MASTER IN **RENEWABLE ENERGY IN THE MARINE** ENVIRONMENT

REM

The (integrated) development of the spar-buoy OWC wave energy converter at IST

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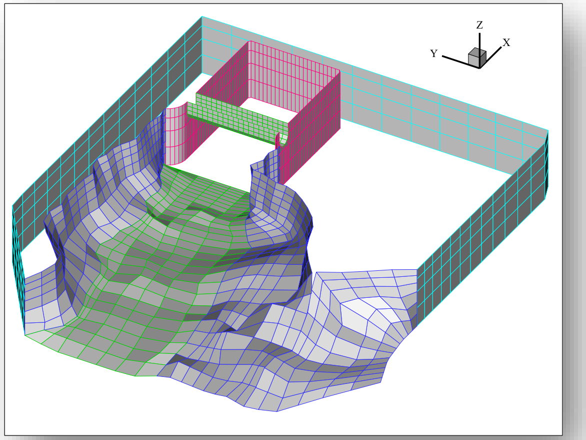
Steps in the development of a wave energy converter

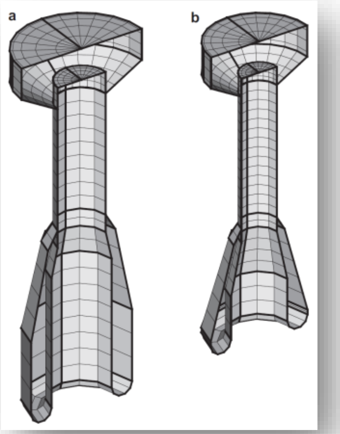
1. Basic conception of device

- **inventor(s)**
- **new patent or from previous concept**

2. Theoretical modelling (hydrodynamics, PTO, control,…)

- **evaluation (is the device promising or not?)**
- **optimization, control studies, …**
- **requires high degree of specialization (not for most inventors…)**





Steps in the development of a wave energy converter

3. Model testing in wave tank

• to complement and validate the theoretical/numerical modelling

• scales 1:100 (in small tanks) to 1:10 (in very large tanks)

• essential before full-sized testing in real sea

4. Technical demonstration: design, construction and testing of a large model (1/4th scale) or full-sized prototype in real sea:

