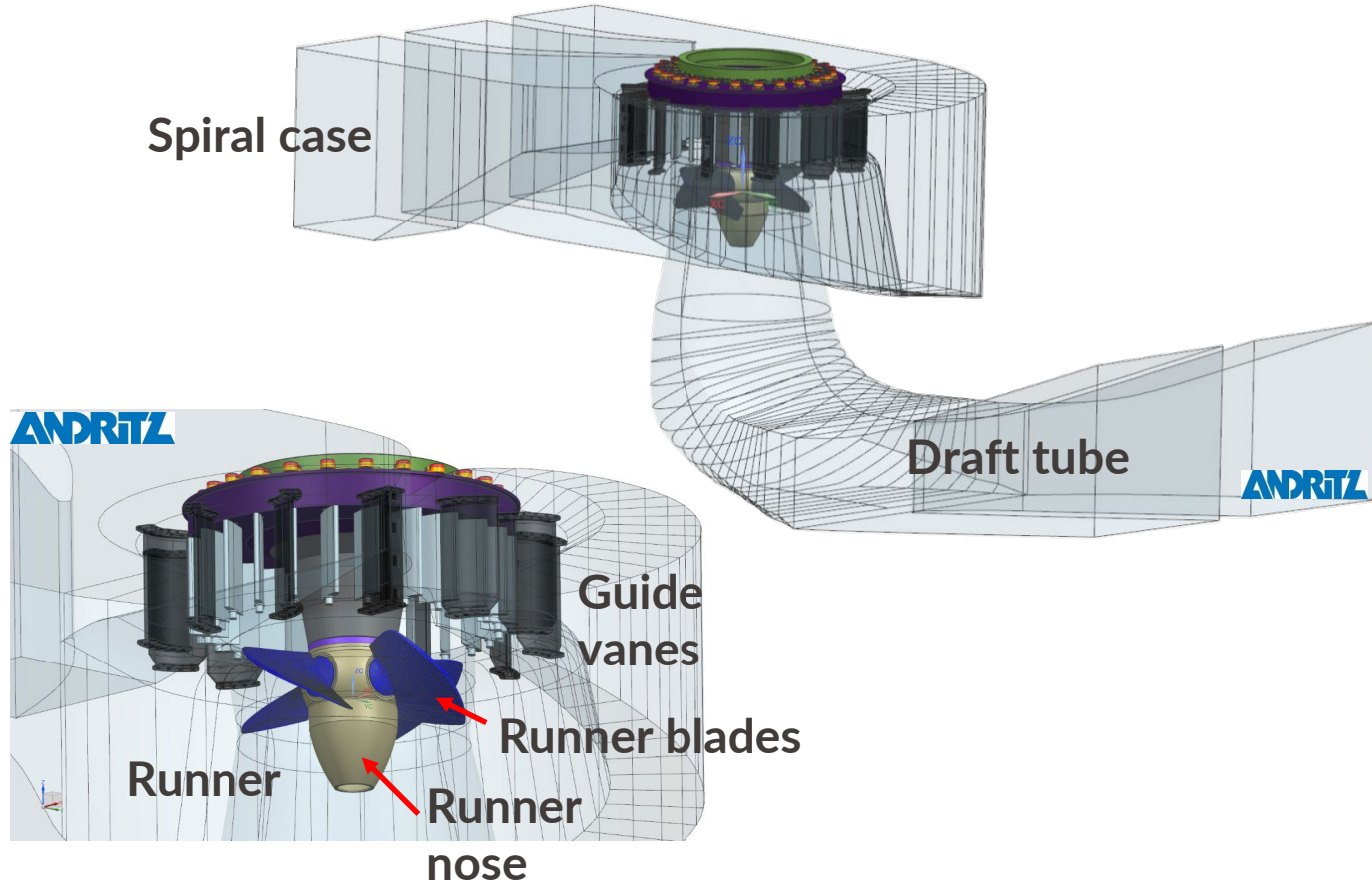
$$D_{1e} = 4.800 \text{ m}$$

$$D_{1i} = 2.050 \text{ m}$$

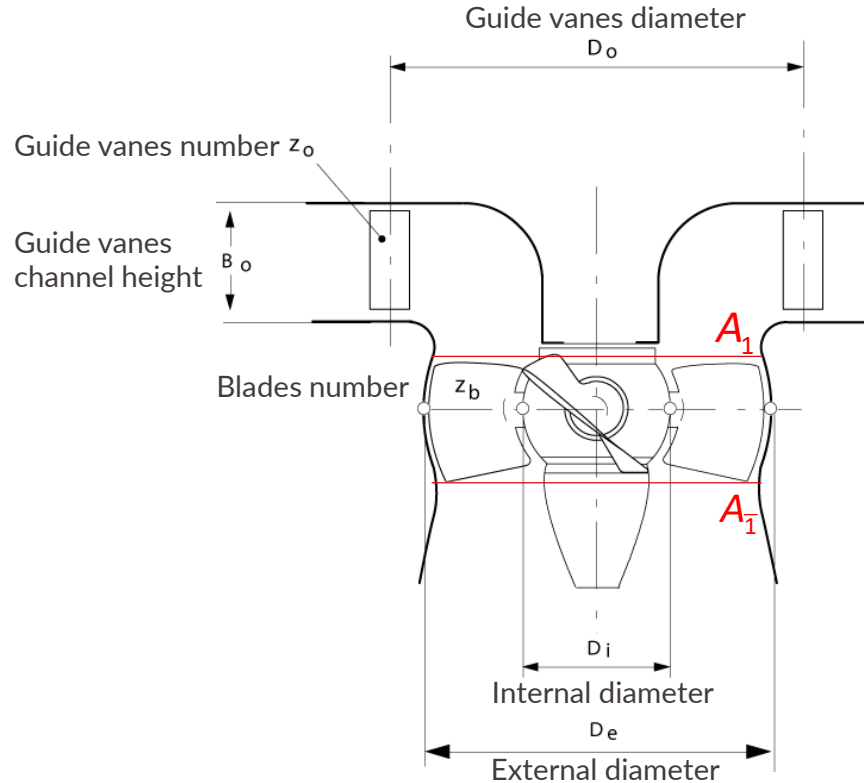
$$B_o = 1.600 \text{ m}$$



Main Geometrical Data of a Kaplan turbine



Main Geometrical Data of a Kaplan runner



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

