L6 – Reaction Turbines

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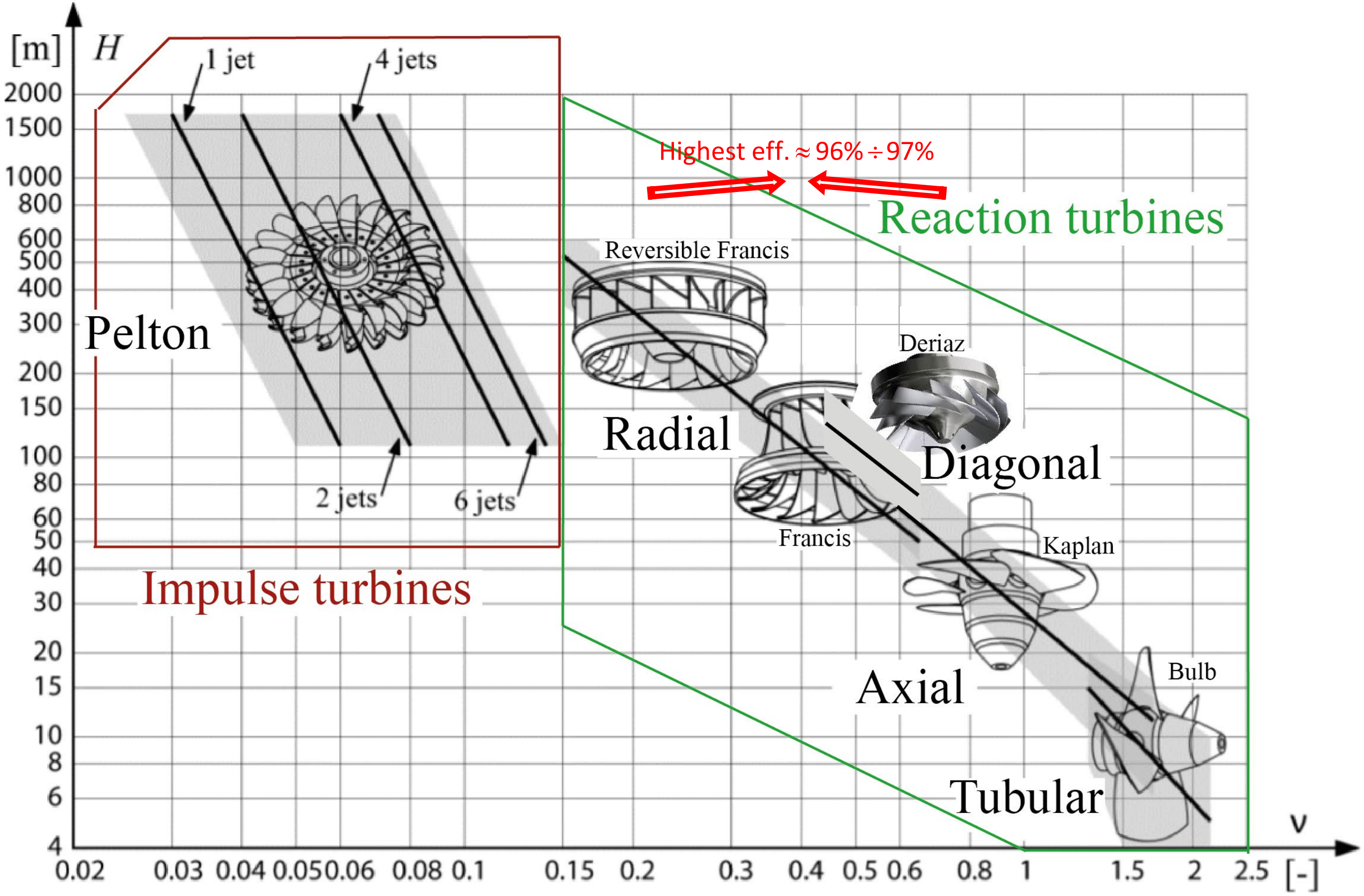
Topics of the lecture

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

From L2: Classification of Hydraulic Runners



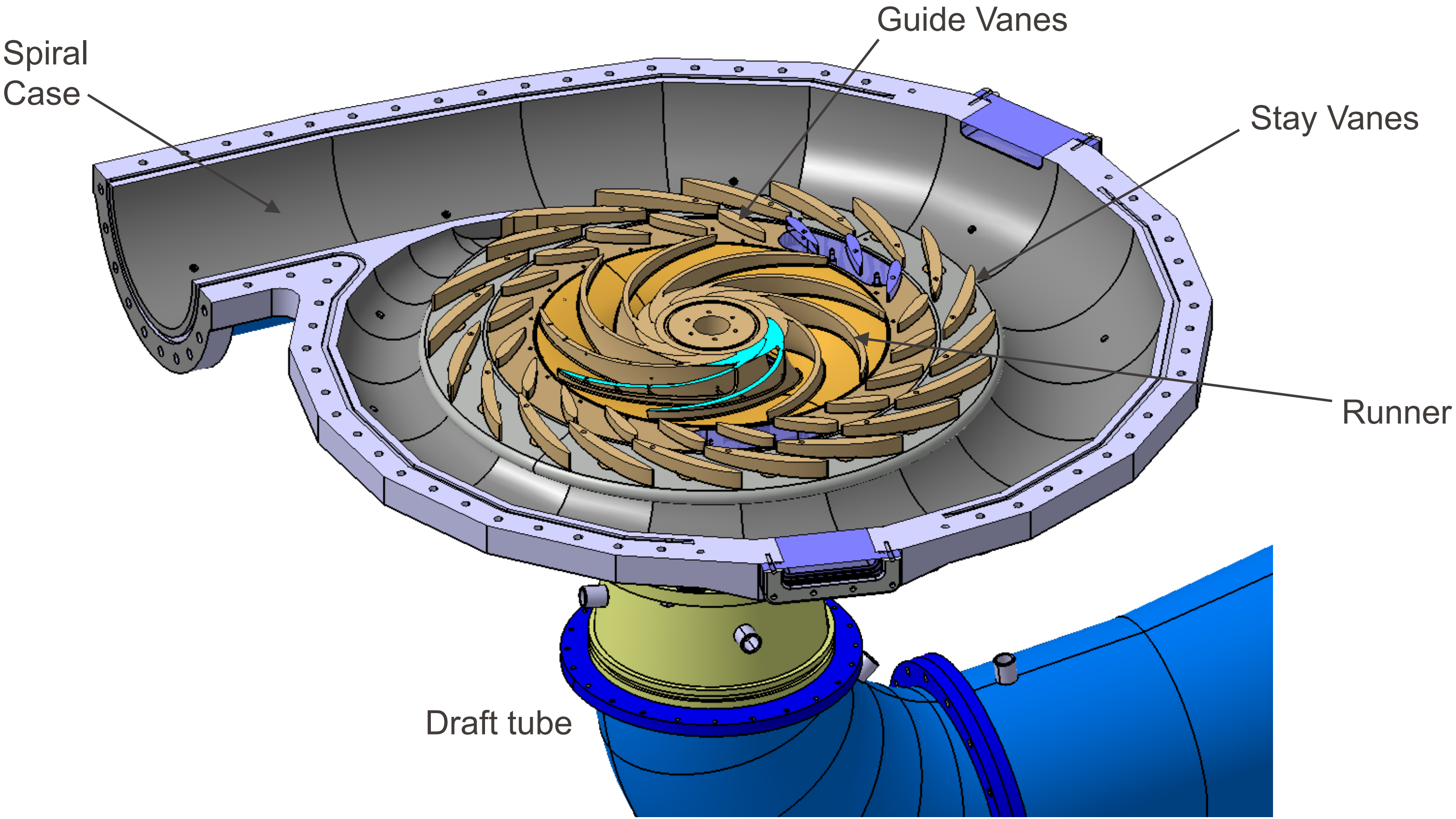
Head = H (m)

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

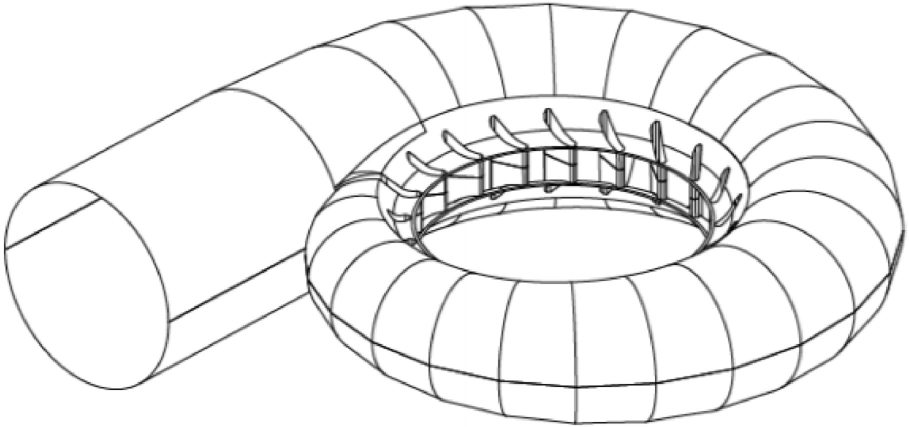
Speed = N $(\mathrm{min^{-1}})$

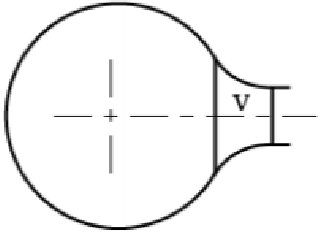
$$\nu = 2^{\frac{1}{4}} \pi^{\frac{1}{2}} \times n \times \frac{Q^{\frac{1}{2}}}{E^{\frac{3}{4}}}$$

Classification and geometrical proprieties

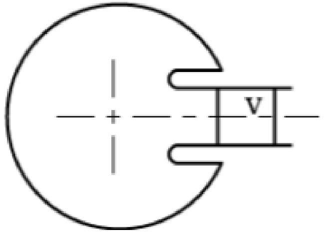


Types of Spiral Case





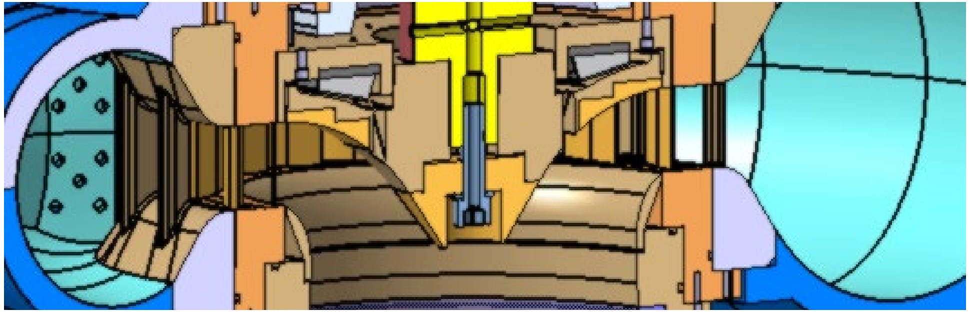
Double curvature

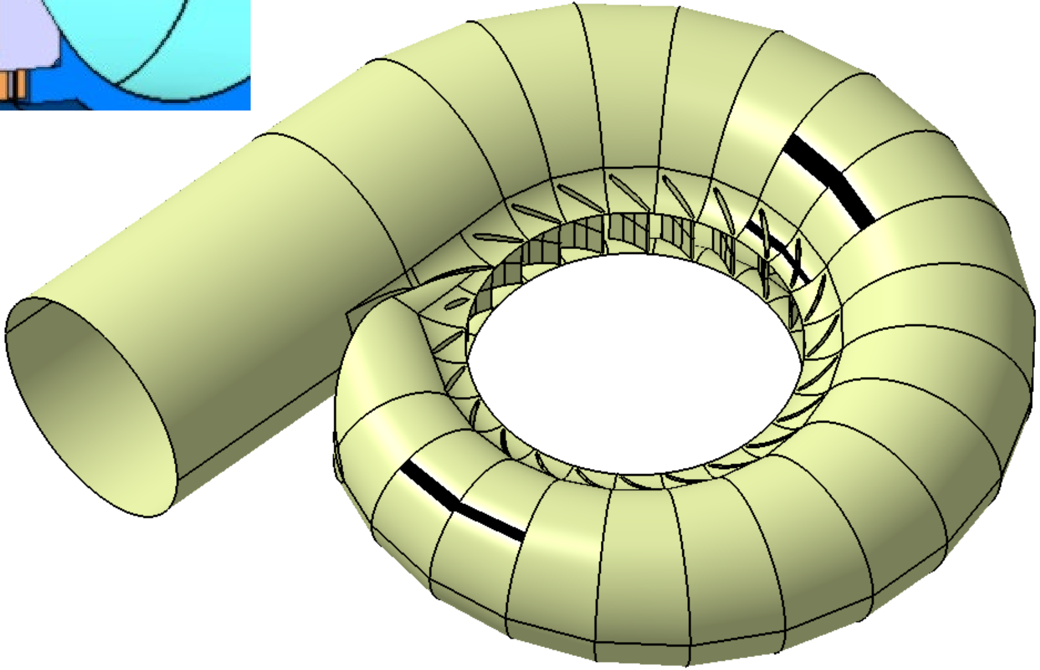


Piguet type

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

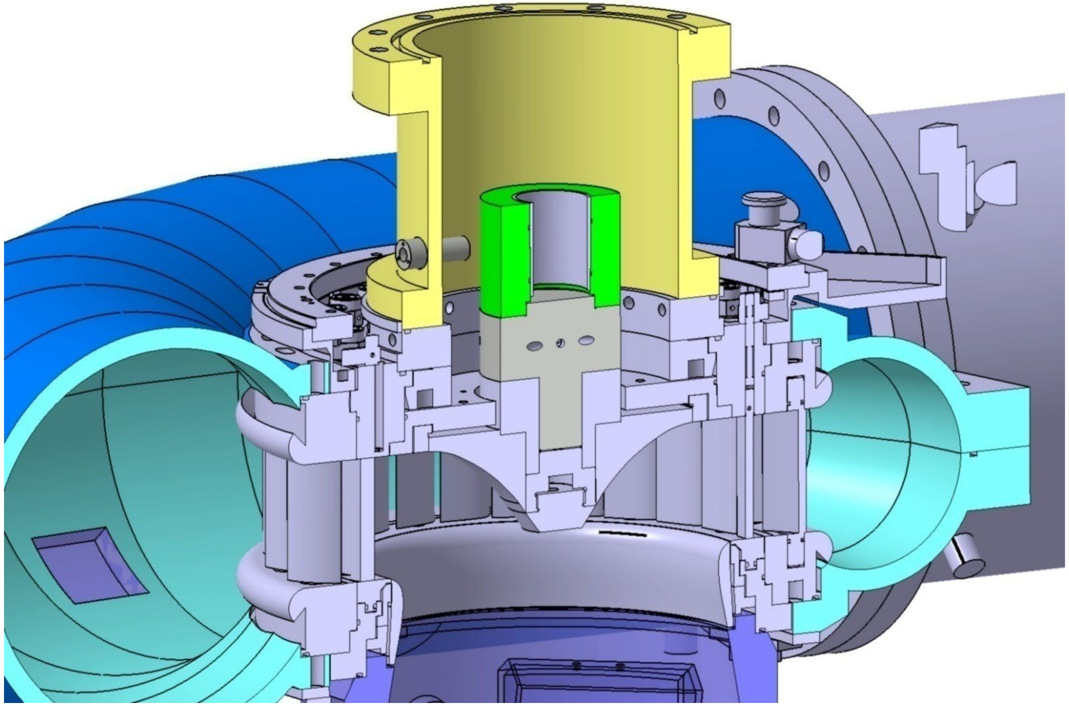




- Historical Casting Process
- Complex Distribution of Stresses
- Stay vanes are welded