• the real proof of technical viability of the system

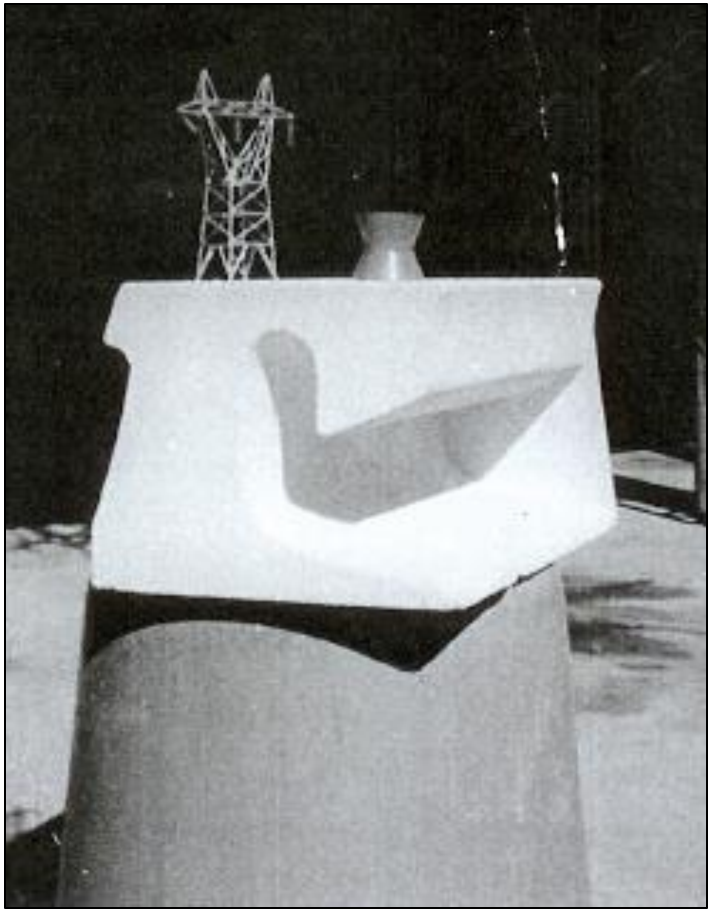
• cost: up to tens of M€

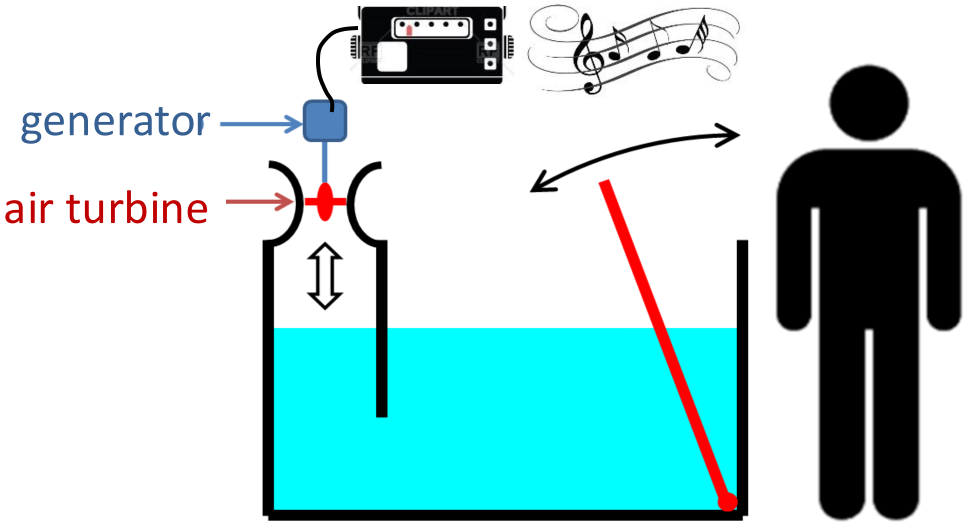
5. Commercial demonstration: multi-MW plant in the open sea (normally a wave farm) with permanent connection to the electrical grid.

The IST Wave Energy Group 1975-…

About 1975…

About 1975, **Agnelo David,** a simple merchant, went to **IST** looking for scientific support to develop his invention: a **fixed OWC**





About 1975...

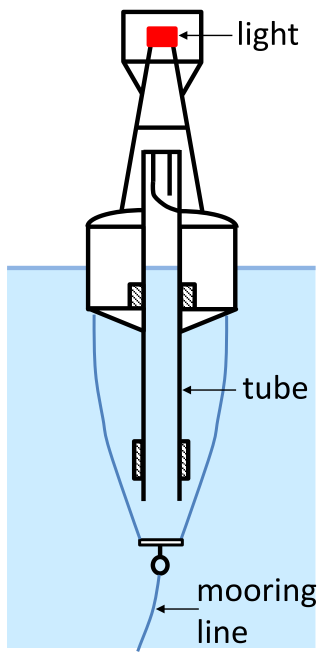
- From the interest of Professor António Falcão in this “invention” resulted the R&D in wave energy at IST (and in Portugal)

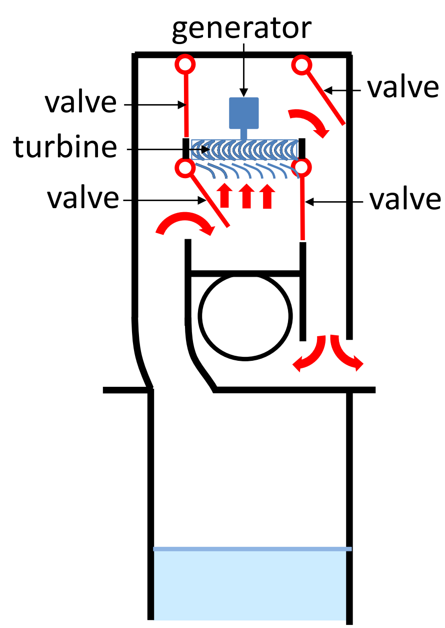
- In fact, Agnelo David was **not** the first inventor of the oscillating water column!