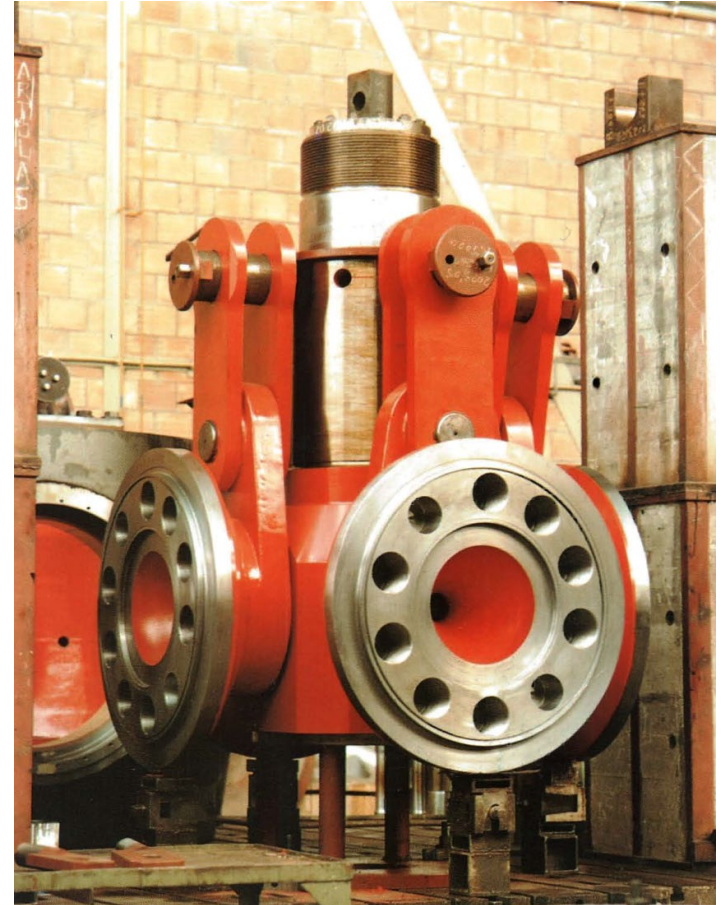
$$A_{\bar{1}} = \pi \frac{D_{\bar{1}e}^2 - D_{\bar{1}i}^2}{4}$$

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

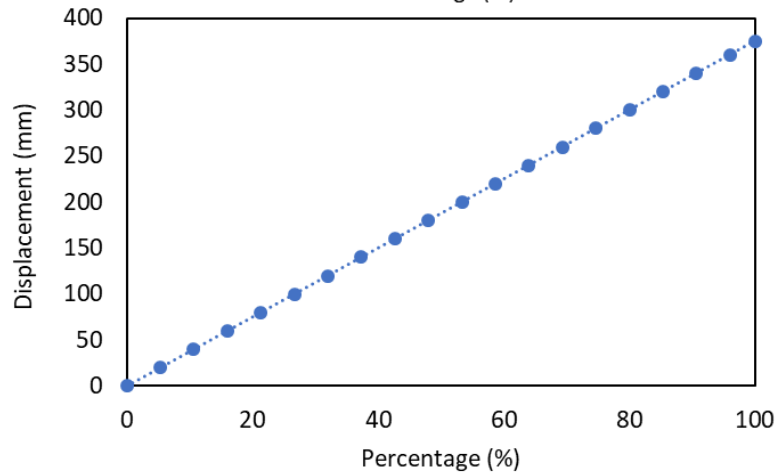
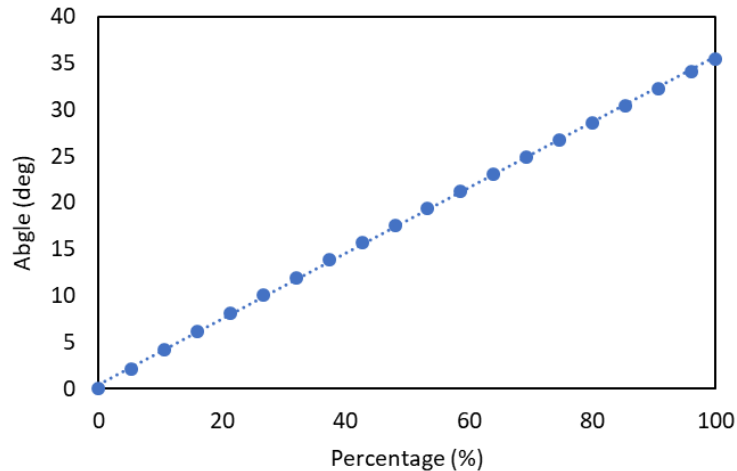
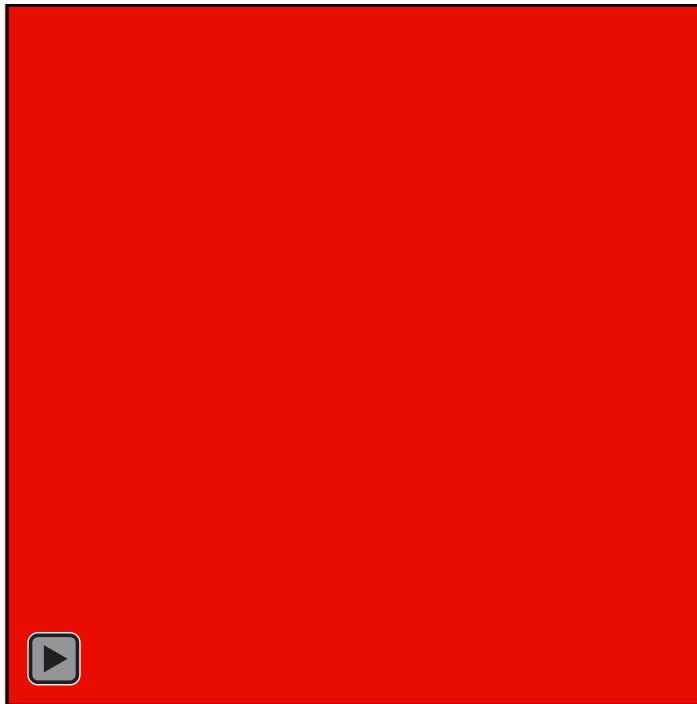
Controllable Pitch Kaplan Runner