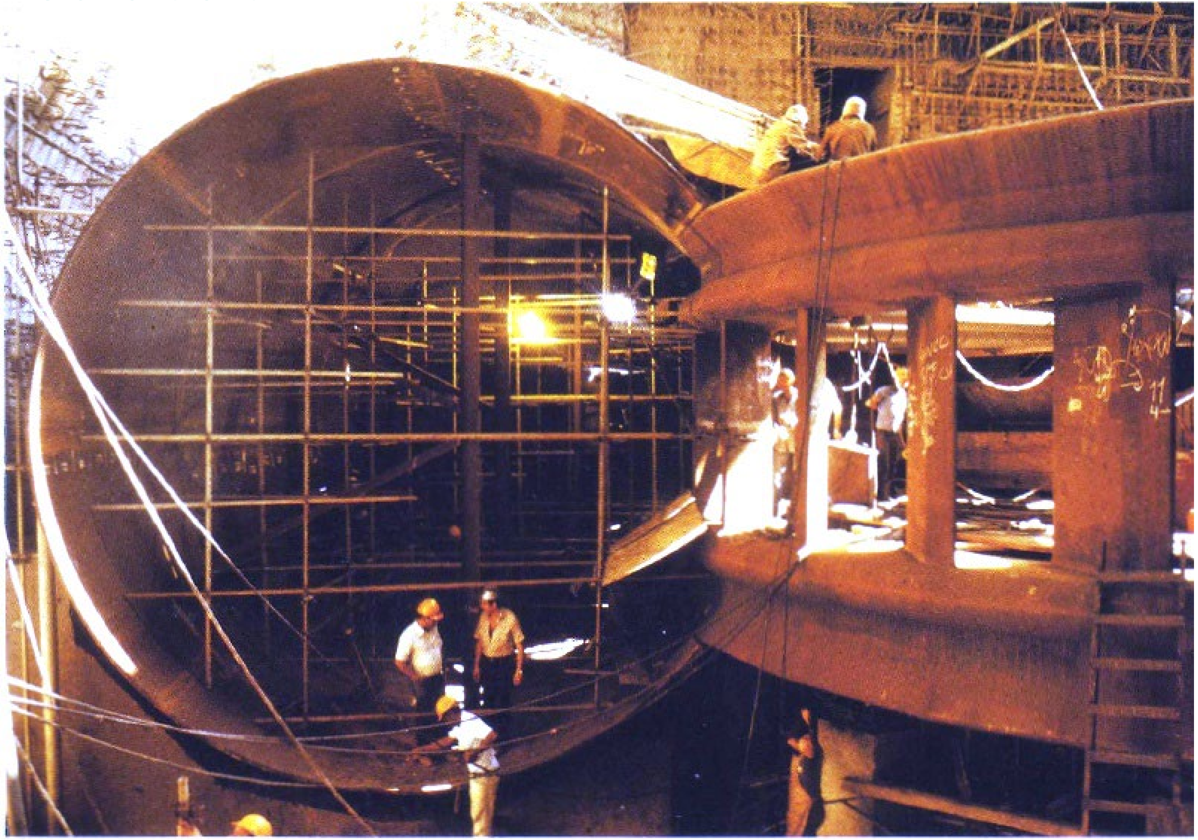
Spiral Case of Piguet Type

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



Spiral Case of Piguet Type

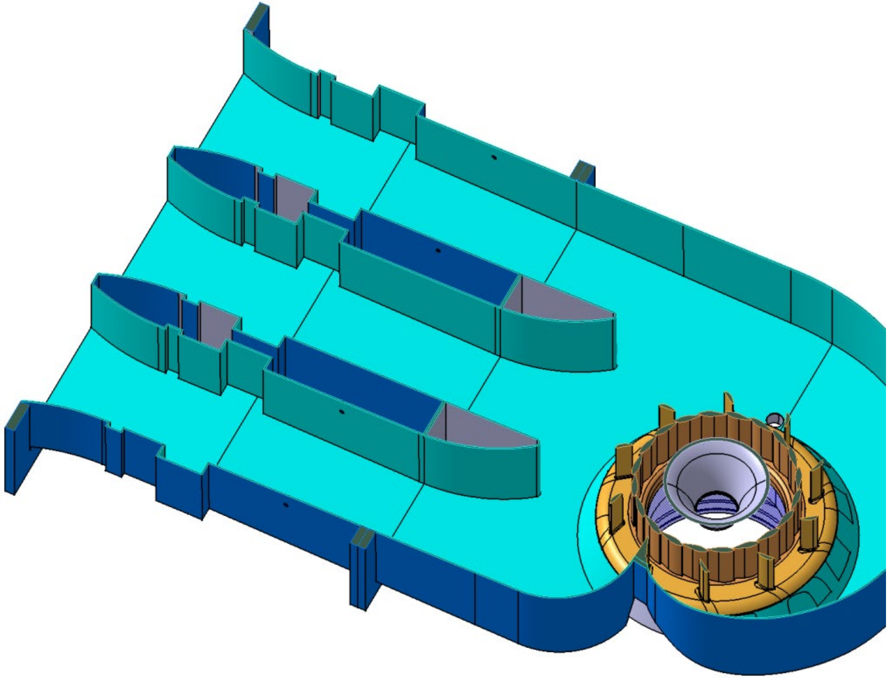
Construction

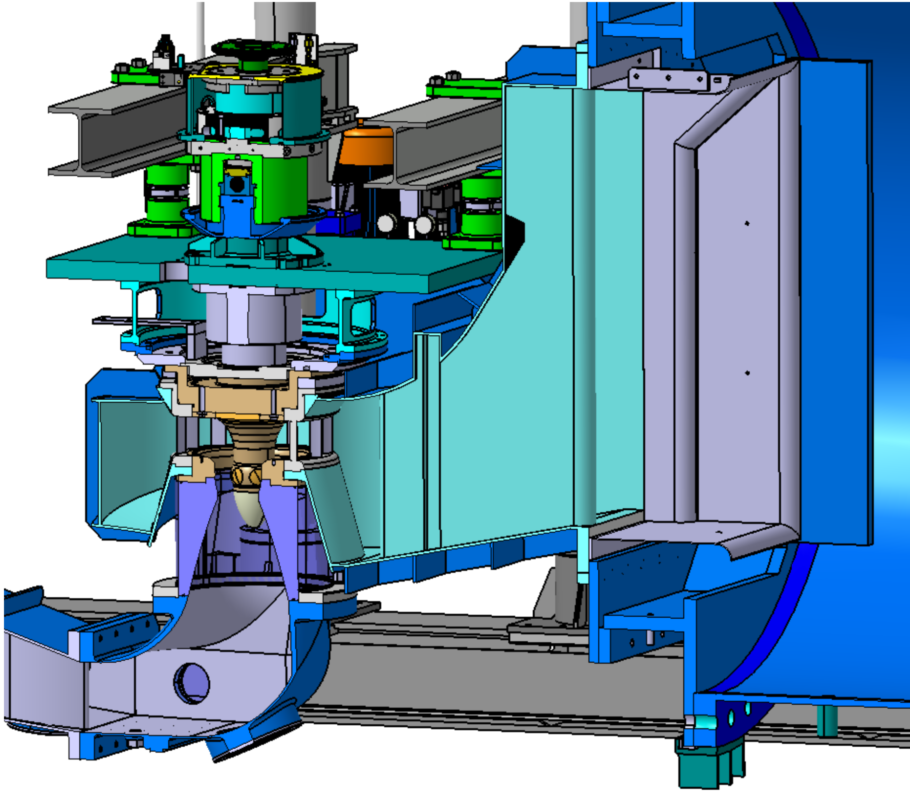


Construction of Itaipu Turbines

Semi Spiral Case

For low-head turbines

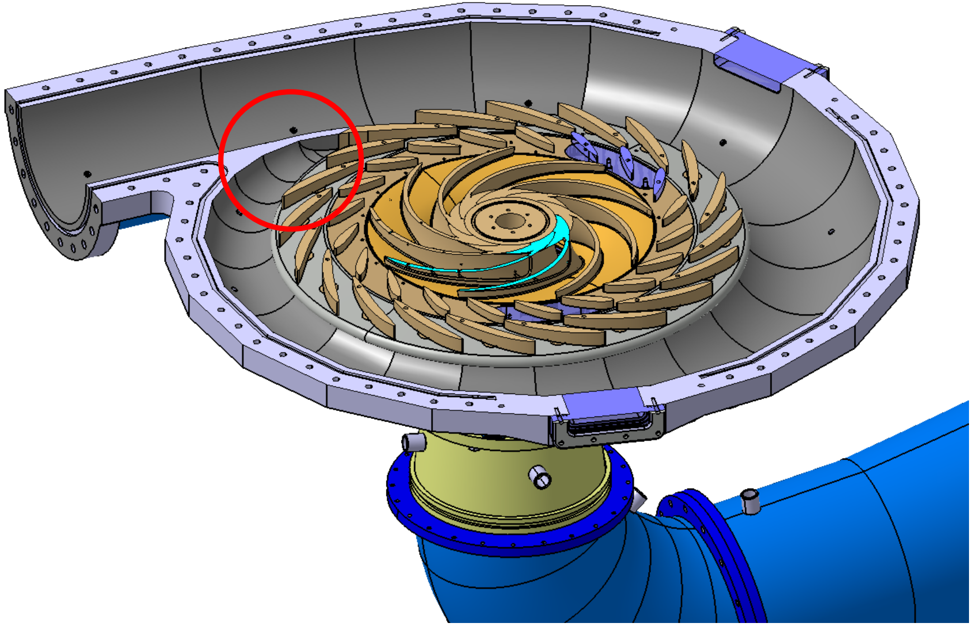




Made of concrete and included in civil works

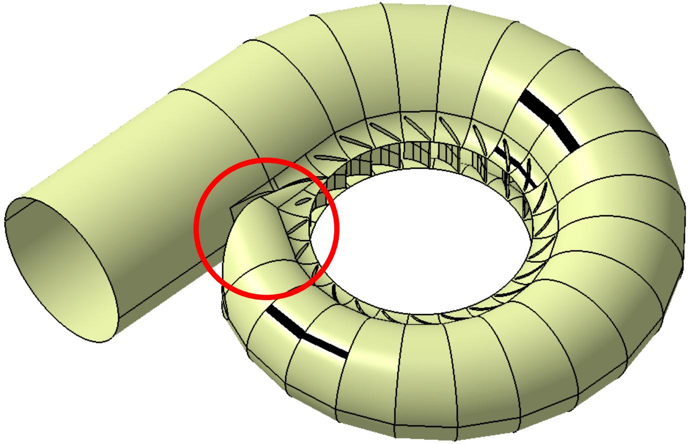
Spiral Case

Tongue or Nose vane

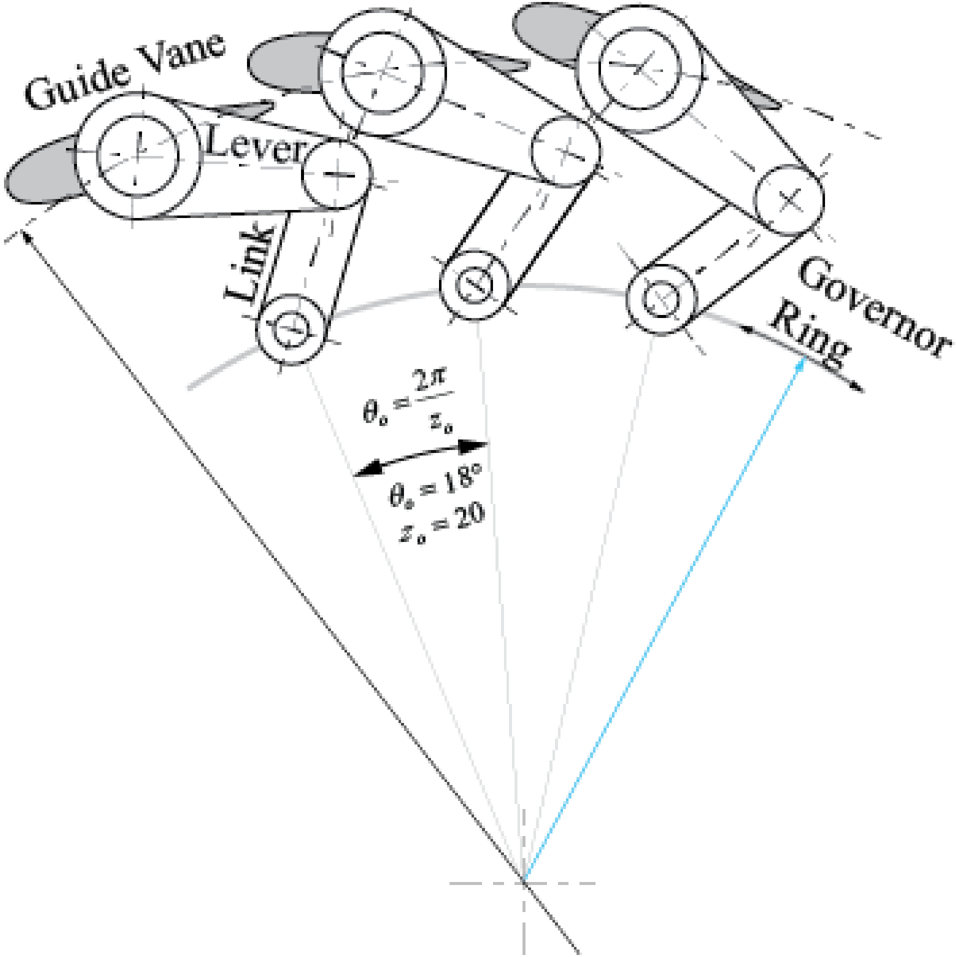


Spiral Case

Tongue or Nose vane

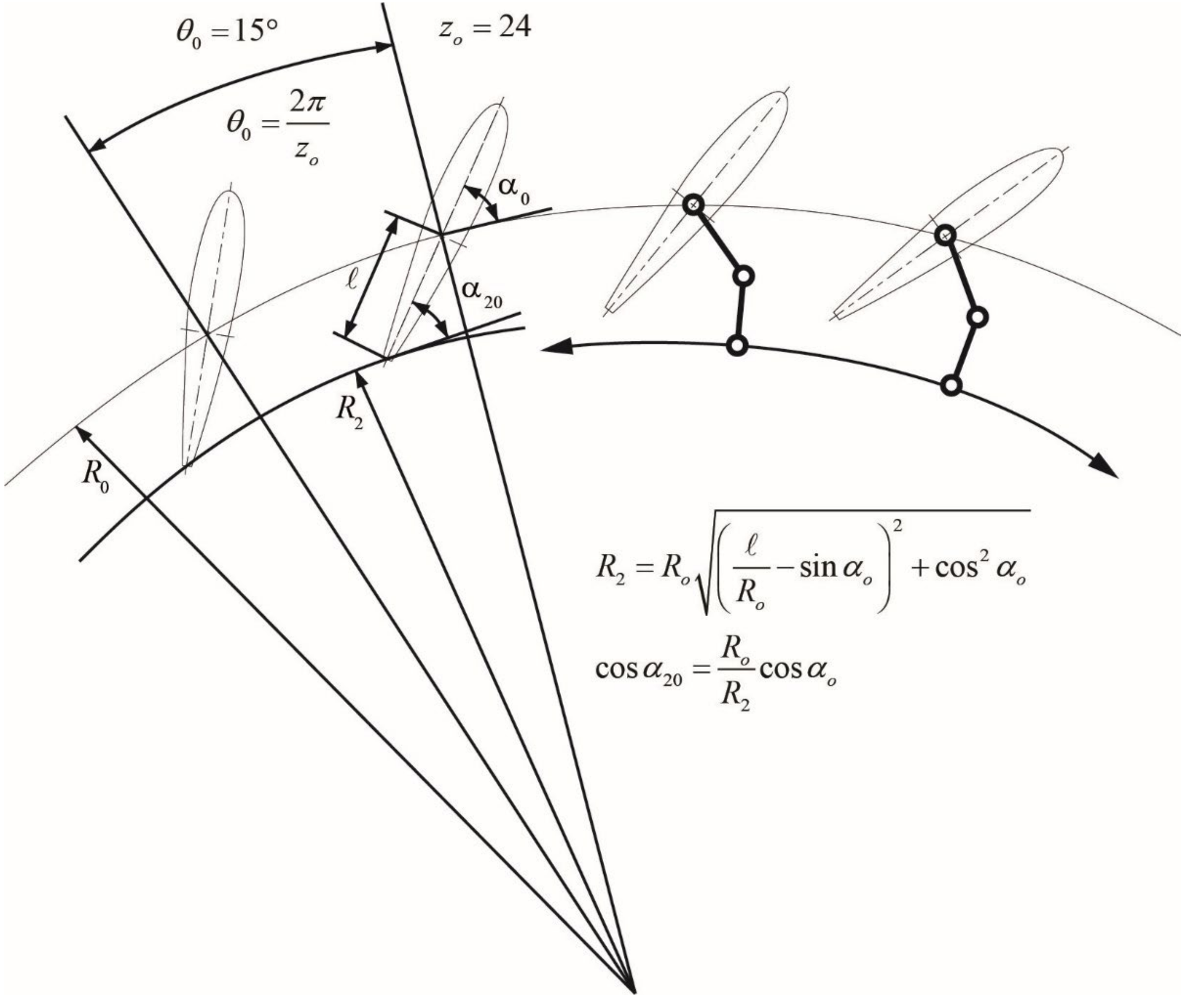


Guide Vanes


Guide Vane
Lever
Link
Governor Ring
$\theta_o = \frac{2\pi}{z_o}$
$\theta_o = 18°$
$z_o = 20$

Guide Vanes

- Angular Momentum Control
- Sealed at Closed Position



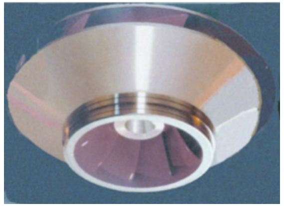
$$R_2 = R_o\sqrt{\left(\frac{\ell}{R_o} - \sin\alpha_o\right)^2 + \cos^2\alpha_o}$$

$$\cos\alpha_{20} = \frac{R_o}{R_2}\cos\alpha_o$$

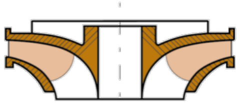
Classification of Hydraulic Runners

Francis Runners and Impellers

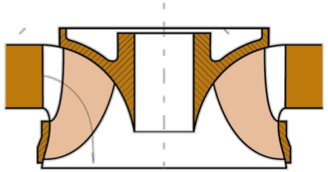
- Francis-type turbine and pump-turbine
  - Reaction machine
  - Radial flow
  - Medium Head