Prof. António Falcão

The first successful applications of wave energy

- Yoshio Masuda (1925-2009), Japan
- A pioneer in wave energy since the late 1940s
- Lighting buoys based on the OWC principle since the 1960s
- Low-efficiency turbines due to the use of rectifying valves
  - Professor António Falcão taught Turbomachinery at IST…



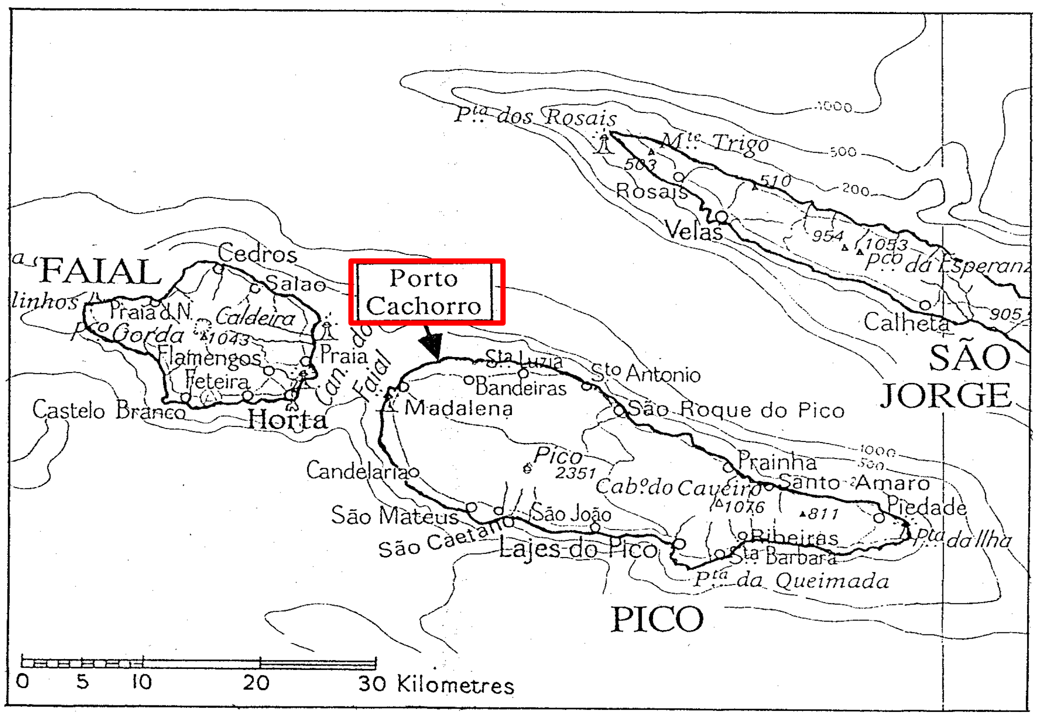


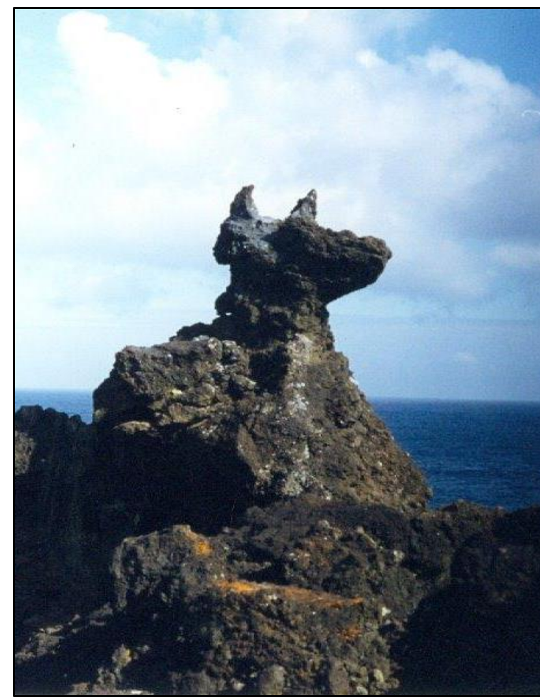

The Odyssey of the
Azores

September-October 1986 - site selection

The public utility of the Azores archipelago (EDA), promoted visit to 5 islands to find a site for a wave energy plant of shoreline type

Best site: Porto Cachorro (Dog's harbor), island of Pico.