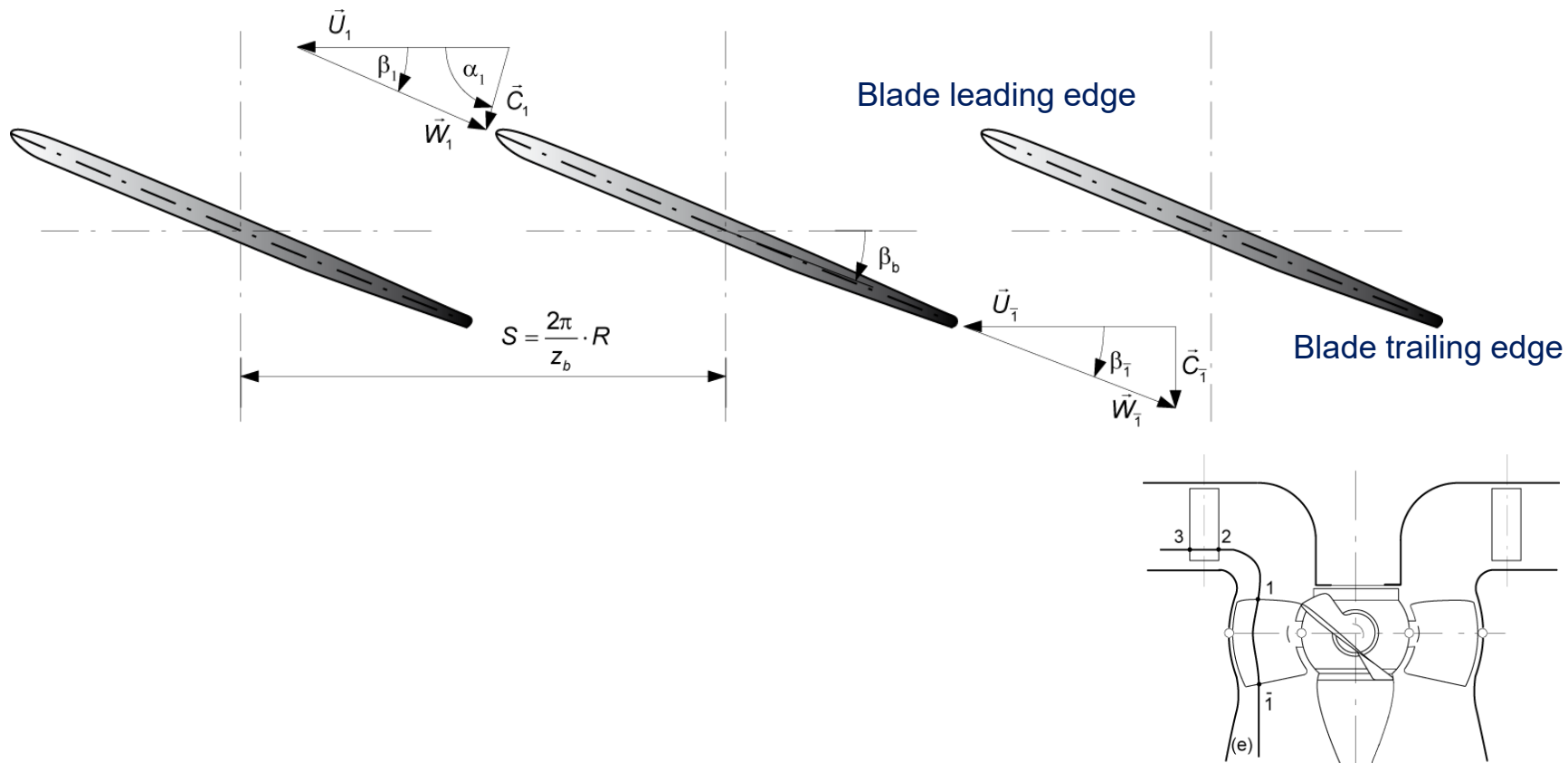
- Blade Base Plates
- Levers
- Connecting Rods
- Piston