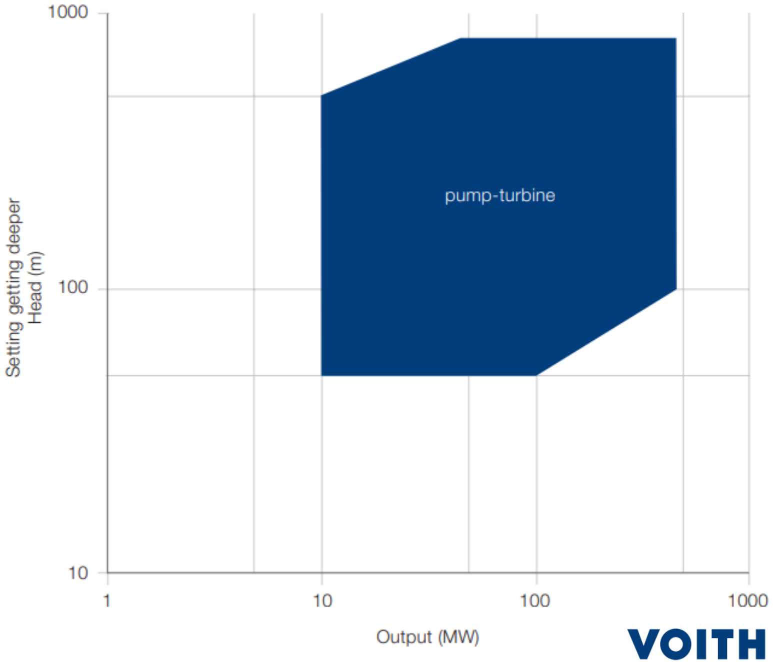


n_q = 12........35
ν = 0.10....0.22
n_{QE} = 0.04....0.10



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





VOITH
Engineered Reliability

Low Specific Speed Francis Runner

Example: Alto Lindoso (Portugal)

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

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

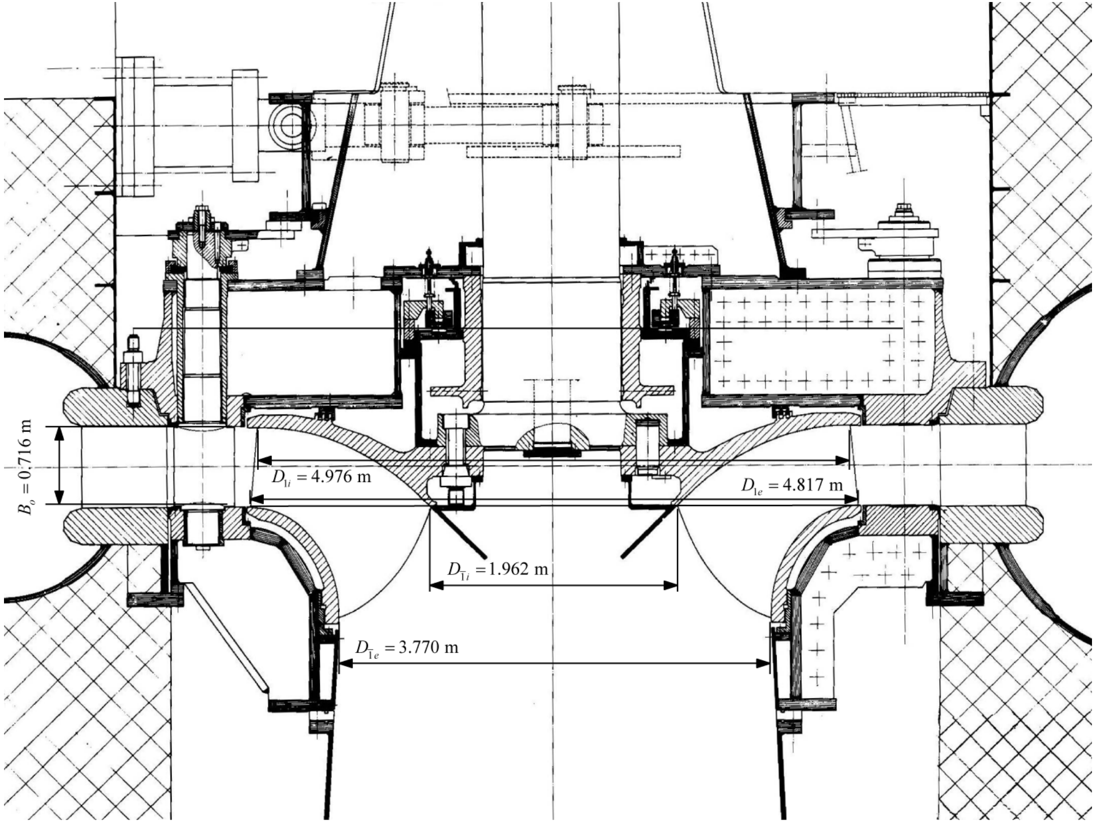
$$P = 317.0\ \mathrm{MW}$$

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

$$D_{\bar{1}e} = 3.770\ \mathrm{m}$$

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

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



High Specific Speed Francis Runner

Example: Tucurui (Brazil)

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

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

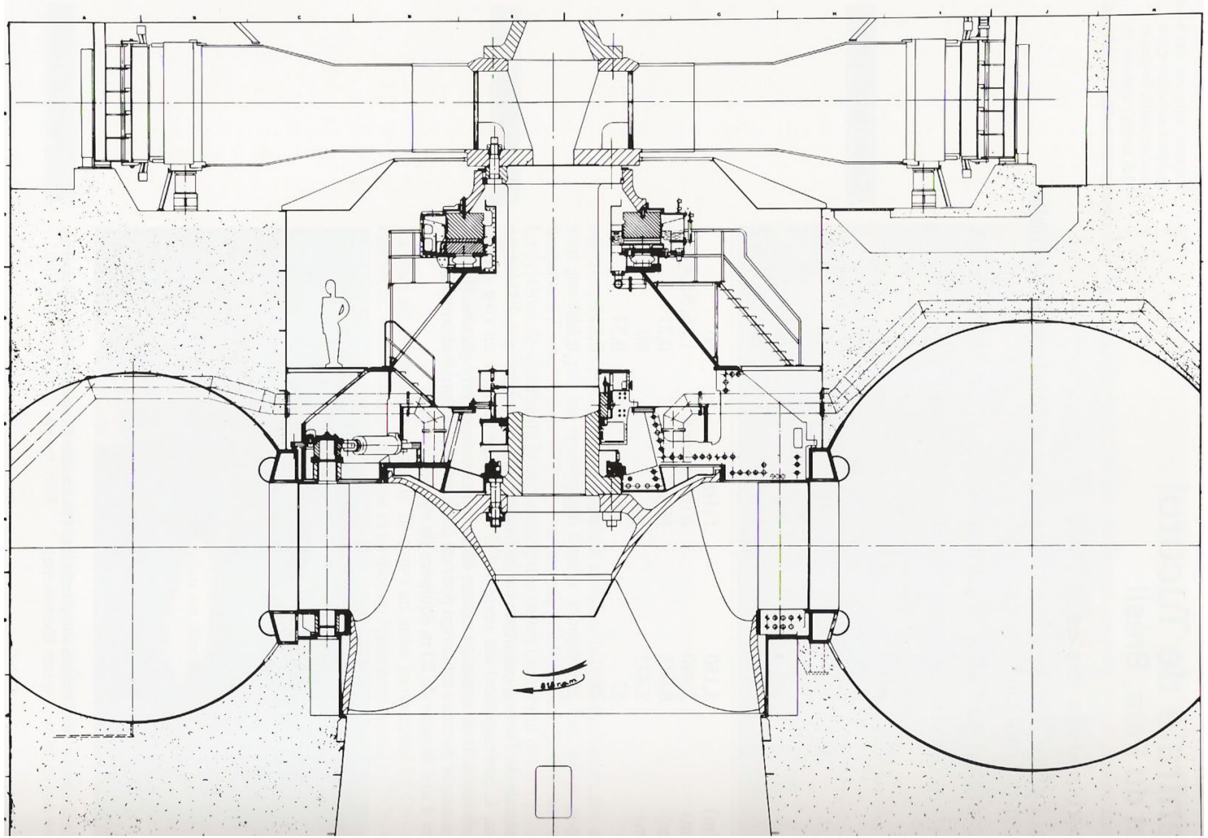
$$P = 320\ \mathrm{MW}$$

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

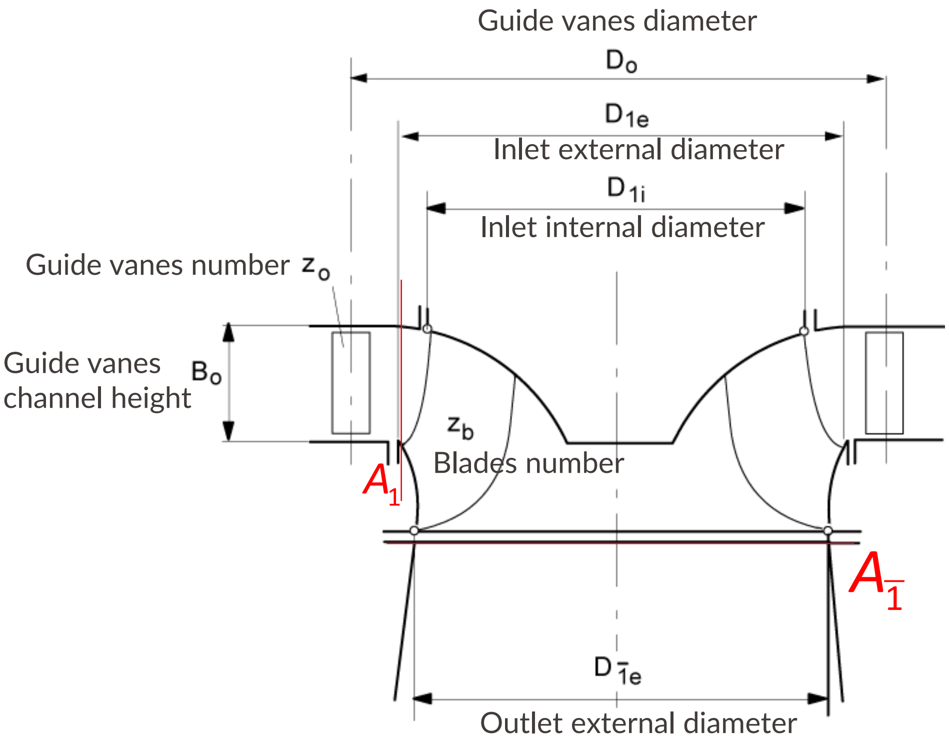
$$D_{\overline{1}e} = 8.150\ \mathrm{m}$$

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

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



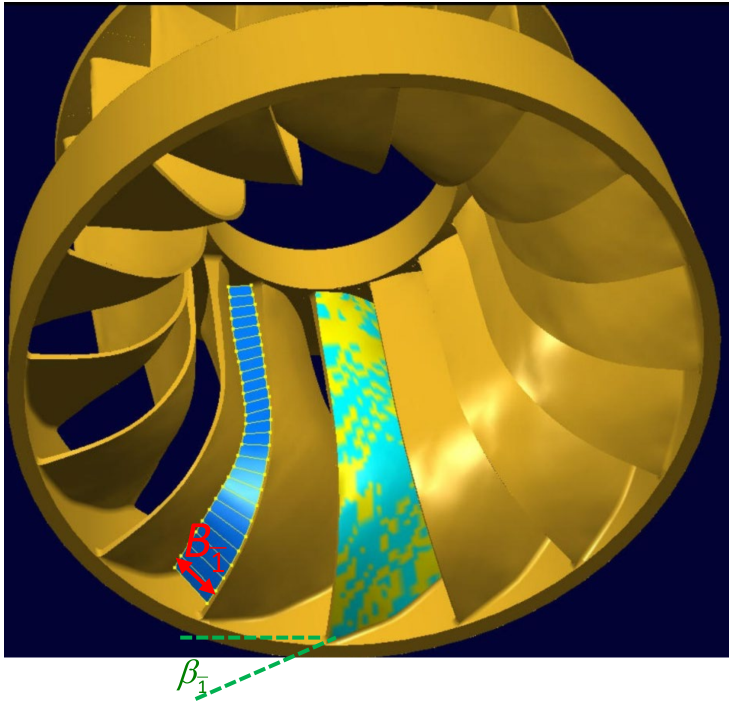
Main Geometrical Data of a Francis runner



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

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

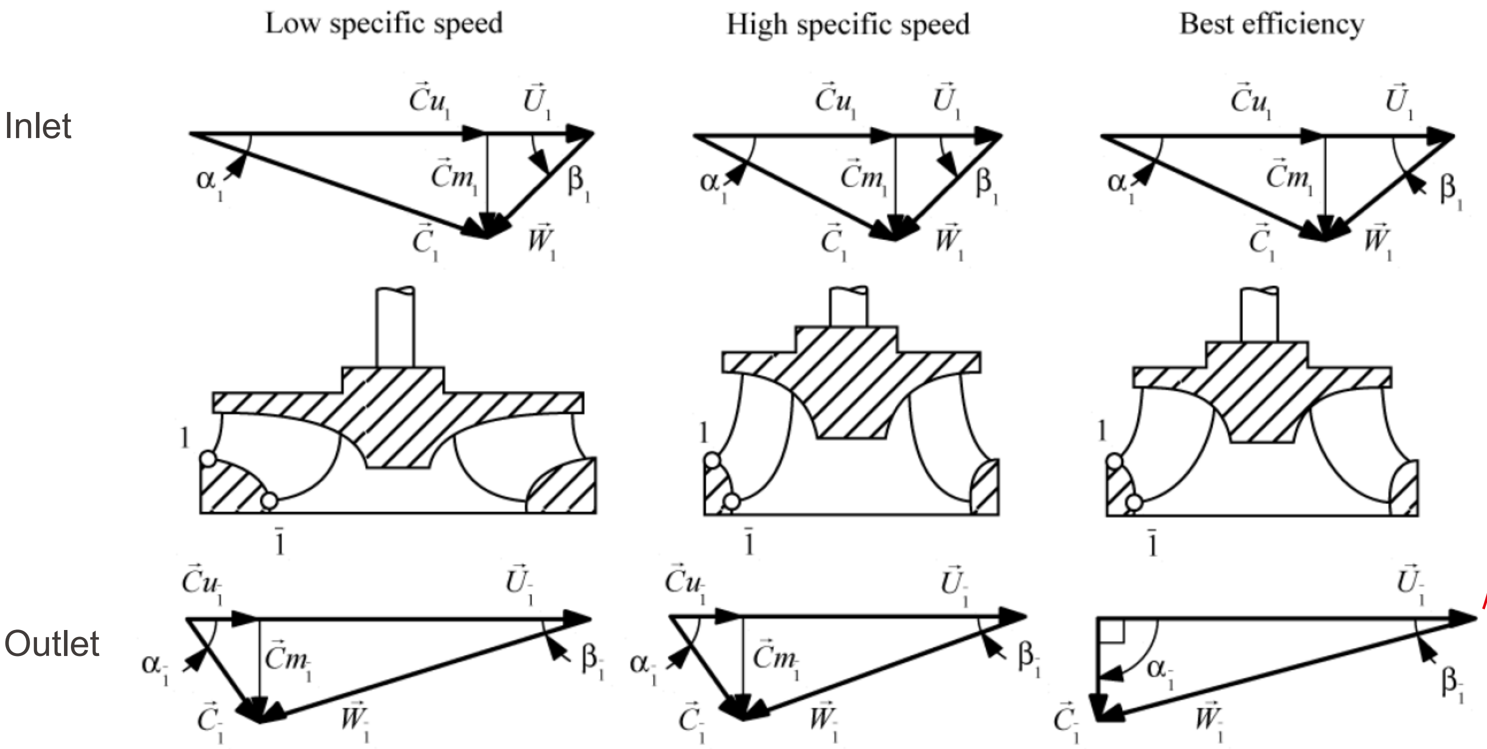
Vent Opening (Flow passage section)



$$\sin\beta_{\bar{1}} = \frac{z_b B_{\bar{1}}}{2\pi R_{\bar{1}}}$$

Turbine Runner Velocity Triangles

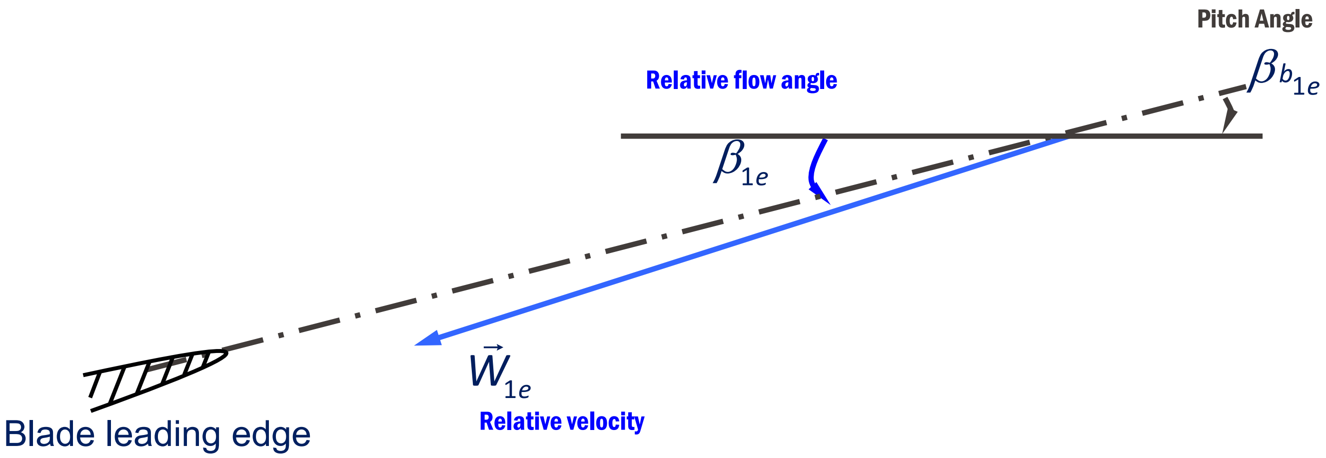
$$E_t = U_{1e} Cu_{1e} \cancel{- k_{C_{u\bar{1}e}} U_{\bar{1}e} Cu_{\bar{1}e}}$$