But in 1987 there was no $$$$$$$ to build a wave power plant…

Seek for funding

1991 – The European Parliament aproves the inclusion of wave energy into the renewable energy programme of the European Commission

- **European Wave Energy Pilot Plant on the Island of Pico, Azores, Portugal** (contract No. JOU2-CT93-0314, 1994-96, coordinator: **Instituto Superior Técnico**).
- **European Wave Energy Pilot Plant on the Island of Pico, Azores, Portugal. Phase Two: Equipment** (contract No. JOR3-CT95-0012, 1996-99, coordinator: **Instituto Superior Técnico**).

  Partners: EDA, EDP, EFACEC, Profabril, University College Cork, Queen's University Belfast
- **Performance Improvement of OWC Power Equipment** (contract No. JOR3-CT-98-0282, 1999-2002, coordinator: **Instituto Superior Técnico**).

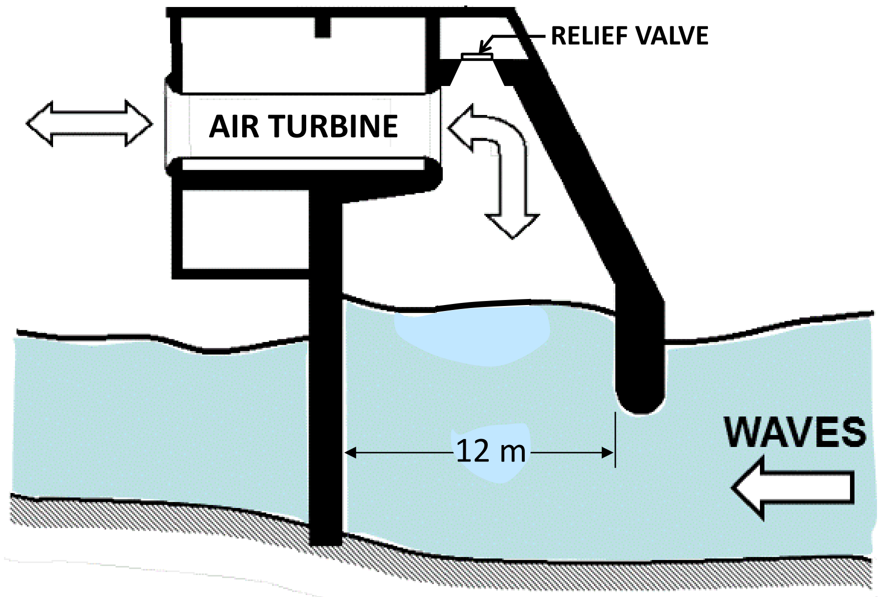
Construction of the Pico plant, 1995-99

before…

underwater concreting

… during

Construction of the Pico plant, 1995-99



The Pico plant (400 kW) was operational until 2017, 18 years after it operated for the first time in 1999!

CORES FP7 European project

(Components for Ocean Renewable Energy Systems)