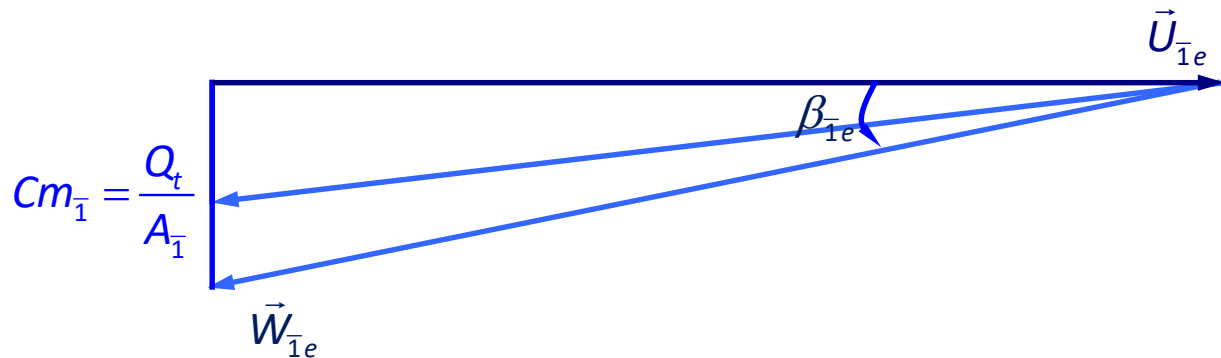
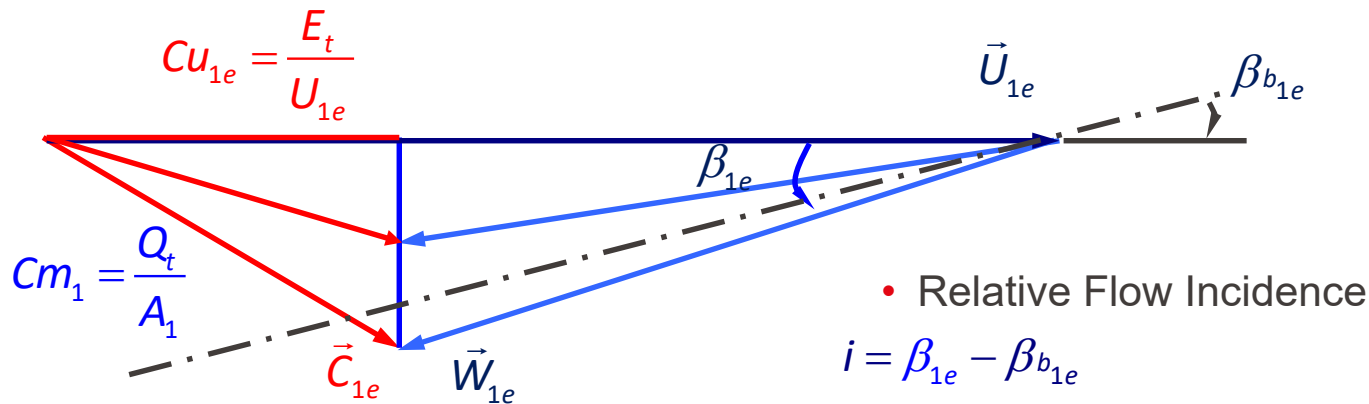
Controllable Pitch Kaplan Runner