Axial
outlet
flow

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

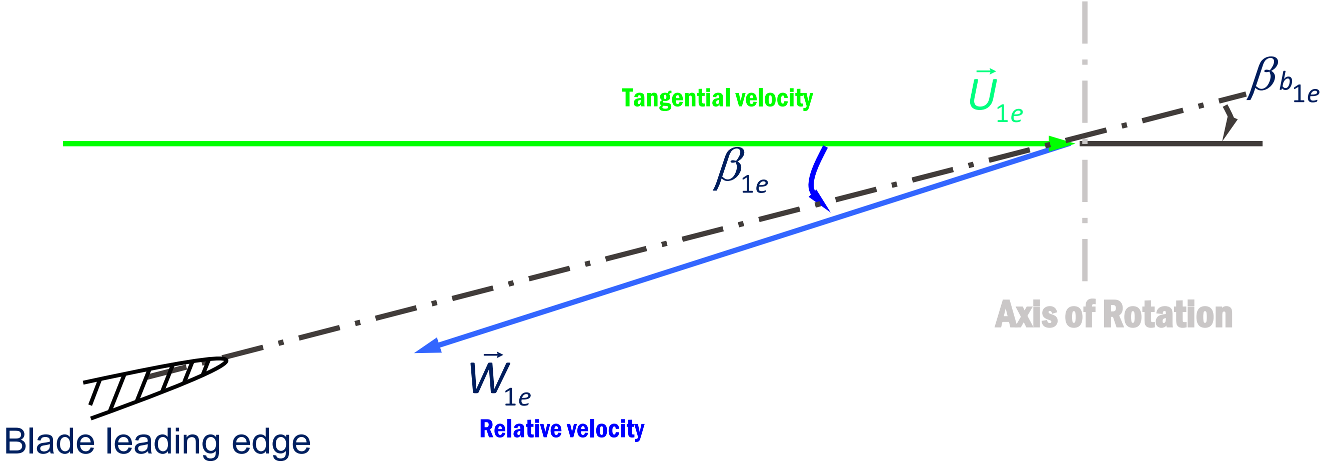
Flow Velocity Diagram



- Relative Flow Incidence

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

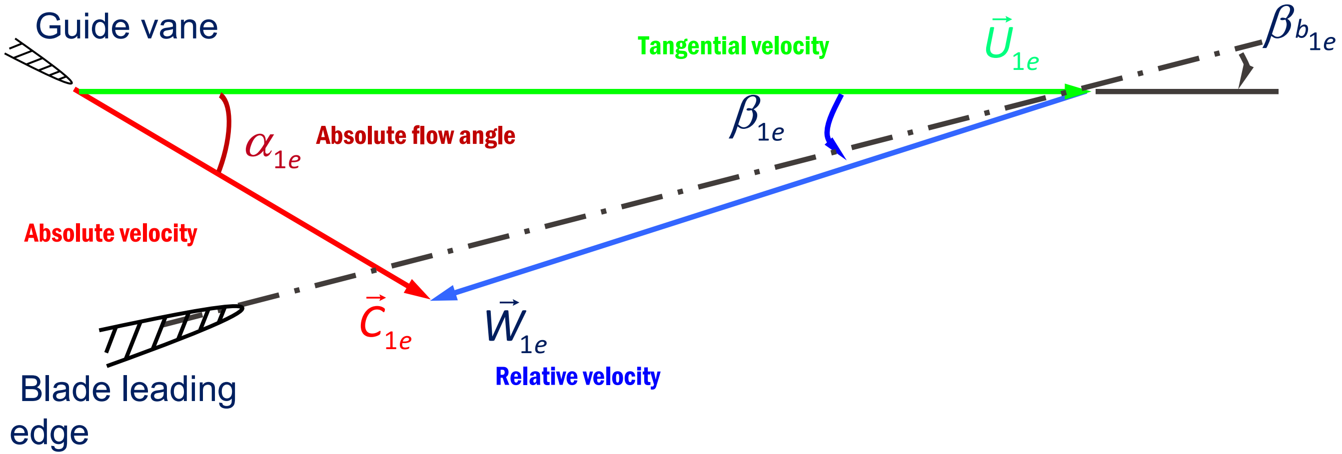
Flow Velocity Diagram



- Relative Flow Incidence

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

Flow Velocity Diagram

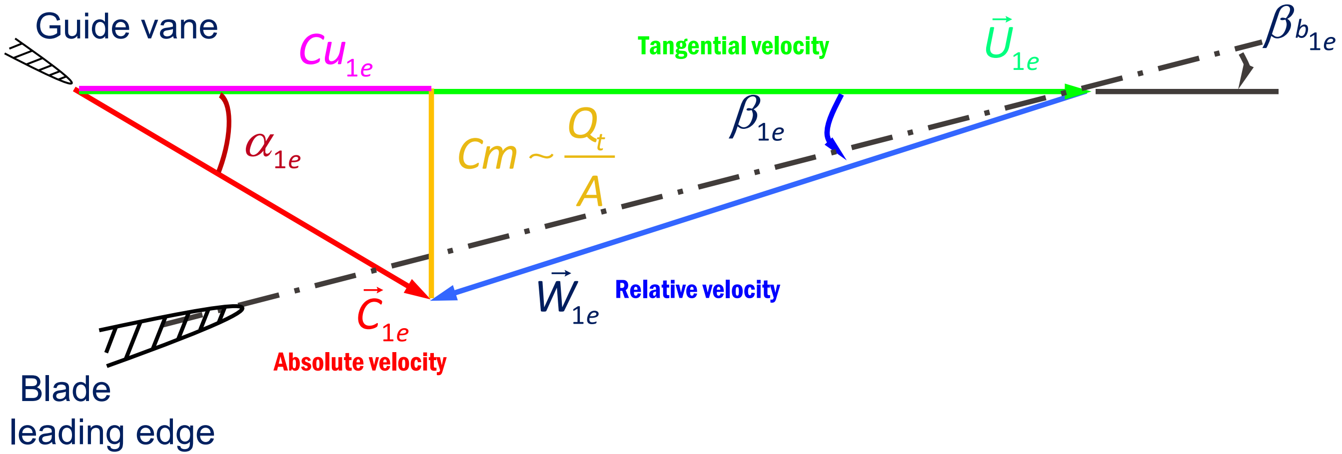


Absolute velocity $\vec{C} = \vec{U} + \vec{W}$

- Relative Flow Incidence

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

Flow Velocity Diagram

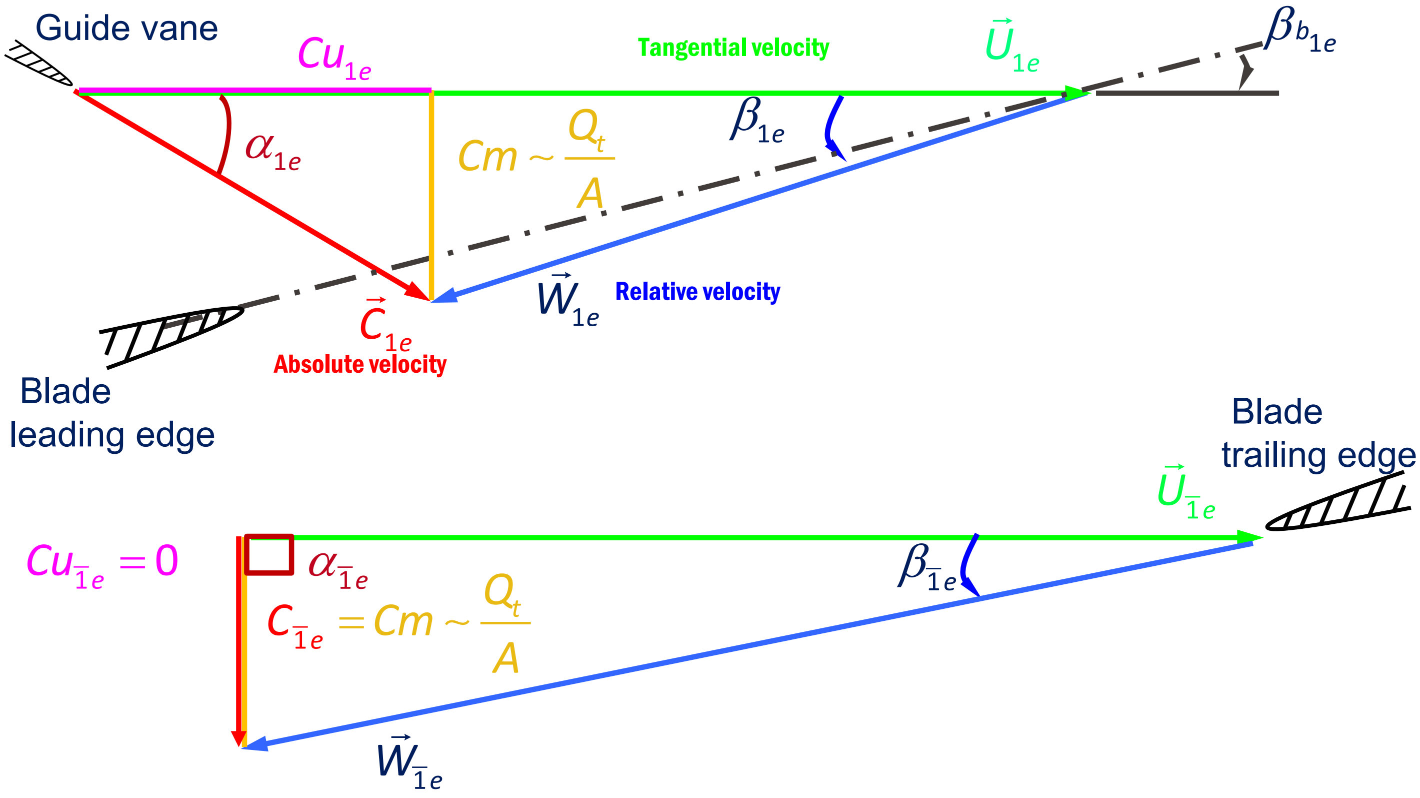


Meridional component of the absolute velocity

Tangential component of the absolute velocity

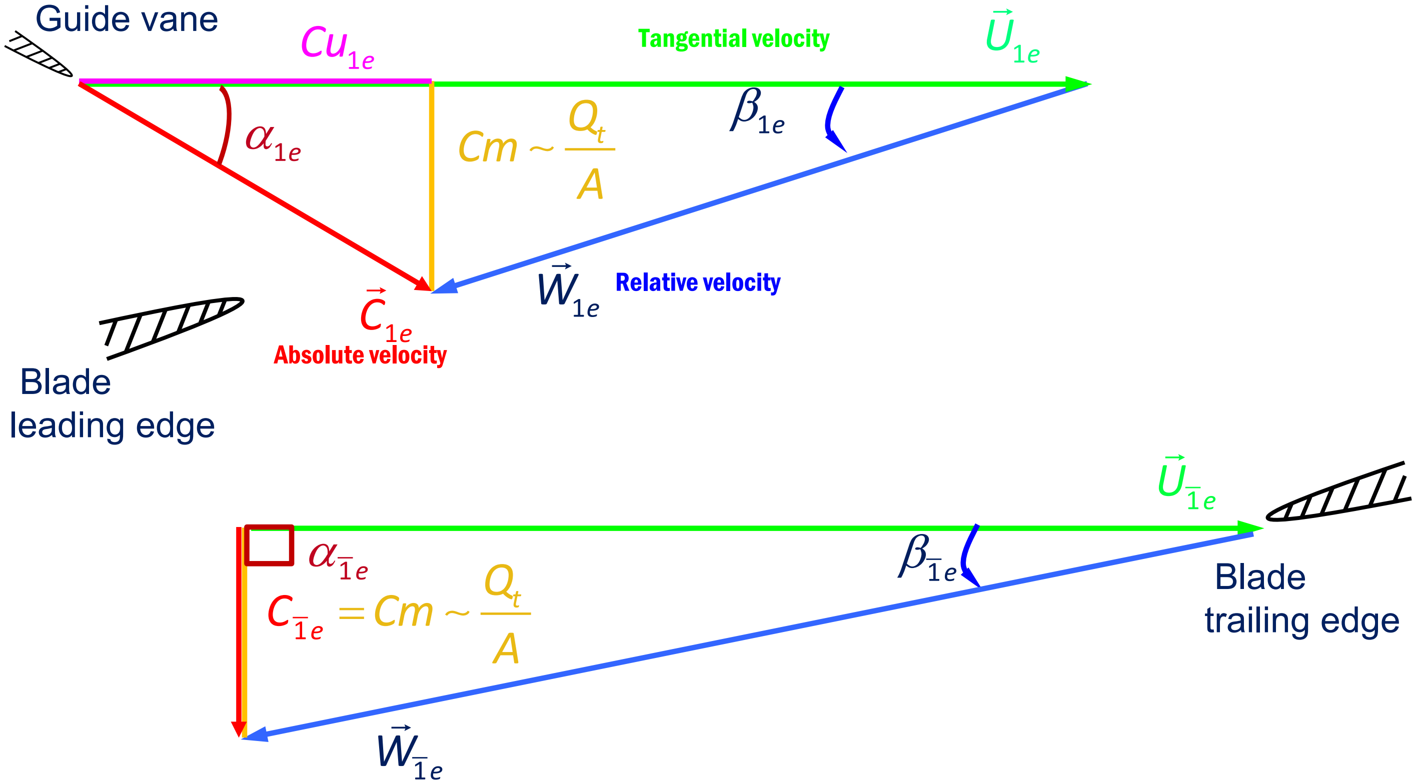
$$Cu = \frac{Cm}{tg\alpha} = U - \frac{Cm}{tg\beta}$$