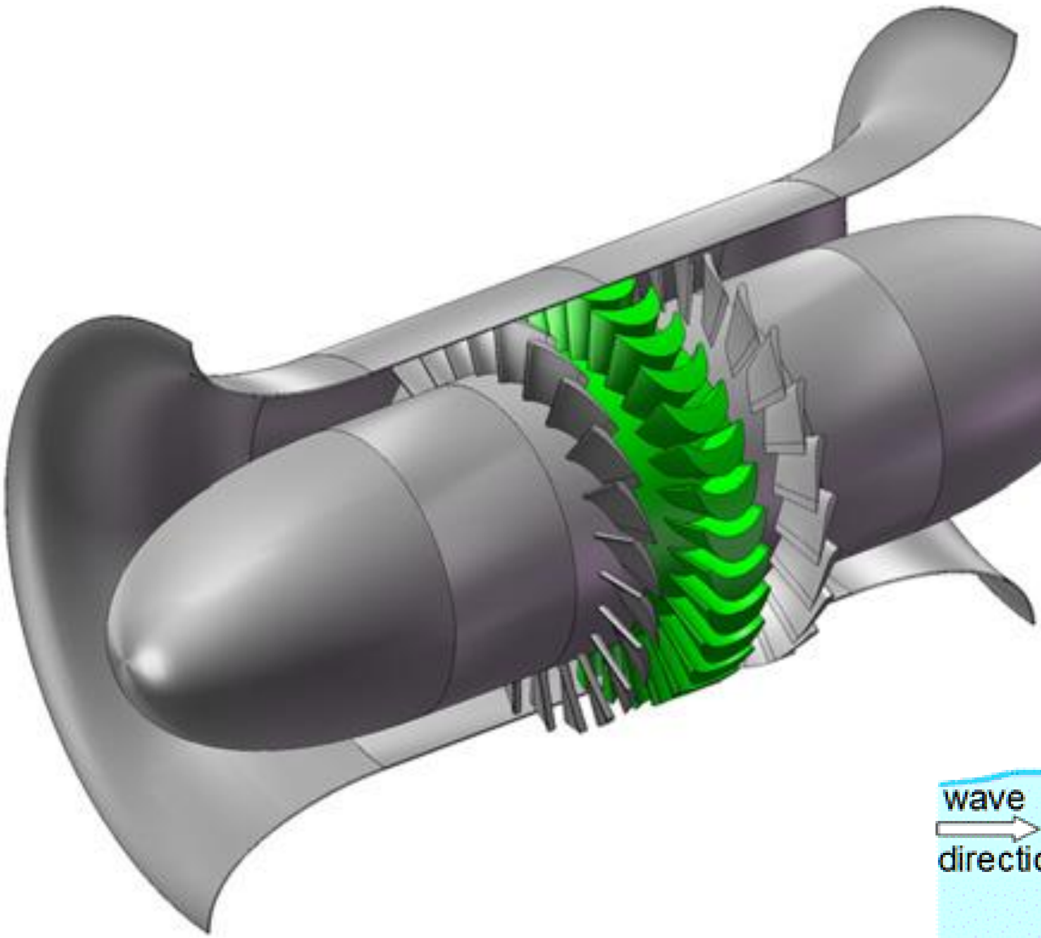
Backward Bent Ducted Buoy (BBDB)

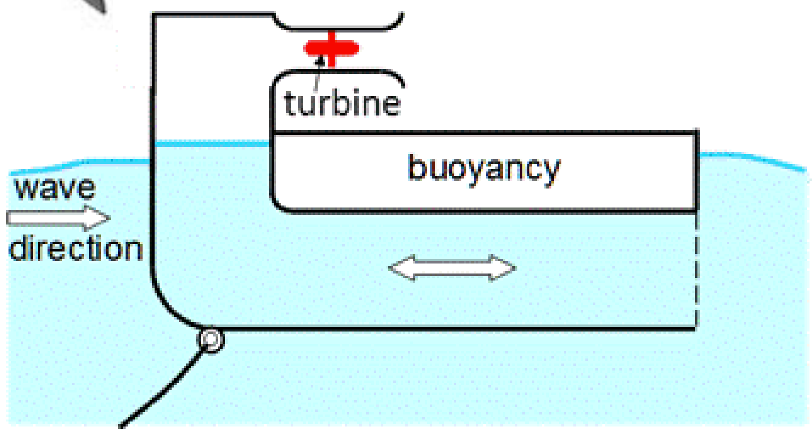
Tests at 1:4th-scale, Galway Bay, Ireland

BBDB concept was invented also by **Yoshio Masuda**

Axial impulse turbine (CORES project)