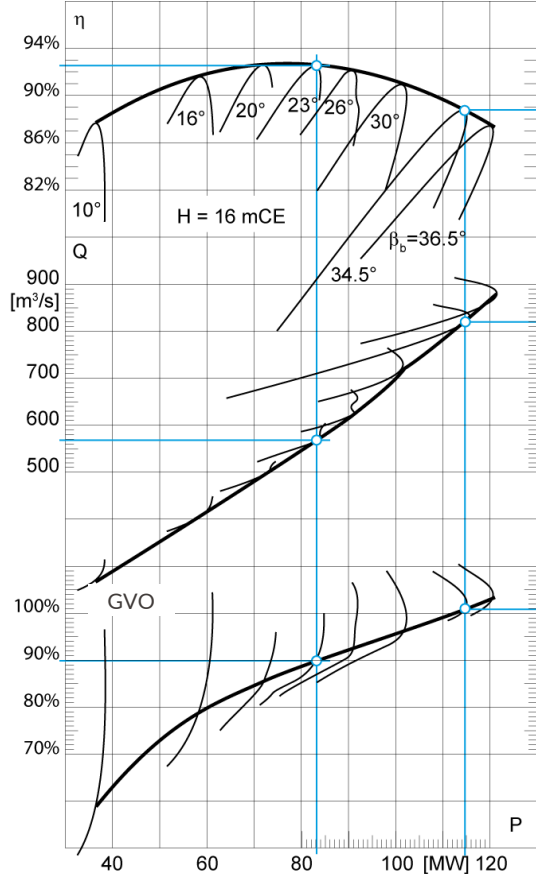
Controllable Pitch Kaplan Runner



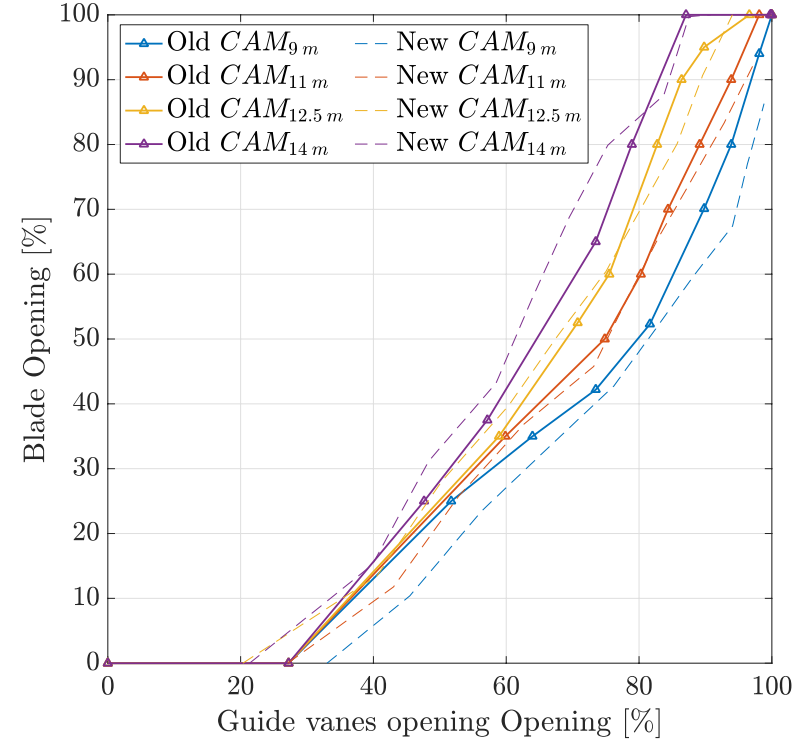
Flow Velocity Diagram



Hydraulic characteristics and on-cam curve



Yacretre Power Plant

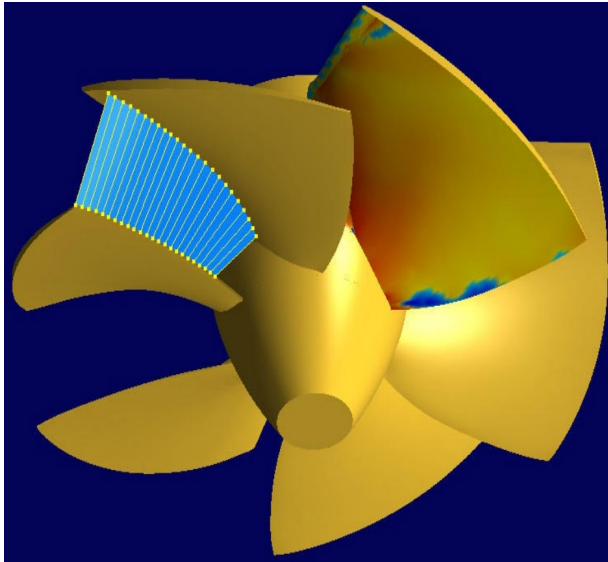


Vogelgrun Power Plant

Vent Opening (Flow passage section)

- Propeller Flow Passage

$$\sin \beta_1 = \frac{z_b B_1}{2\pi R_1}$$



From L2: Power Balance

Turbine Hydraulic Power Breakdown per Turbine Components

Hydraulic Power

$$P_h = \rho Q E \longrightarrow$$

Power lost in spiral case

$$P_{rsc} = \rho Q E_{rsc}$$

Power lost in stay vanes

$$P_{rv} = \rho Q E_{rv}$$

Power lost in guide vanes

$$P_{ro} = \rho Q E_{ro}$$

Transferred Power

$$P_t = \rho Q_t E_t$$

Power lost in the blades

$$P_{rb} = \rho Q_t E_{rb}$$

Power lost through leakage

$$P_{rq} = \rho q_r \underbrace{(E_t + E_{rb})}_{=E_b = gH_1 - gH_1^-}$$

$$\rho Q E = \rho Q (E_{rsc} + E_{rv} + E_{ro})$$

$$+ \rho Q_t E_t + \rho Q_t E_{rb}$$

$$+ \rho q_r (E_t + E_{rb})$$

$$+ \rho Q E_{rd}$$

$$E = E_{rsc} + E_{rv} + E_{ro} + \frac{Q_t + q_r}{Q} (E_t + E_{rb}) + E_{rd}$$

$$= E_{rsc} + E_{rv} + E_{ro} + E_t + E_{rb} + E_{rd}$$

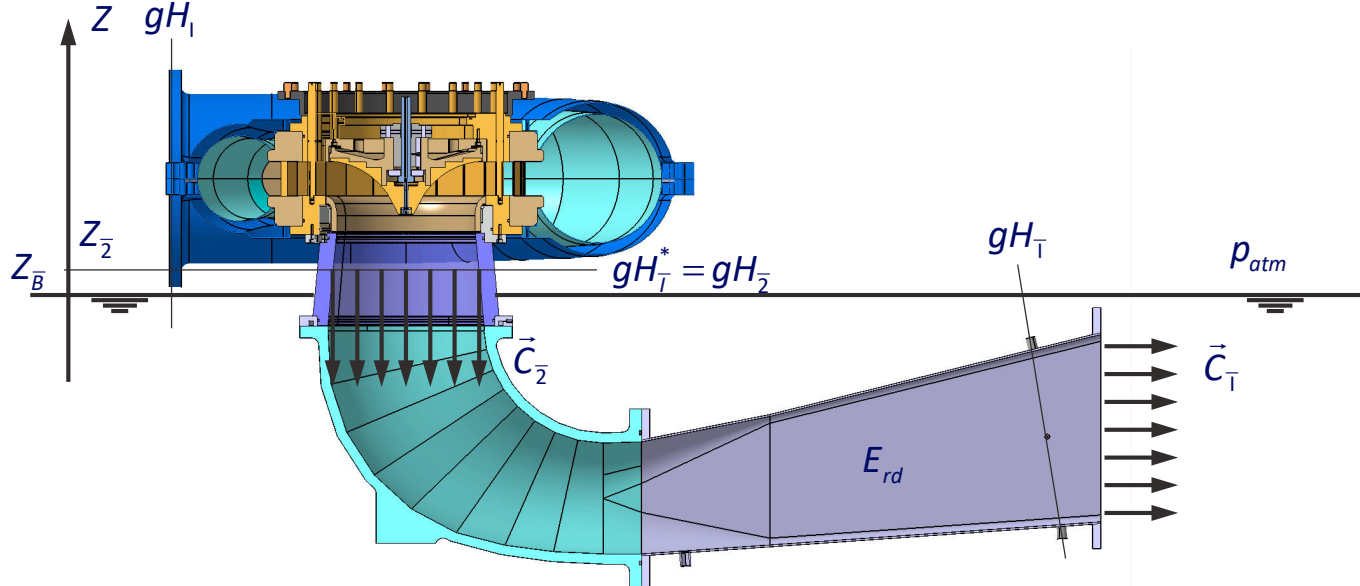
Power lost in the draft tube $P_{rd} = \rho Q E_{rd}$