Flow Velocity Diagram



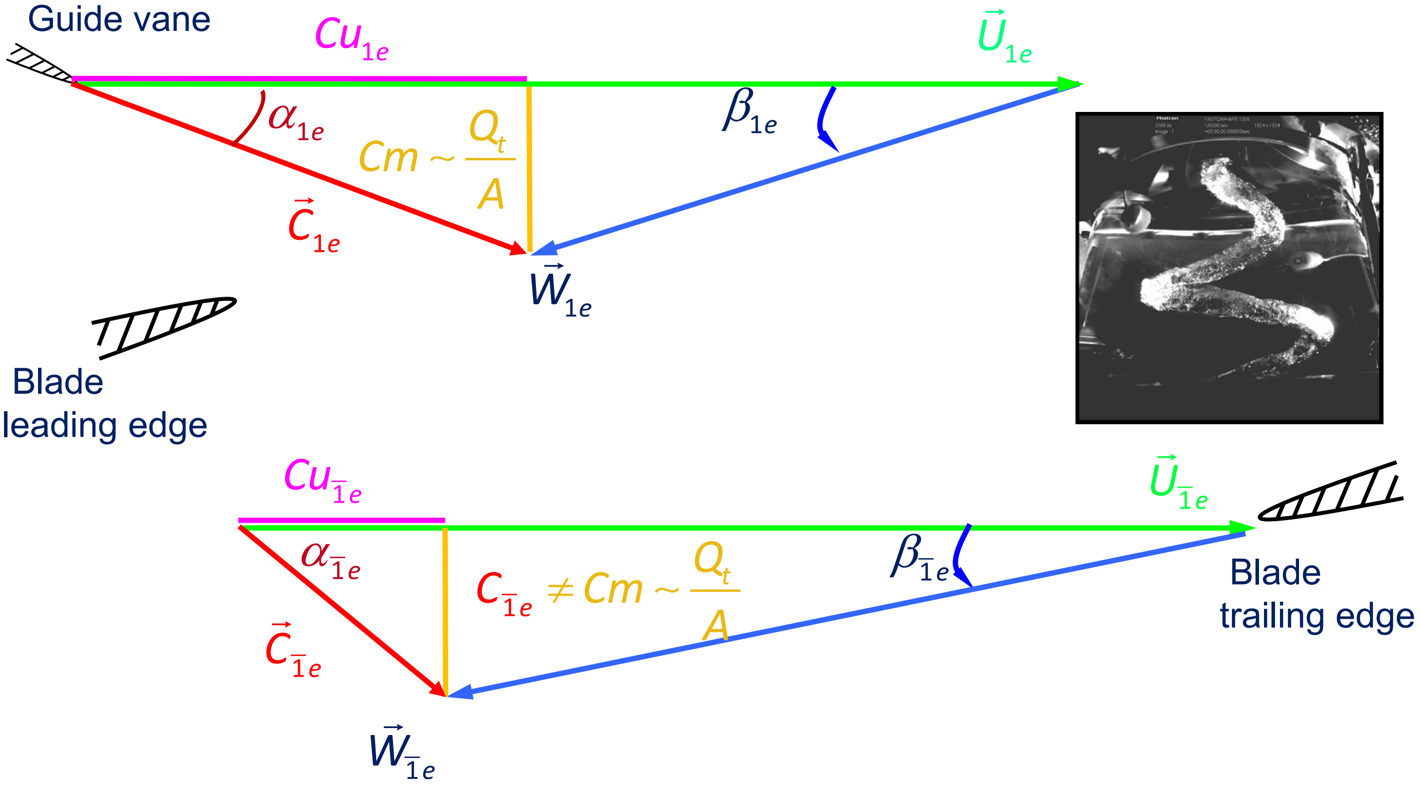
Flow Velocity Diagram

Let’s imagine the discharge decreases



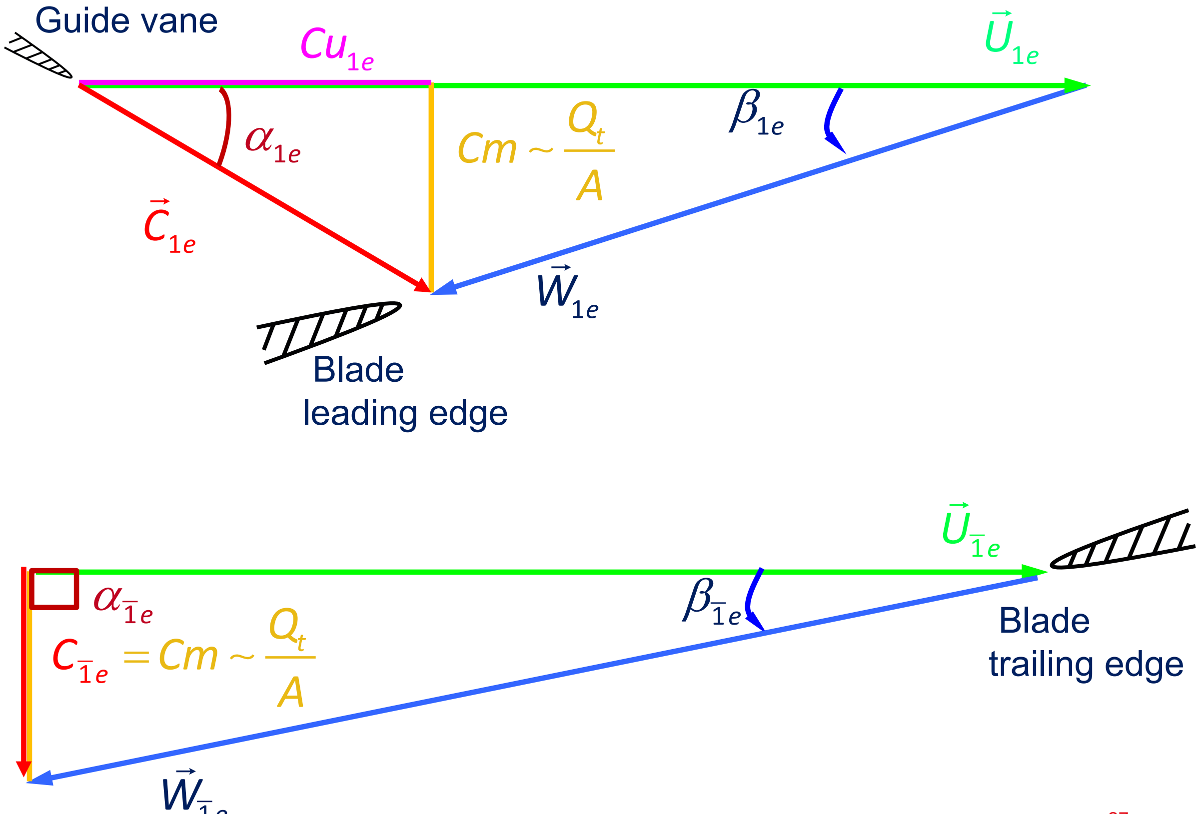
Flow Velocity Diagram

Let’s imagine the discharge decreases: Part load condition



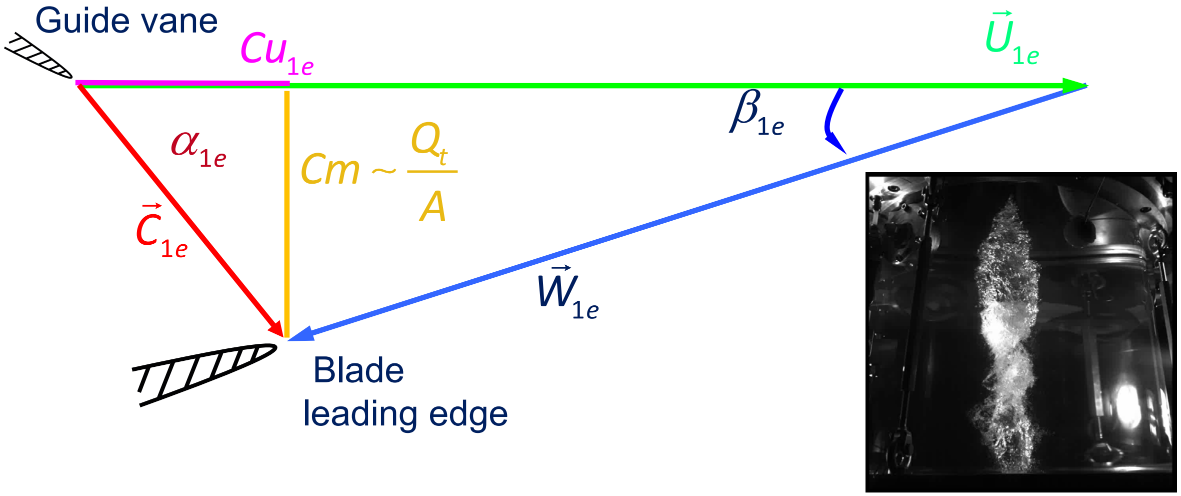
Flow Velocity Diagram

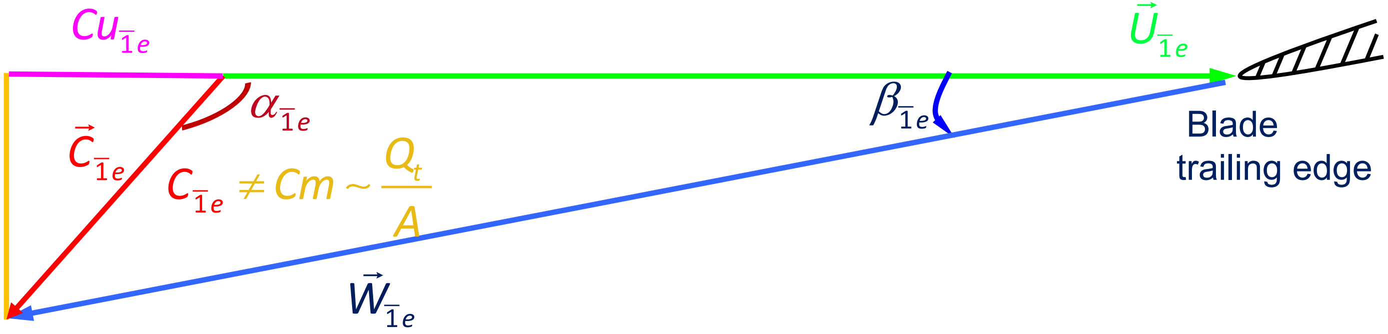
Let’s imagine the discharge increases



Flow Velocity Diagram

Let’s imagine the discharge increases: Full load condition

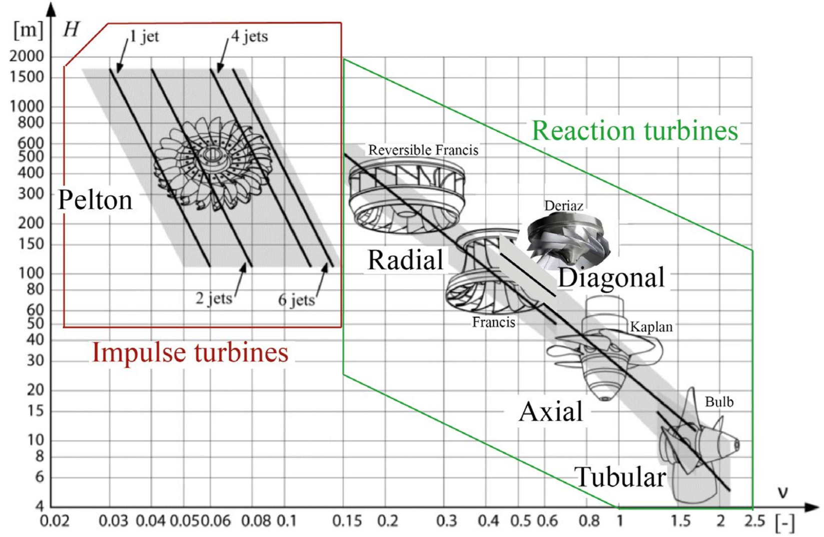


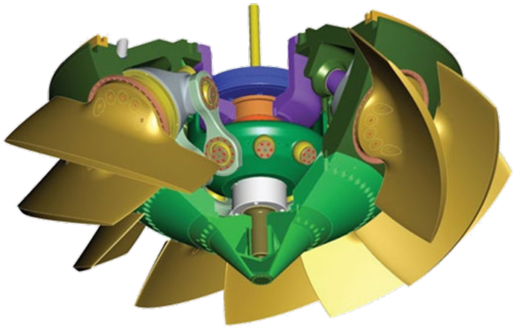


Classification of Hydraulic Runners

Deriaz turbines

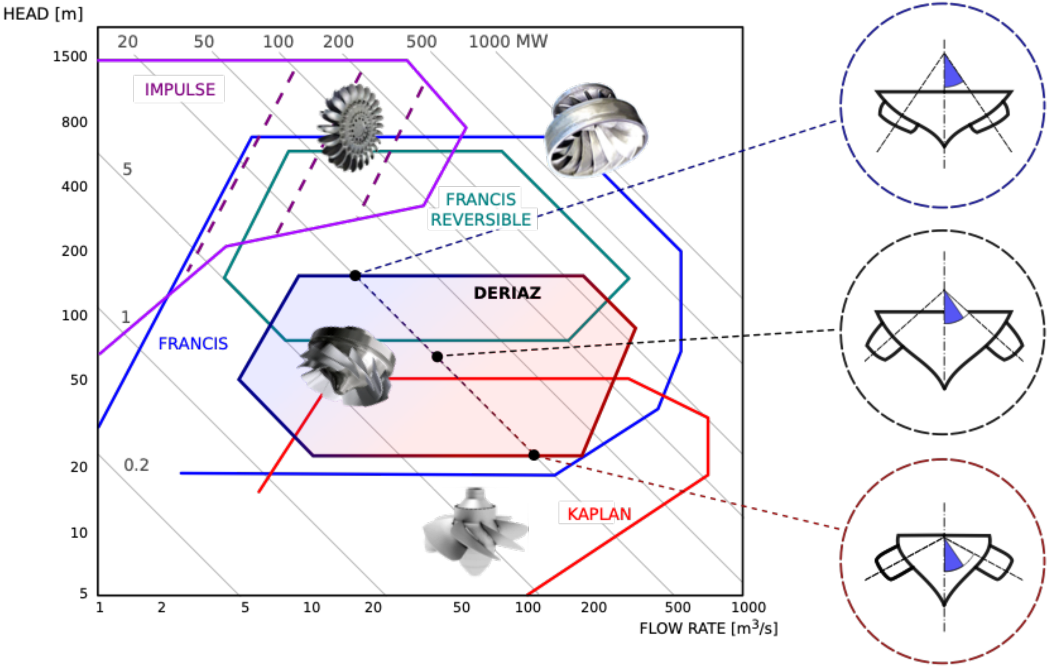
- Mixed flow hydraulic turbomachine
- Reversible
- Adjustable runner blades





Classification of Hydraulic Runners

Deriaz Turbines



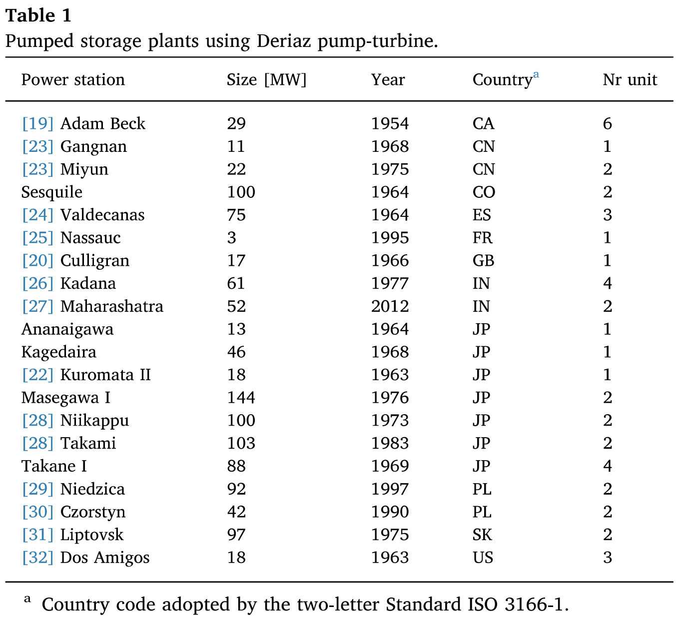


Table 1

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] Valdecanas	75	1964	ES	3
[25] Nassauc	3	1995	FR	1
[20] Culligran	17	1966	GB	1
[26] Kadana	61	1977	IN	4
[27] Maharashatra	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

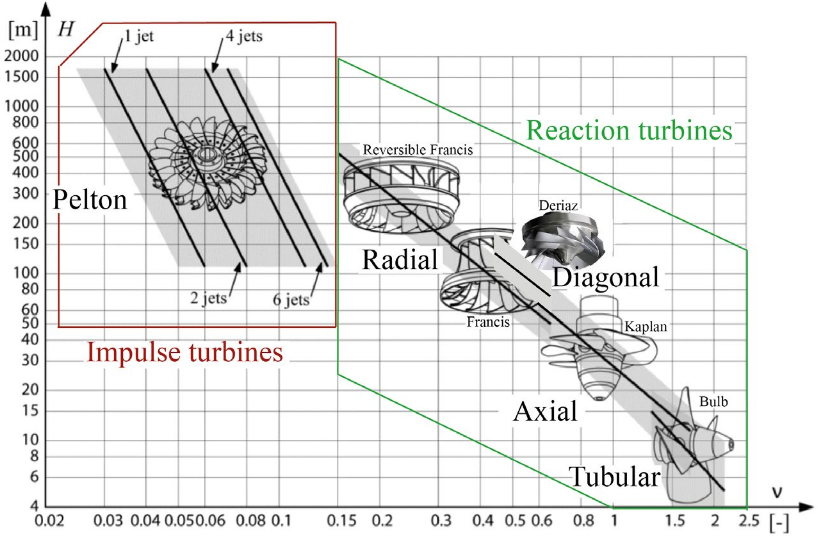
Deriaz turbines

- 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

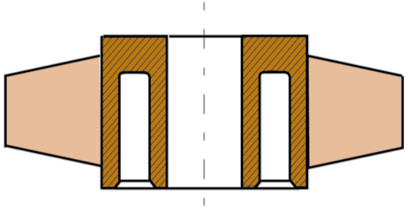
- Kaplan Turbine
  - Reaction machine
  - Axial flow
  - Low head