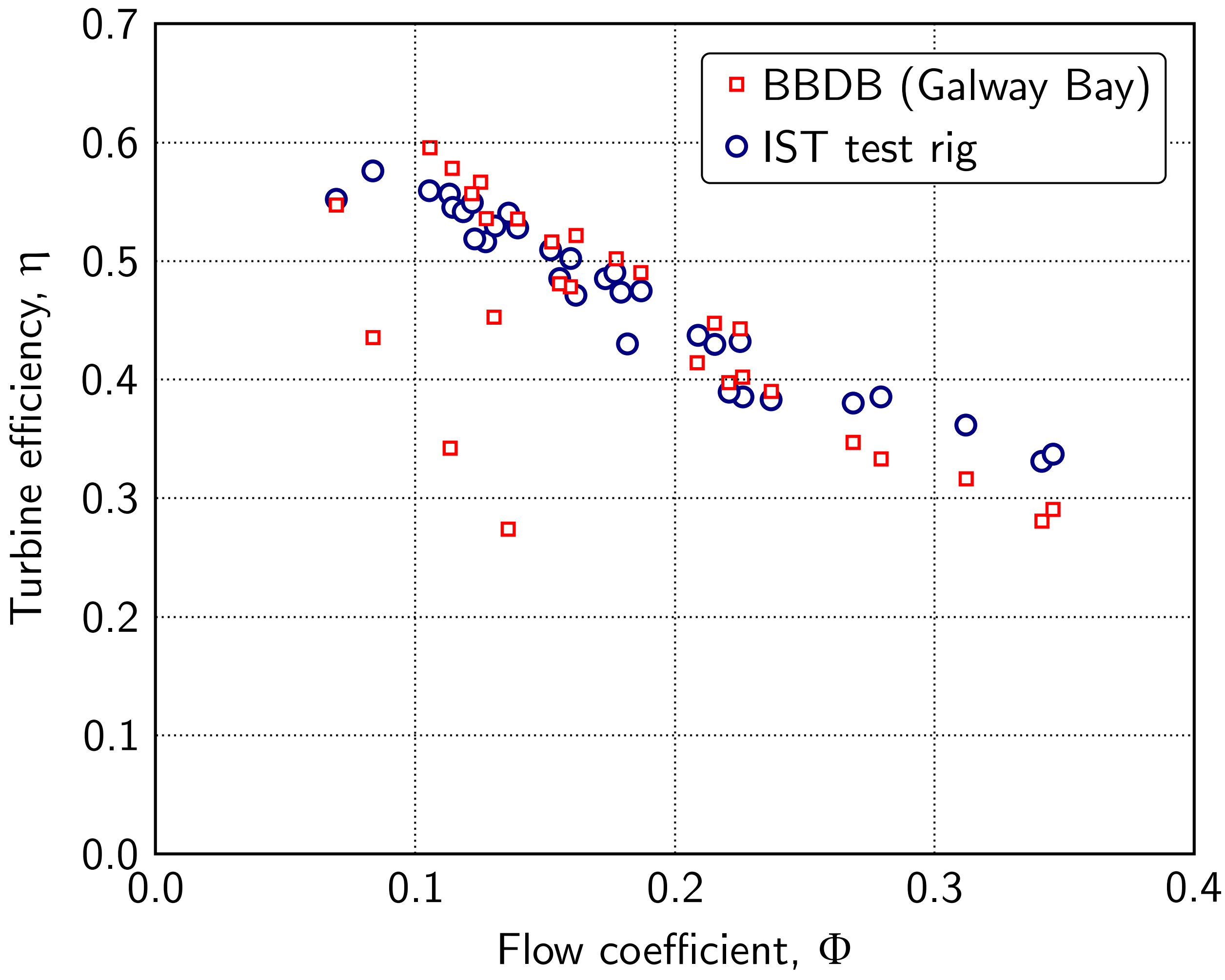
- **IST –** Air turbine aerodynamic design and dry testing





Axial impulse turbine (CORES project)