HP: all leakage losses are recovered by the draft tube

Diffuser

Elbow Draft-Tube (Francis and Kaplan)

- Static Pressure Recovery





E_{rv} Energy lost in stay vanes

E_{ro} Energy lost in guide vanes

E_{rb} Energy lost in the blades

E_{rd} Energy lost in the draft tube

Specific Energy Balance $E = gH_i - gH_f$
turbine inlet-outlet

$$= E_t + E_{rsc} + E_{rv} + E_{ro} + E_{rb} + E_{rd}$$

With draft tube: $E_t = gH_I - gH_T - E_{rsc} - E_{rv} - E_{ro} - E_{rb} - E_{rd}$

Without draft tube: $E_t^* = gH_l - gH_l^* - E_{rsc} - E_{rv} - E_{ro} - E_{rb} - E_{rd}^*$

$$E_t - E_t^* = -(gH_{\bar{I}} - gH_{\bar{I}}^*) - (E_{rd} - E_{rd}^*)$$

$$gH_I = gZ_I + \frac{p_I}{\rho} + \frac{C_I^2}{2} = \frac{p_{atm}}{\rho} + gZ_B + \frac{C_I^2}{2}$$

$$= \frac{p_{atm}}{\rho} + gZ_B - gZ_I$$

Let's evaluate the difference between the 2 cases (with/without draft tube)

$$\rightarrow gH_I^* = gZ_2 + \underbrace{\frac{p_2}{\rho}}_{=\frac{p_{atm}}{\rho}} + \frac{C_2^2}{2} = gZ_2 + \frac{p_{atm}}{\rho} + \frac{C_2^2}{2} \rightarrow$$

$$E_t - E_t^* = - \left(gZ_{\bar{B}} + \frac{C_{\bar{I}}^2}{2} - gZ_{\bar{2}} - \frac{C_{\bar{2}}^2}{2} \right) - (E_{rd} - \cancel{E_{rd}^*})$$

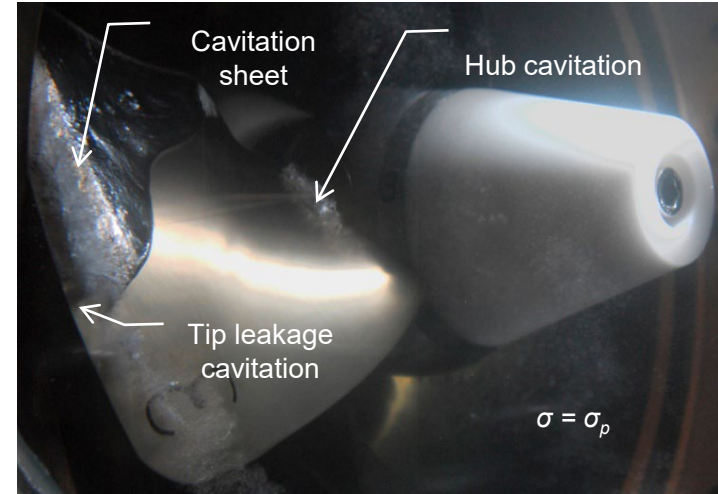
$$E_t - E_t^* = \underbrace{\frac{C_2^2}{2} - \frac{C_I^2}{2}}_{\text{Specific Kinetic Energy}} + \underbrace{g(Z_2 - Z_B)}_{\text{Specific Potential Energy}} - \underbrace{E_{rd}}_{\text{Draft Tube Loss}}$$

$E_t - E_t^* > 0$ unless E_{rd} are very important

Kaplan & Bulb Turbines:

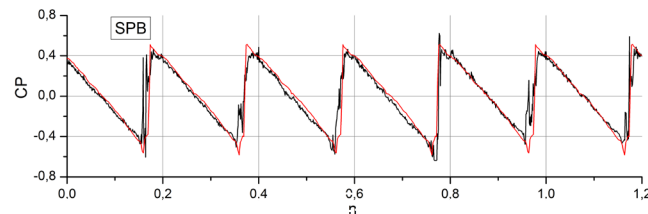
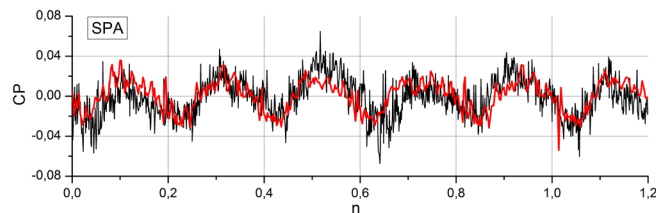
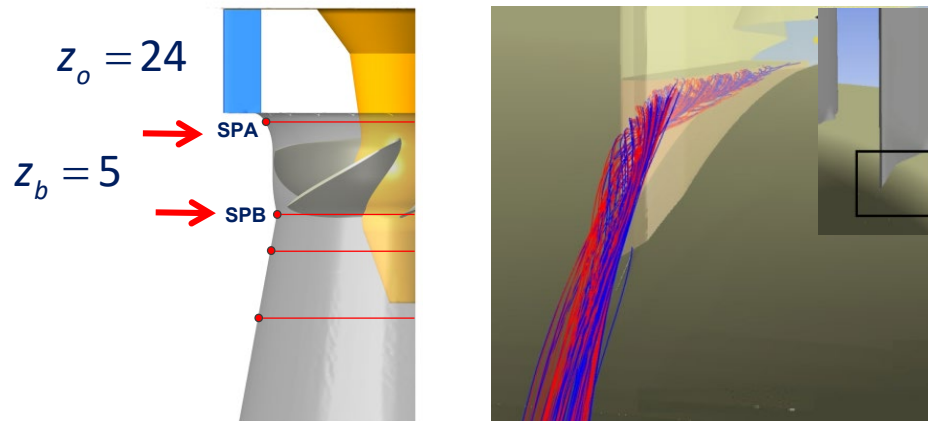
Main Issues