n_q = 200.....400

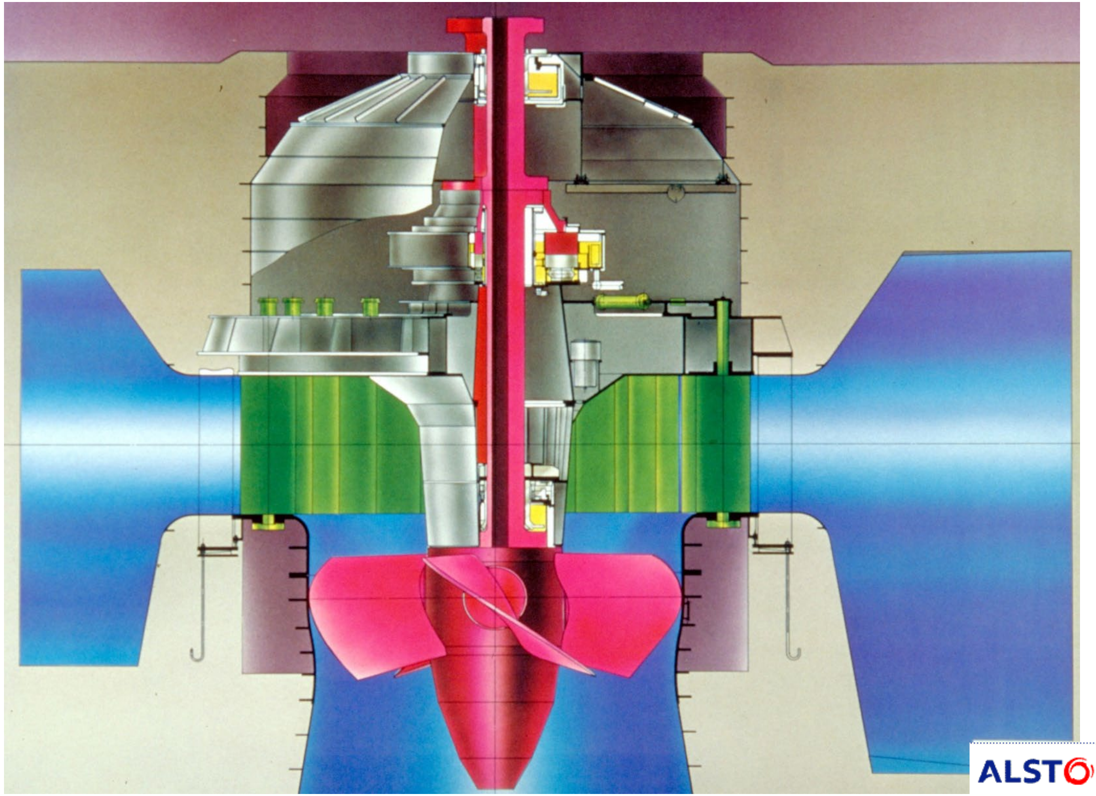
ν = 1.25....2.50

n_{QE} = 0.50...1.20



Classification of Hydraulic Runners

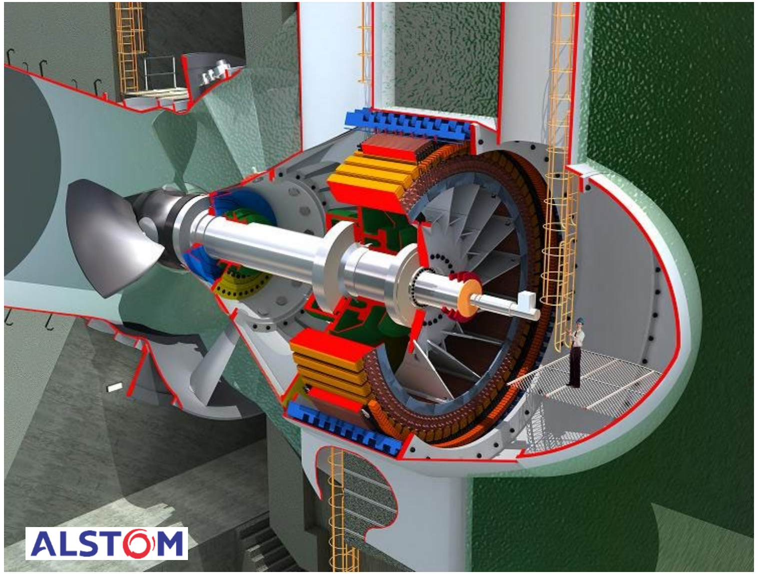
Kaplan Runners

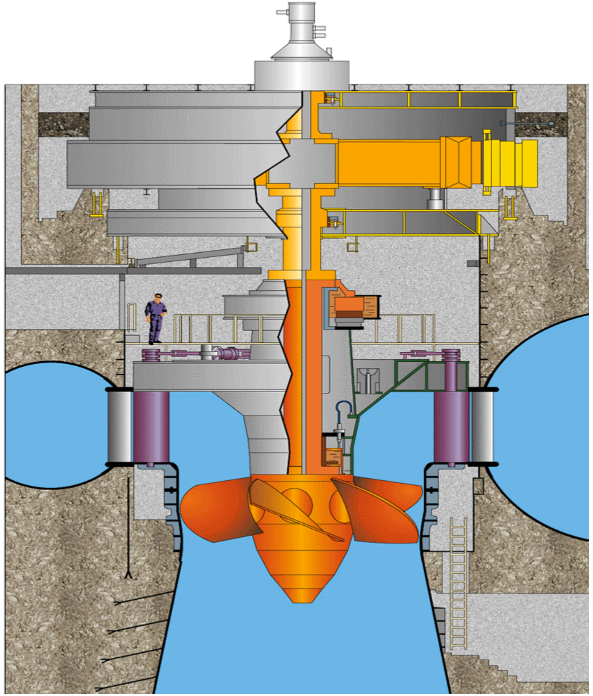


Bulb VS Kaplan

Bulb: fully axial or mixed flow

Kaplan: radial guide vanes and axial runner flow





Kaplan runner

Example: Verbois (Switerland)

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

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

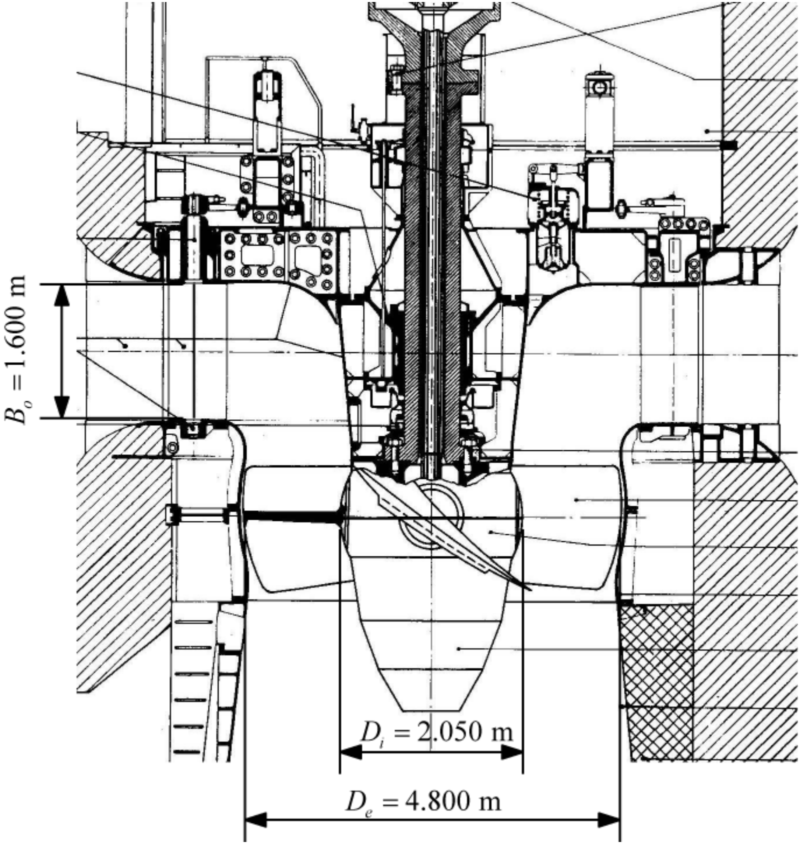
$P = 25.3 \text{ MW}$

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

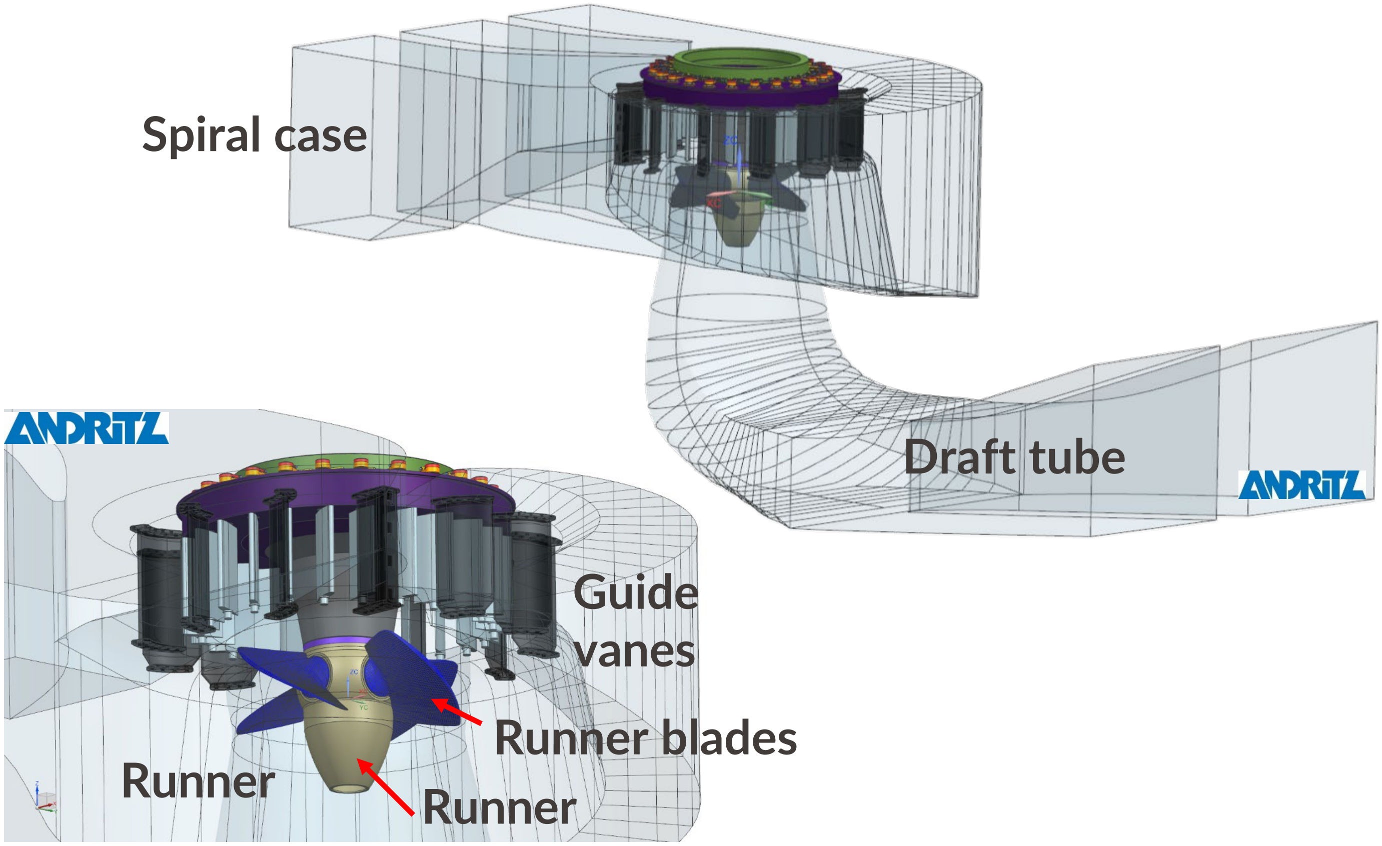
$D_{\bar{1}e} = 4.800 \text{ m}$

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

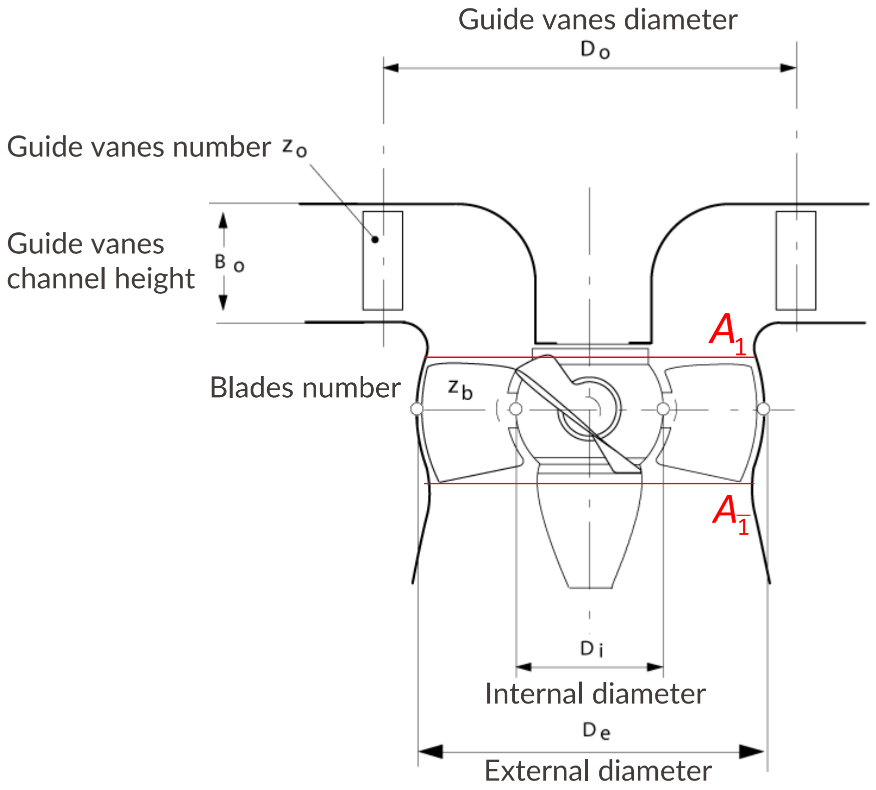
$B_o = 1.600 \text{ m}$



Main Geometrical Data of a Kaplan turbine



Main Geometrical Data of a Kaplan runner



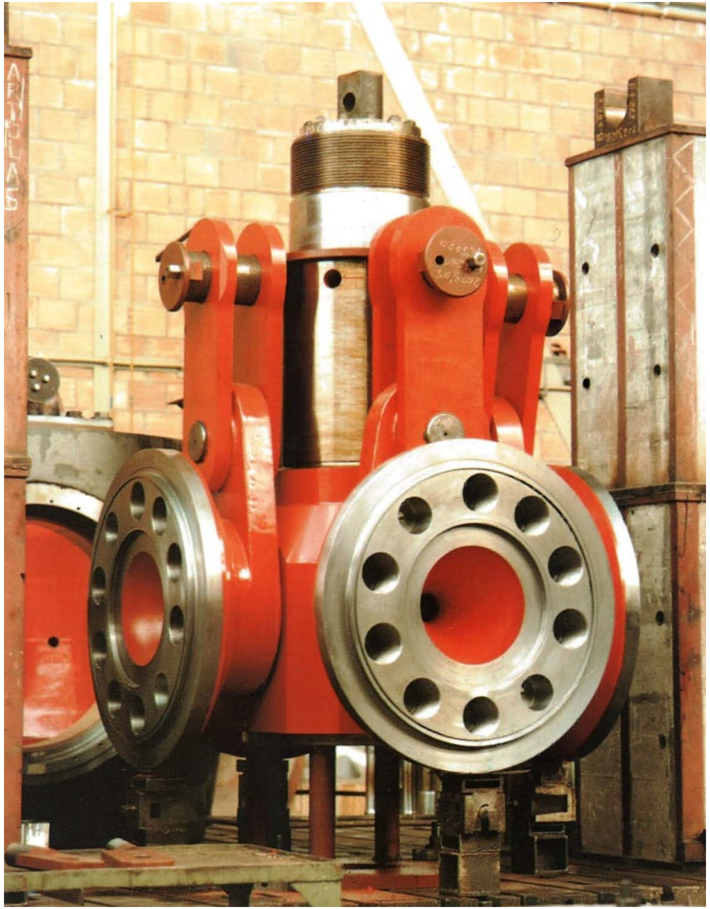
$$A_1 = \pi \frac{D^2_{1e} - D^2_{1i}}{4}$$