CORES project

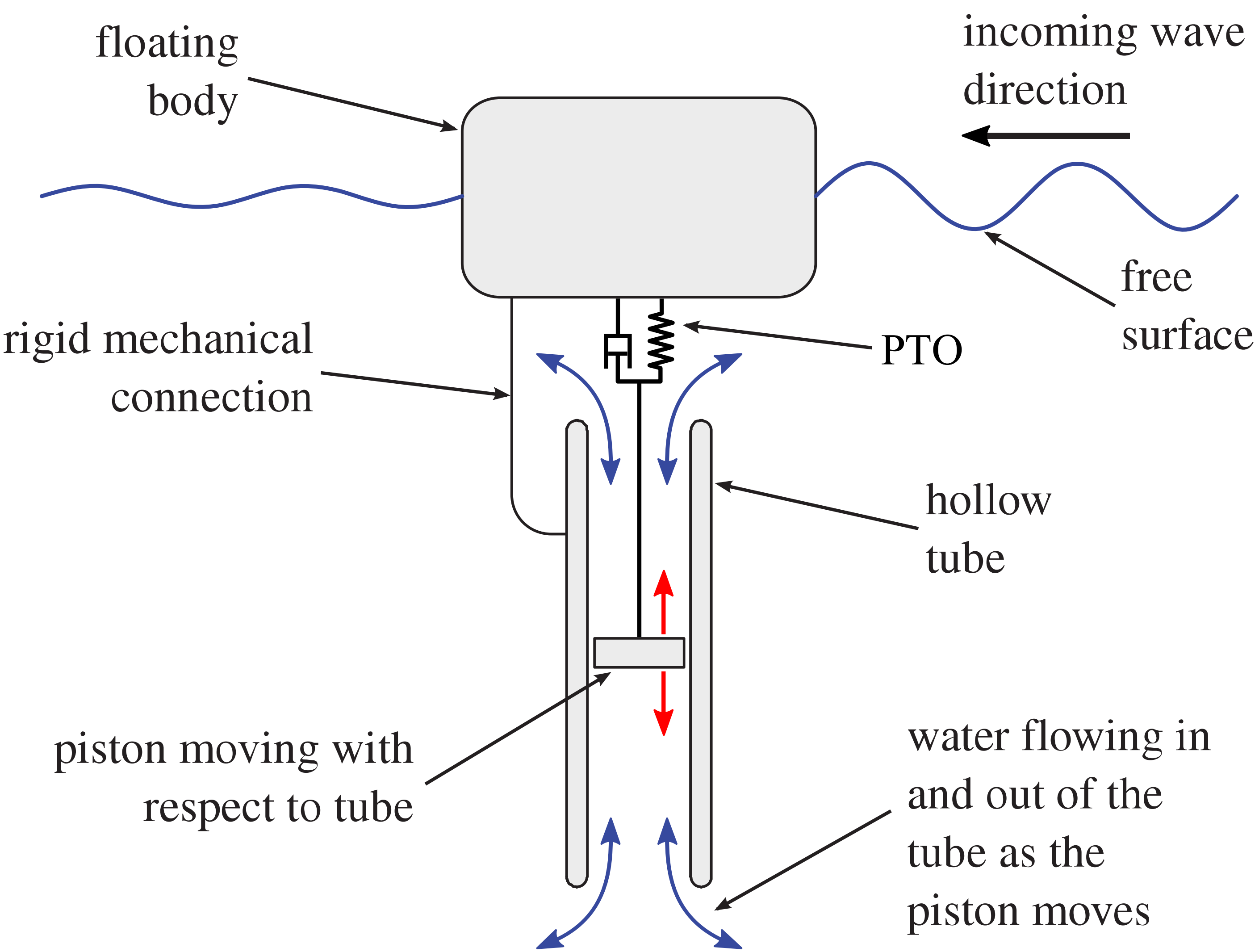


- During sea trials, the impulse axial turbine matched the efficiency measured at the IST dry laboratory tests

Studies about the IPS buoy

(going to large array deployment)