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



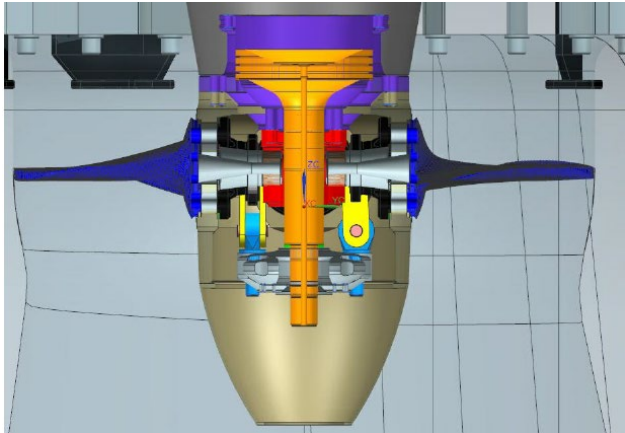
Guide Vane Wakes-Blades interactions

- Guide Vane Wakes
 - Vorticity Advection
 - Interactions with Runner Blades
- Unbalanced Flow
 - Semi Spiral Case
 - Draft Tube



EPFL Wear and Tear

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

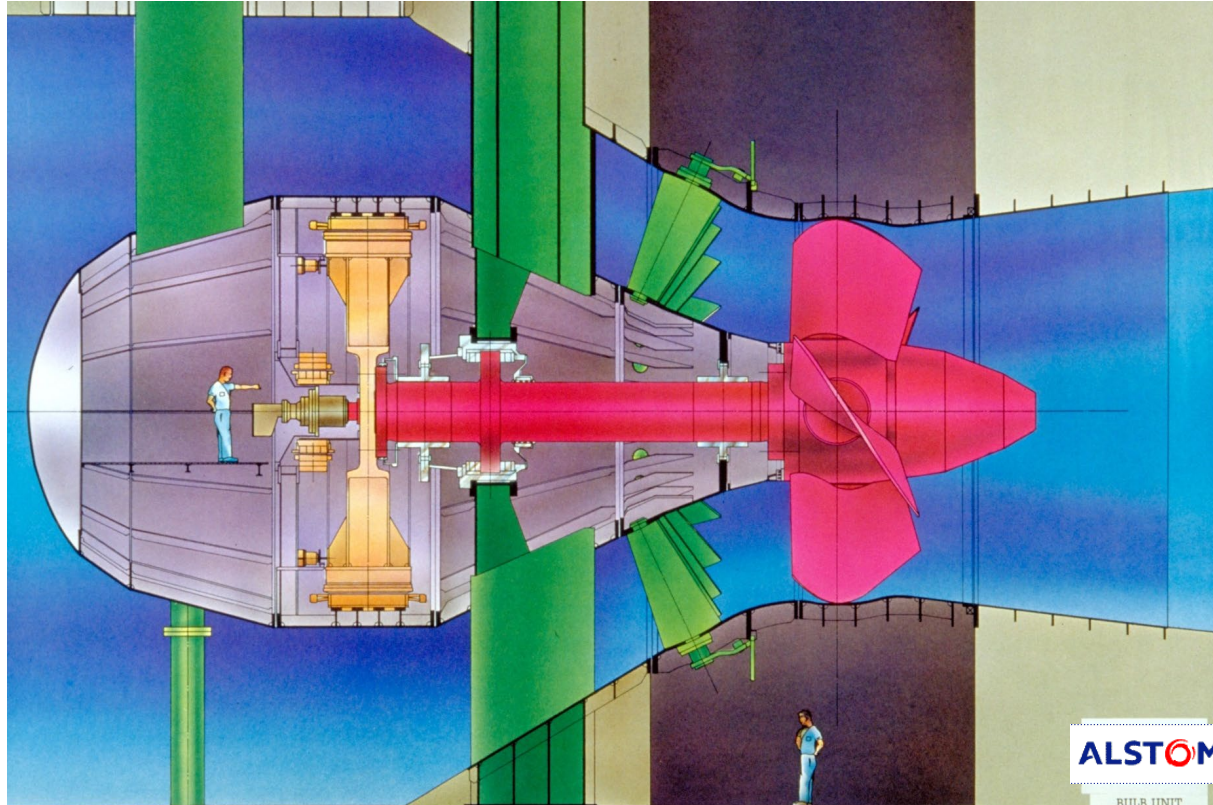


VOGELGRUN , France

- Four vertical Kaplan turbines
 - Battery Hybrid
- $P = 35 \text{ MW}$, $H = 12 \text{ m}$, $Q = 325 \text{ m}^3/\text{s}$