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

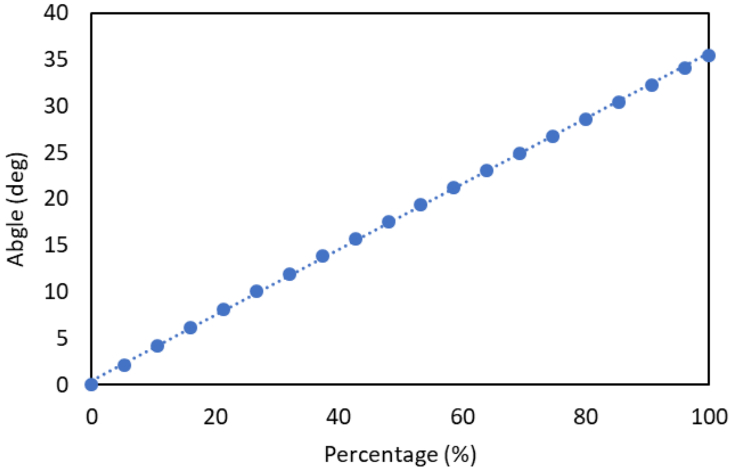
$$A_1 = A_{\bar{1}}$$

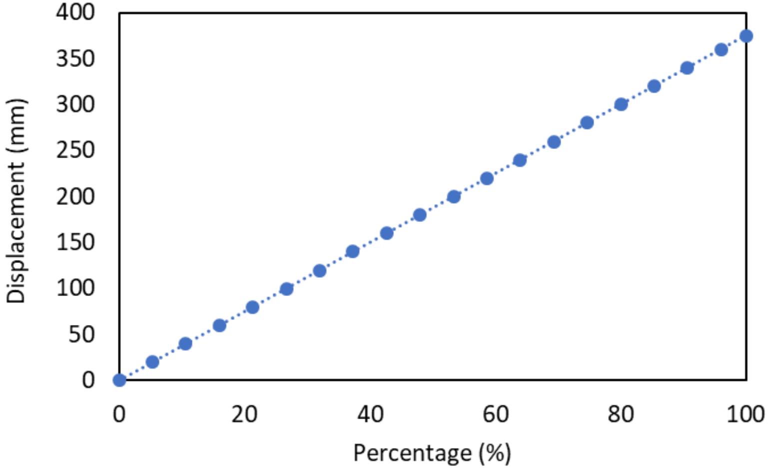
Controllable Pitch Kaplan Runner

- Blade Base Plates
- Levers
- Connecting Rods
- Piston

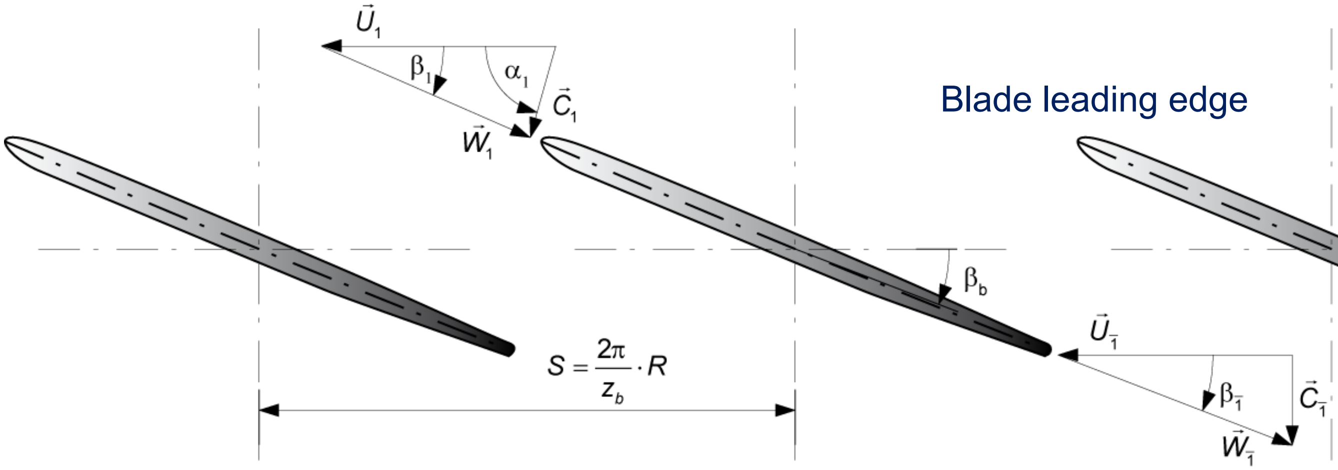


Controllable Pitch Kaplan Runner



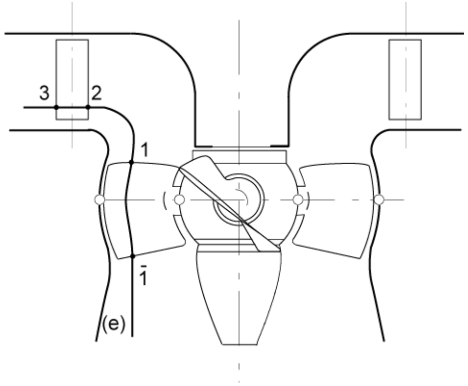


Controllable Pitch Kaplan Runner

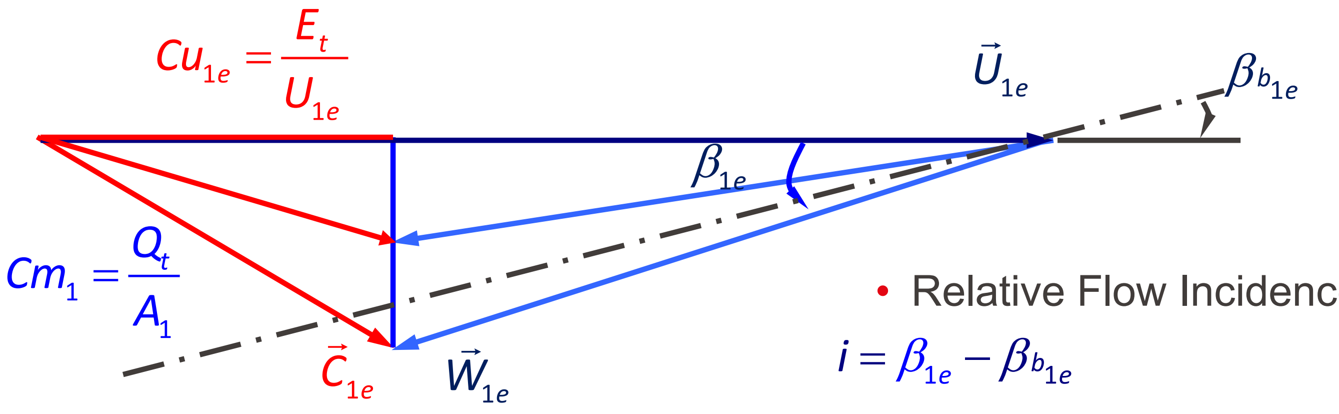


Blade leading edge

Blade trailing edge

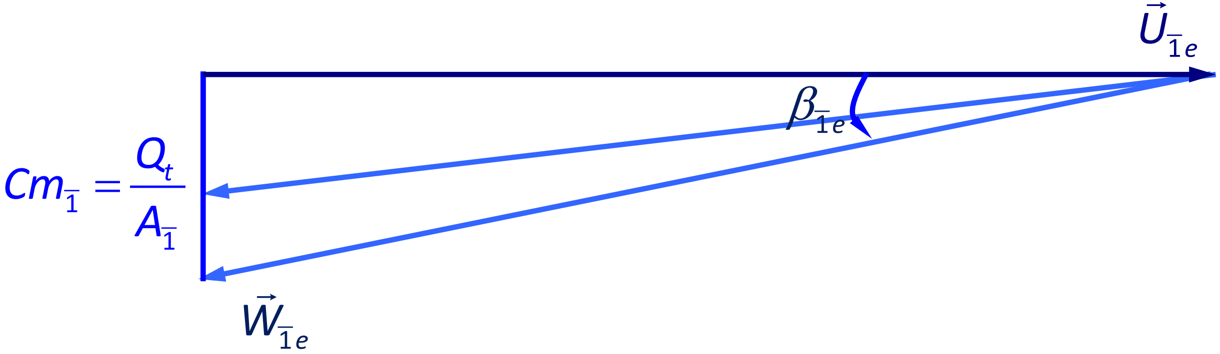


Flow Velocity Diagram

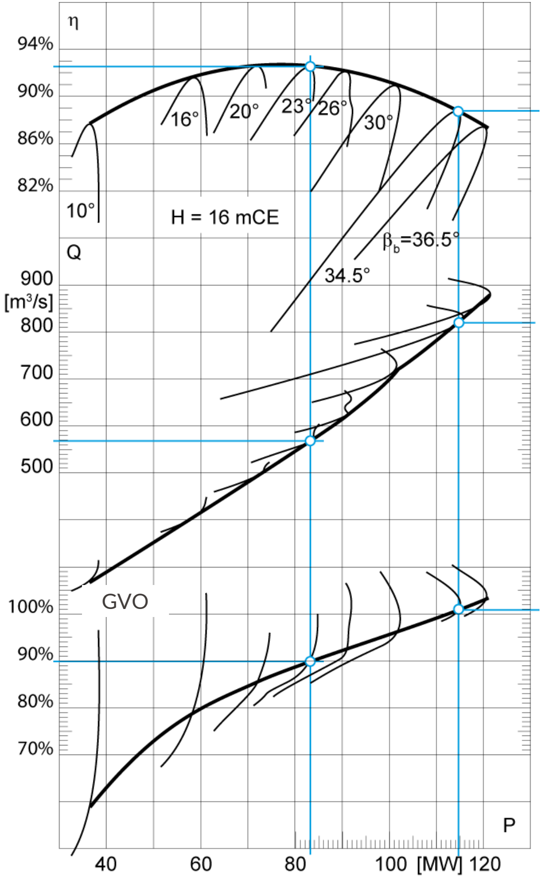


- Relative Flow Incidence

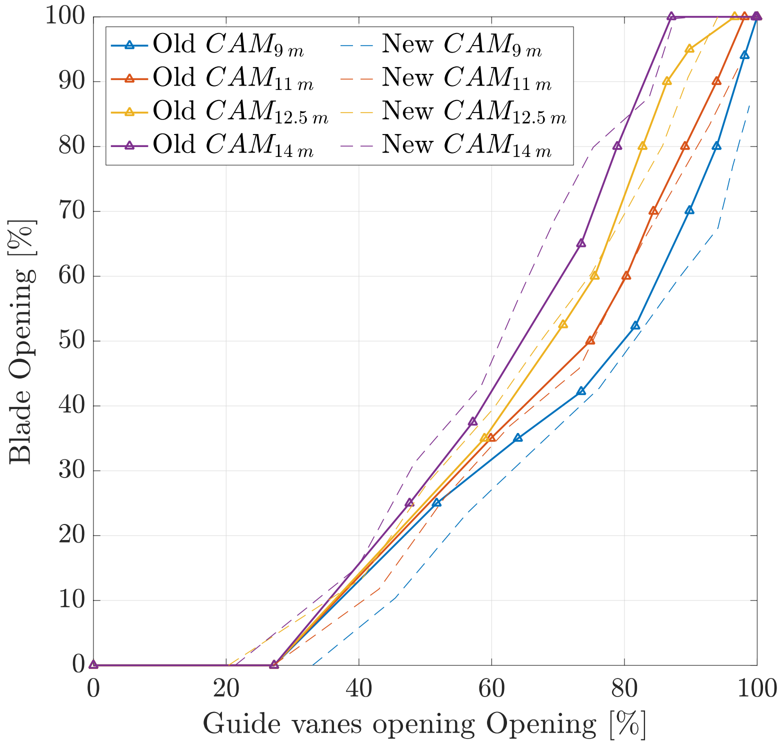
$$i = \beta_{1e} - \beta_{b_{1e}}$$



Hydraulic characteristics and on-cam curve



Yacyreta Power Plant

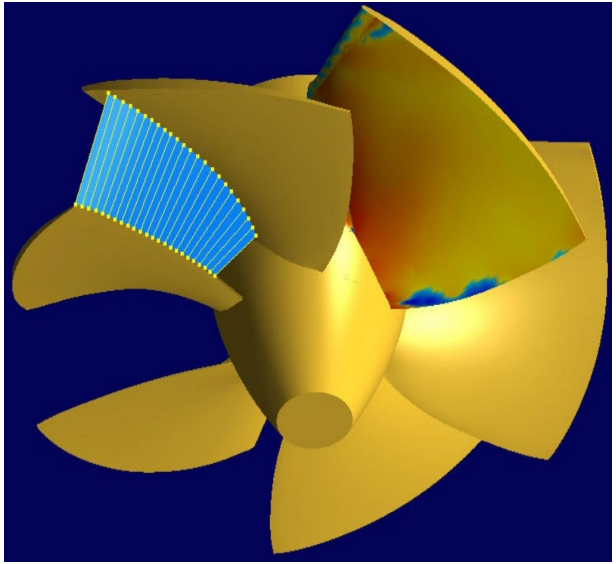


Vogelgrun Power Plant

Vent Opening (Flow passage section)

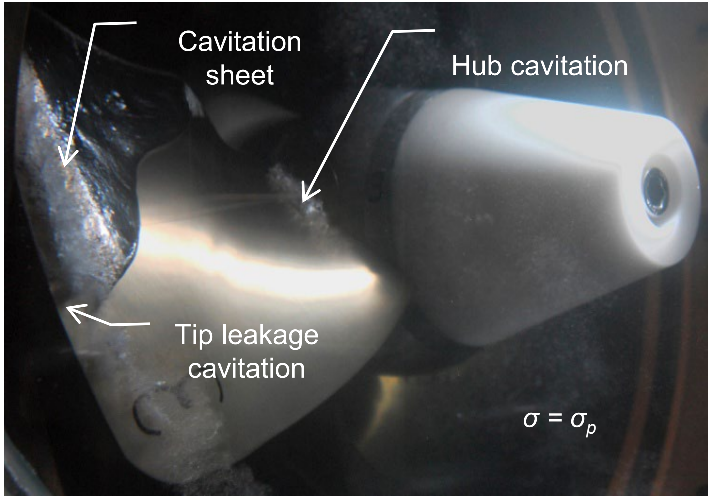
- Propeller Flow Passage

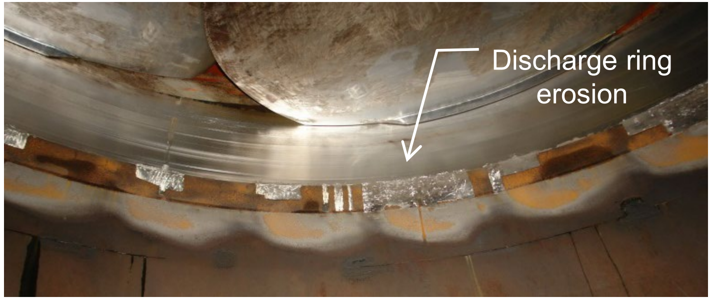
$$\sin\beta_{\bar{1}} = \frac{z_b B_{\bar{1}}}{2\pi R_{\bar{1}}}$$



Kaplan & Bulb Turbines: Main Issues

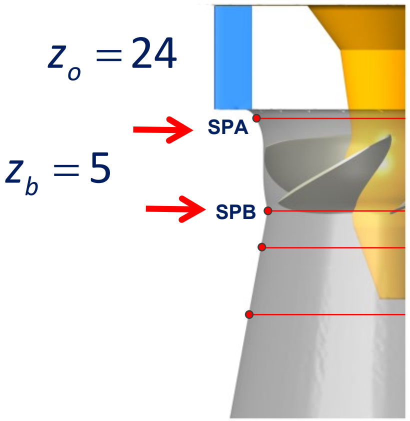
- Erosion Risk
  - Leading Edge Cavitation
  - Tip Vortex
  - Discharge ring erosion
  - Guide Vane Wakes-Blades interactions
- Efficiency Alteration
  - Hub Cavitation
  - Wear and tear

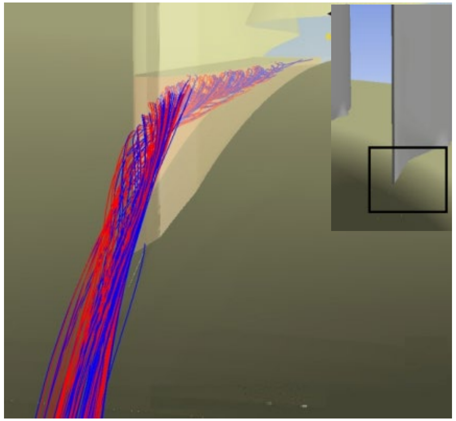


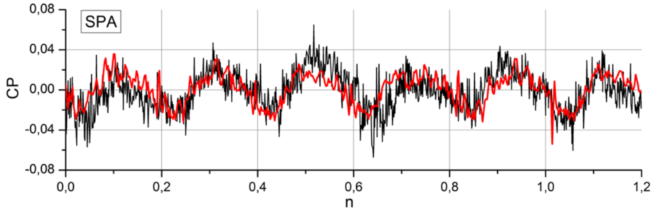


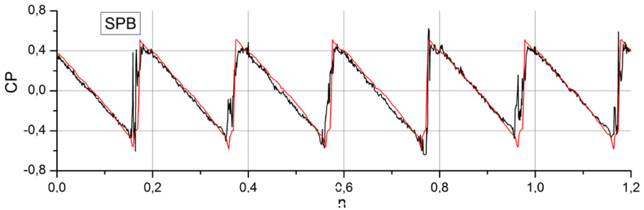
Guide Vane Wakes-Blades interactions

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



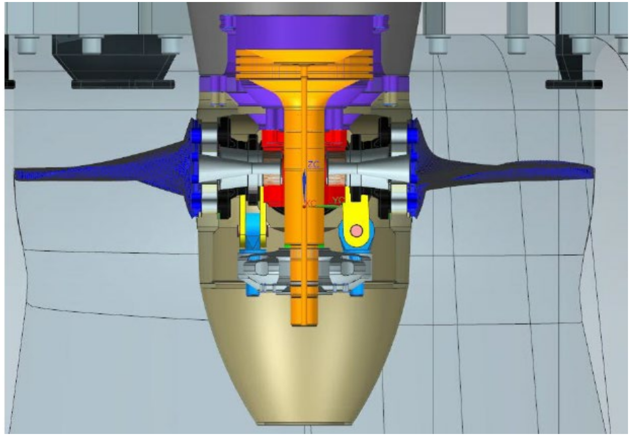






Wear and Tear

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



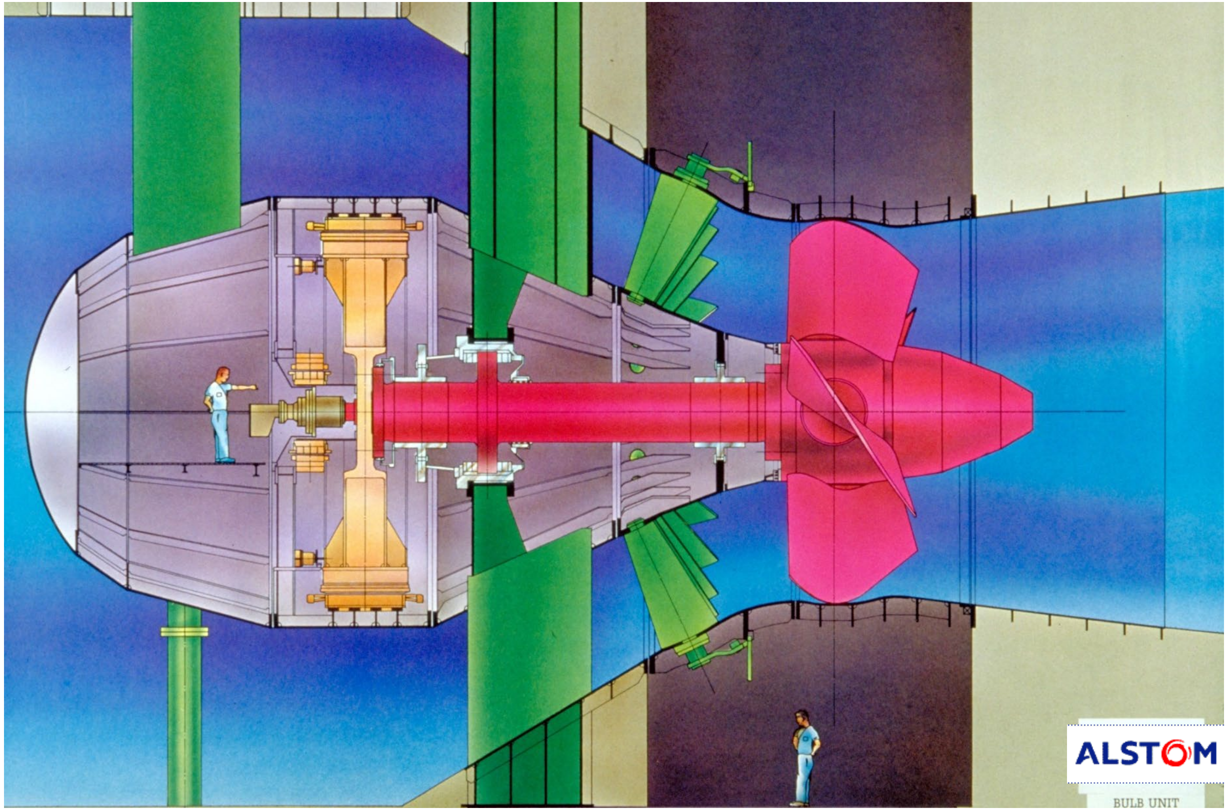
VOGELGRUN , France

- Four vertical Kaplan turbines
- Battery Hybrid

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

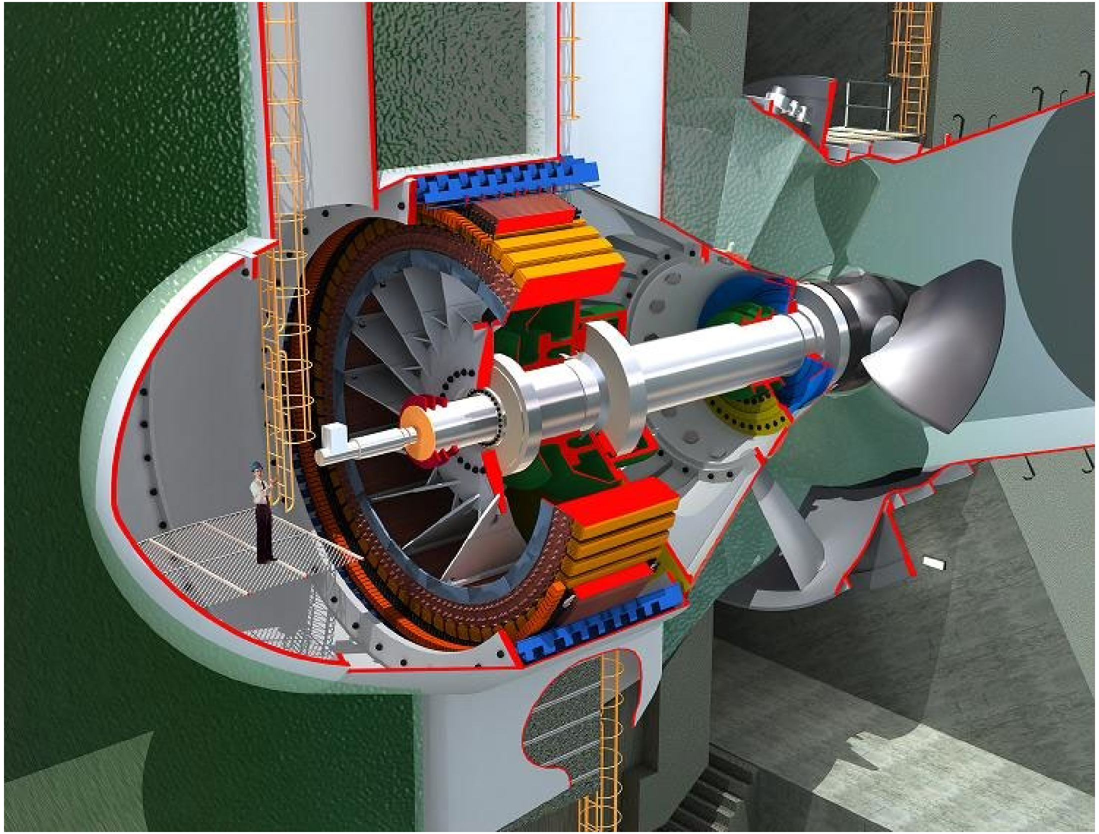
Classification of Hydraulic Runners

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

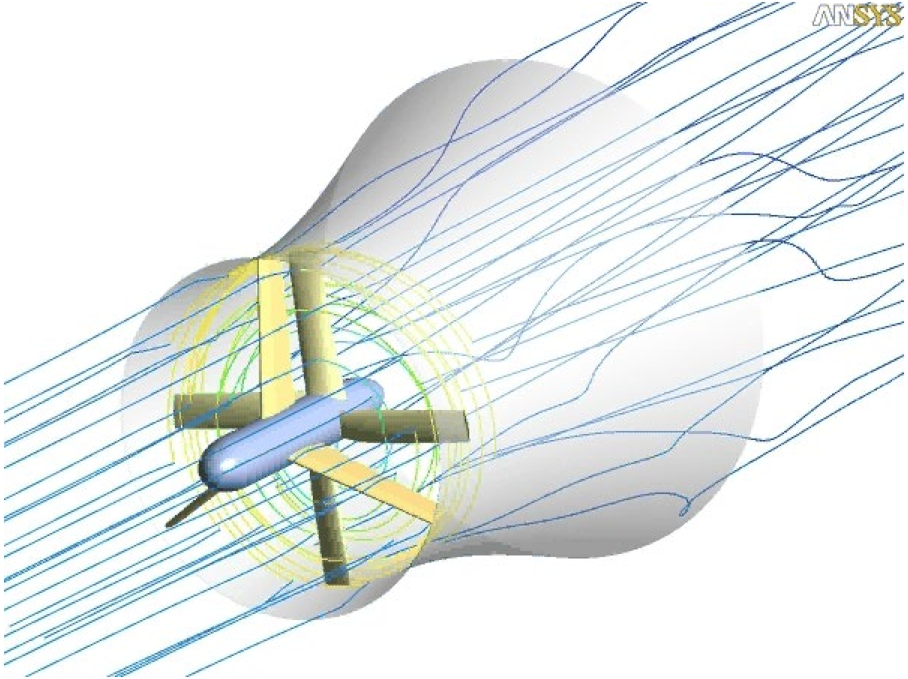
From OpenHydro Group chosen by EDF

10 runners

4 MW

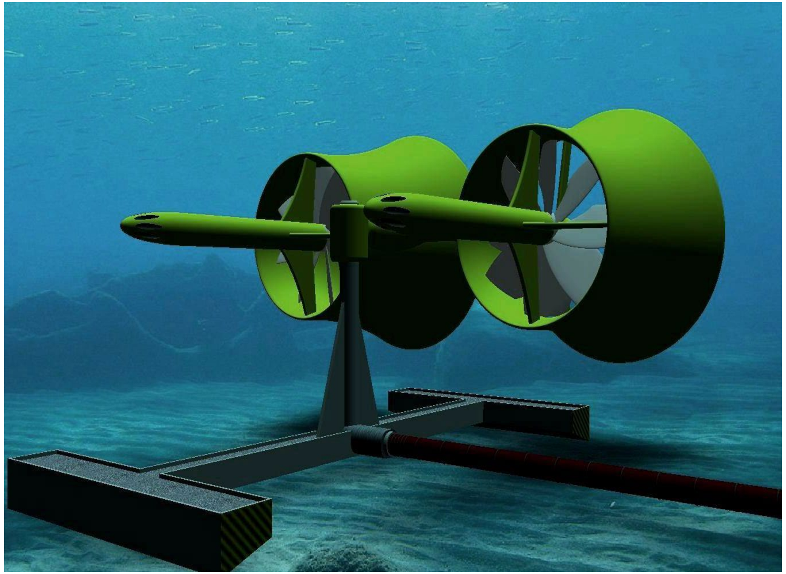
Classification of Hydraulic Runners

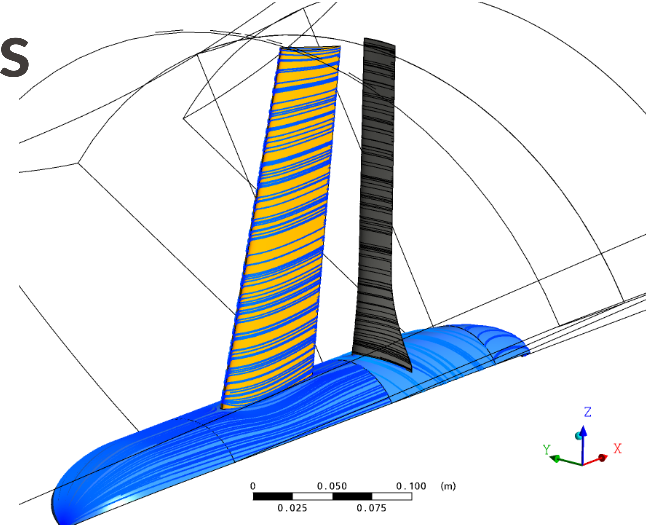
Development of New Renewables Iso Kinetic Turbine

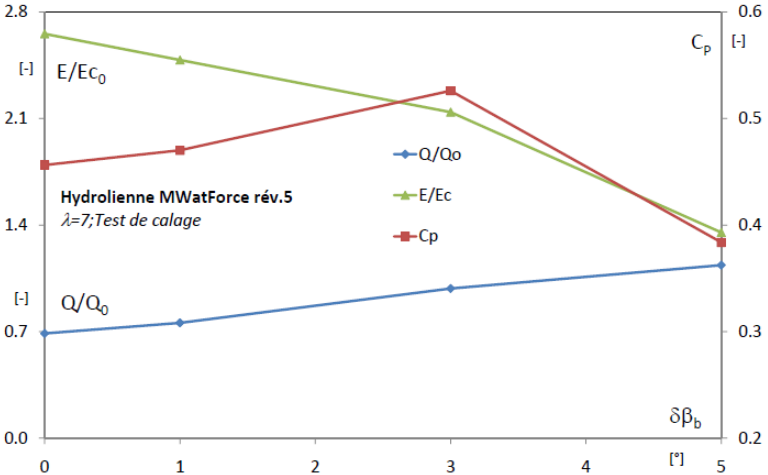


Classification of Hydraulic Runners

New Renewables: Iso Kinetic Turbine







From L2: Power Balance

Turbine Hydraulic Power Breakdown per Turbine Components

Hydraulic Power $P_h = \rho Q E$

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 $P_{ro} = \rho Q E_{r0}$

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 $P_{rq} = \rho q_r \underbrace{\left(E_t + E_{rb}\right)}_{=E_b = gH_1 - gH_{\bar{1}}}$

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

$$
\begin{aligned}
\rho Q E = {} & \rho Q\left(E_{rsc} + E_{rv} + E_{ro}\right) \\
& + \rho Q_t E_t + \rho Q_t E_{rb} \\
& + \rho q_r \left(E_t + E_{rb}\right) \\
& + \rho Q E_{rd}
\end{aligned}
$$

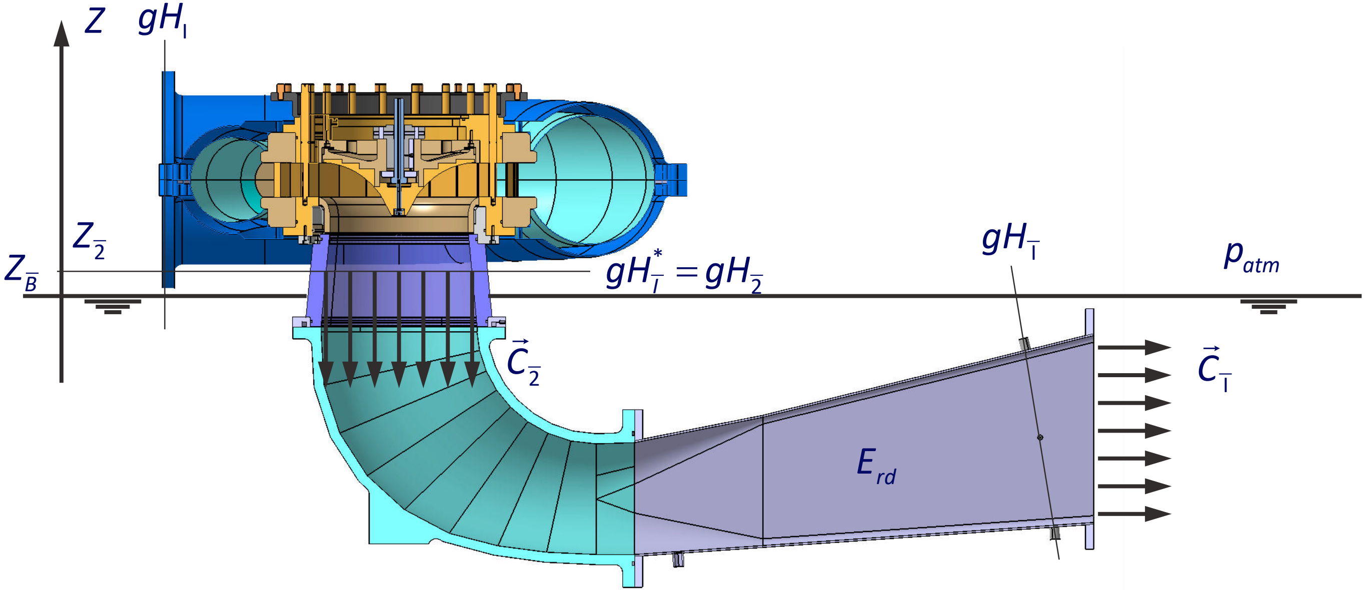
$$
E = E_{rsc} + E_{rv} + E_{ro} + \frac{\cancel{Q_t + q_r}}{\cancel{Q}}\left(E_t + E_{rb}\right) + E_{rd}
$$

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

HP: all leakage losses are recovered by the draft tube

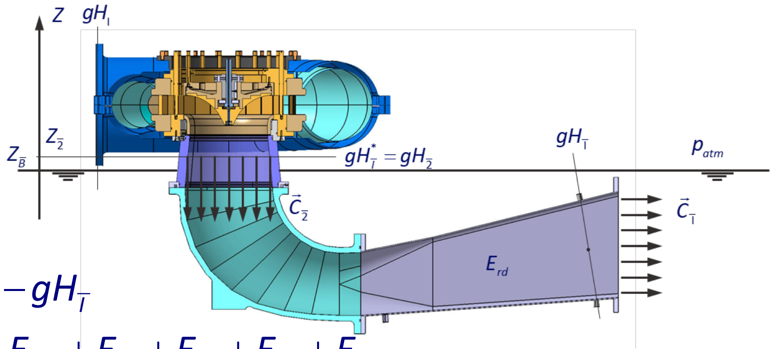
Diffuser
Elbow Draft-Tube (Francis and Kaplan)

- Static Pressure Recovery



Draft Tube

Energy Transfer to the Runner



E_{rsc} Energy lost in spiral case
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 turbine inlet-outlet

$$E = gH_I - gH_{\bar{I}}$$
$$= E_t + E_{rsc} + E_{rv} + E_{ro} + E_{rb} + E_{rd}$$

With draft tube: $E_t = gH_I - gH_{\bar{I}} - E_{rsc} - E_{rv} - E_{ro} - E_{rb} - E_{rd}$

Without draft tube: $E^*_t = gH_I - gH^*_{\bar{I}} - E_{rsc} - E_{rv} - E_{ro} - E_{rb} - E^*_{rd}$

$$E_t - E^*_t = -\left(gH_{\bar{I}} - gH^*_{\bar{I}}\right) - \left(E_{rd} - E^*_{rd}\right)$$

$$gH_{\bar{I}} = gZ_{\bar{I}} + \underbrace{\frac{p_{\bar{I}}}{\rho}}_{=\frac{p_{atm}}{\rho} + gZ_{\bar{B}} - gZ_{\bar{I}}} + \frac{C^2_{\bar{I}}}{2} = \frac{p_{atm}}{\rho} + gZ_{\bar{B}} + \frac{C^2_{\bar{I}}}{2}$$

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

$$gH^*_{\bar{I}} = gZ_{\bar{2}} + \underbrace{\frac{p_{\bar{2}}}{\rho}}_{=\frac{p_{atm}}{\rho}} + \frac{C^2_{\bar{2}}}{2} = gZ_{\bar{2}} + \frac{p_{atm}}{\rho} + \frac{C^2_{\bar{2}}}{2}$$

→

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

$$E_t - E^*_t = \underbrace{\frac{C^2_{\bar{2}}}{2} - \frac{C^2_{\bar{I}}}{2}}_{\text{Specific Kinetic Energy}} + \underbrace{g\left(Z_{\bar{2}} - Z_{\bar{B}}\right)}_{\text{Specific Potential Energy}} - \underbrace{E_{rd}}_{\text{Draft Tube Loss}}$$

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