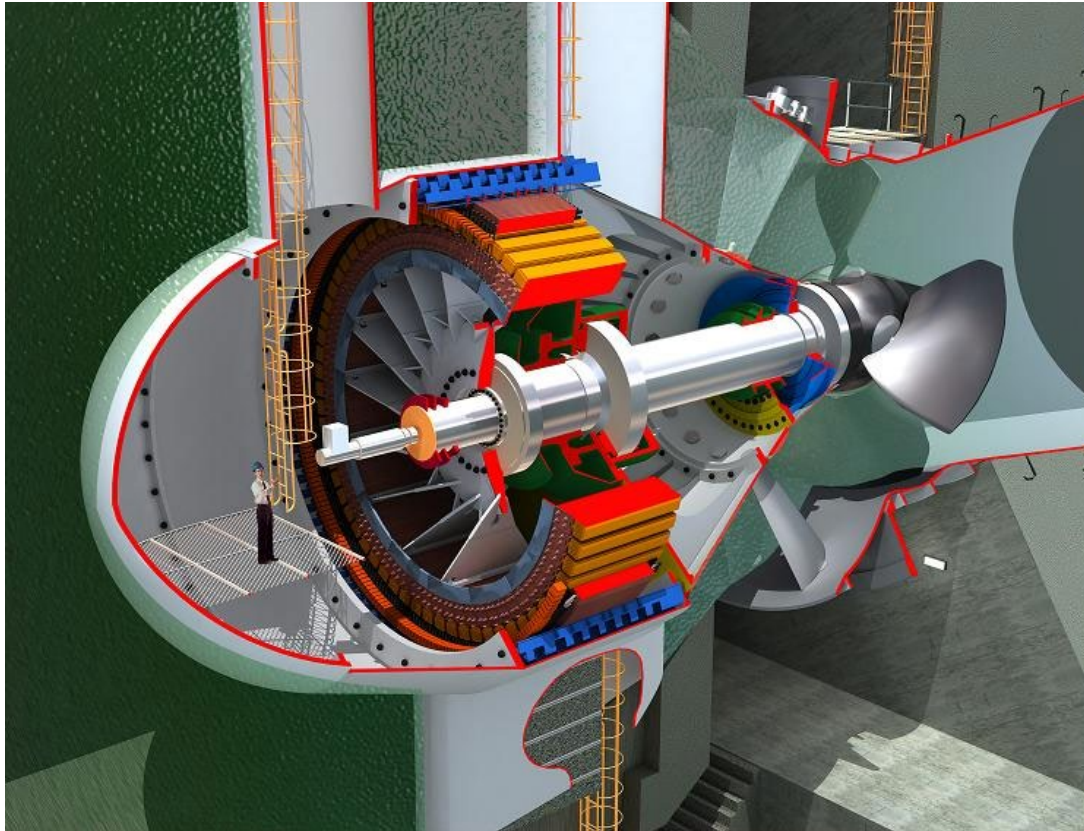
Classification of Hydraulic Runners

Bulb Turbine



Classification of Hydraulic Runners

Sant'Antonio power plant (Brazil)

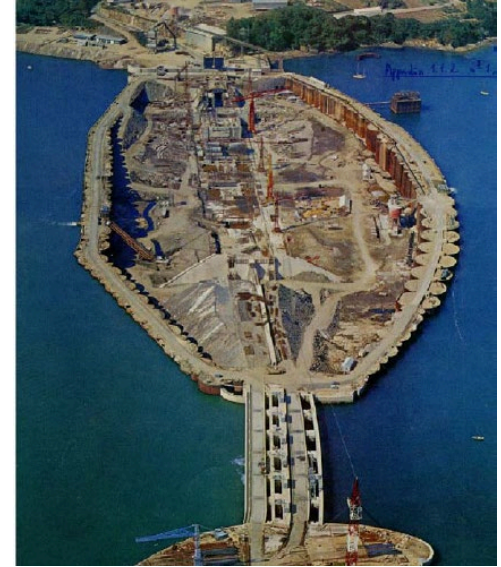


50 Bulb Units 70 MW, 7.50 m Runner

Classification of Hydraulic Runners

La Rance tidal hydropower plant (France)

- 24 Bulb Units
- 10 MW Unit Max Power
- 5.35 m Runner Dia.
- 540 GWh/year



Classification of Hydraulic Runners

Tidal power

Tidal Current Turbine: Examples



“Seagen”

from Marine Current Turbine company

2 runners with a diameter of 16m

1.2 MW



“Open Hydro” 2 to 4 MW

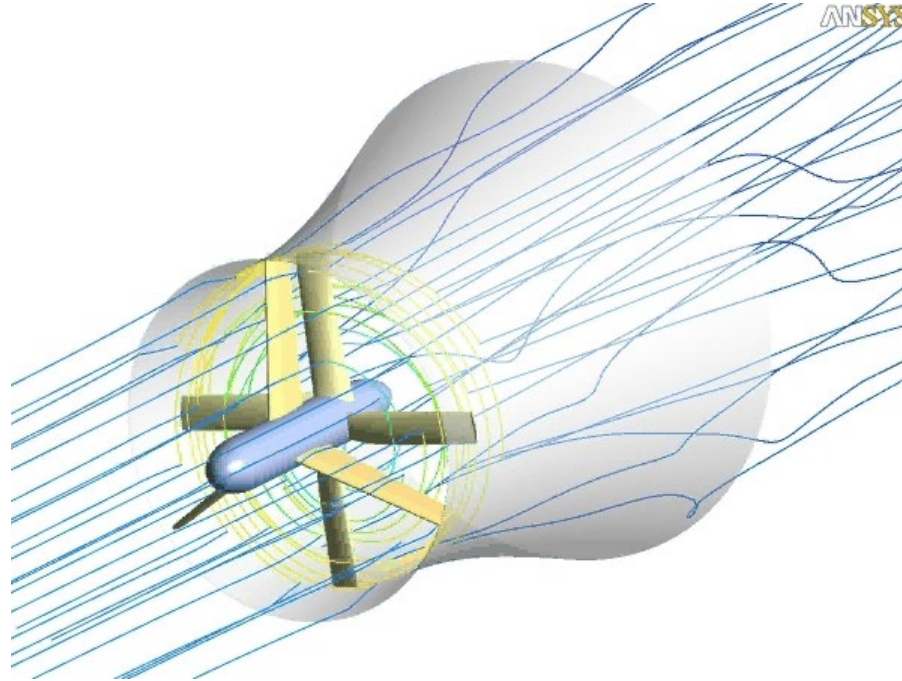
From OpenHydro Group chosen by EDF

10 runners

4 MW

Classification of Hydraulic Runners

Development of New Renewables Iso Kinetic Turbine



Classification of Hydraulic Runners

New Renewables: Iso Kinetic Turbine