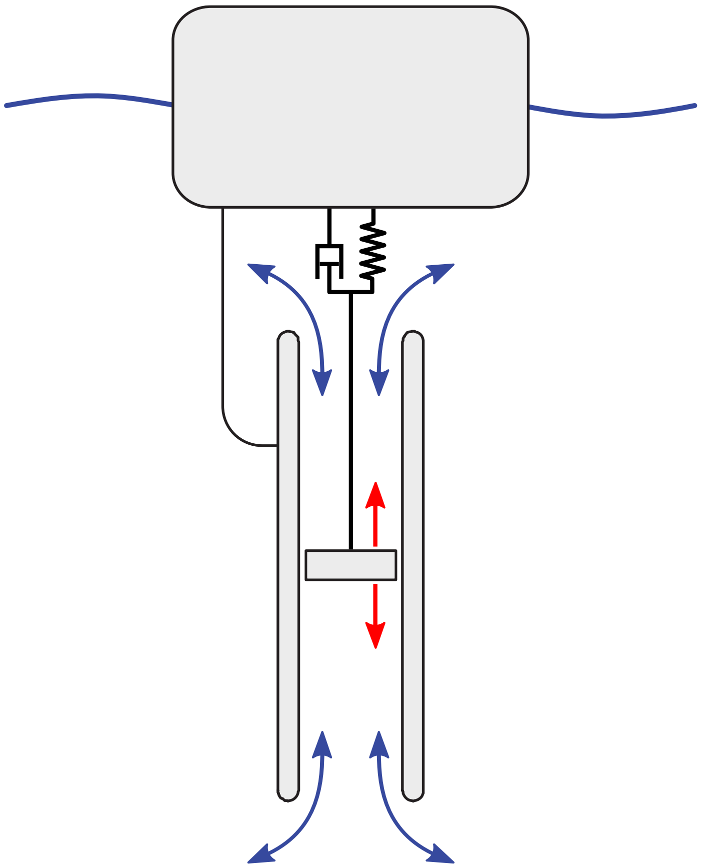
The IPS buoy



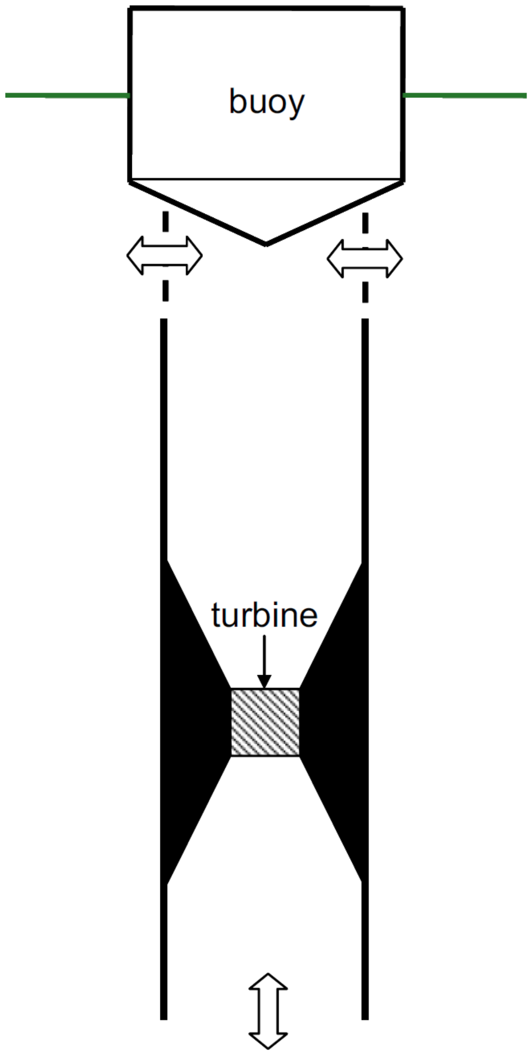
- Two bodies system: the buoy and water in the tube (**free body!**)

The IPS buoy

- **The system has several drawbacks**
  - Low velocities and high Forces in the piston
    - $P = Fv$
  - High torques and low angular speeds in the power take-off system
    - $P = T\Omega$
  - Hydraulic systems are complex **stiff** machines



Why not use a water turbine???



- IPS buoy with the piston replaced by a hydraulic turbine

Why not use a water turbine???

- By setting $Q_{\text{water}} = Q_{\text{air}}$ and $P_{\text{water}} = P_{\text{air}}$ we get

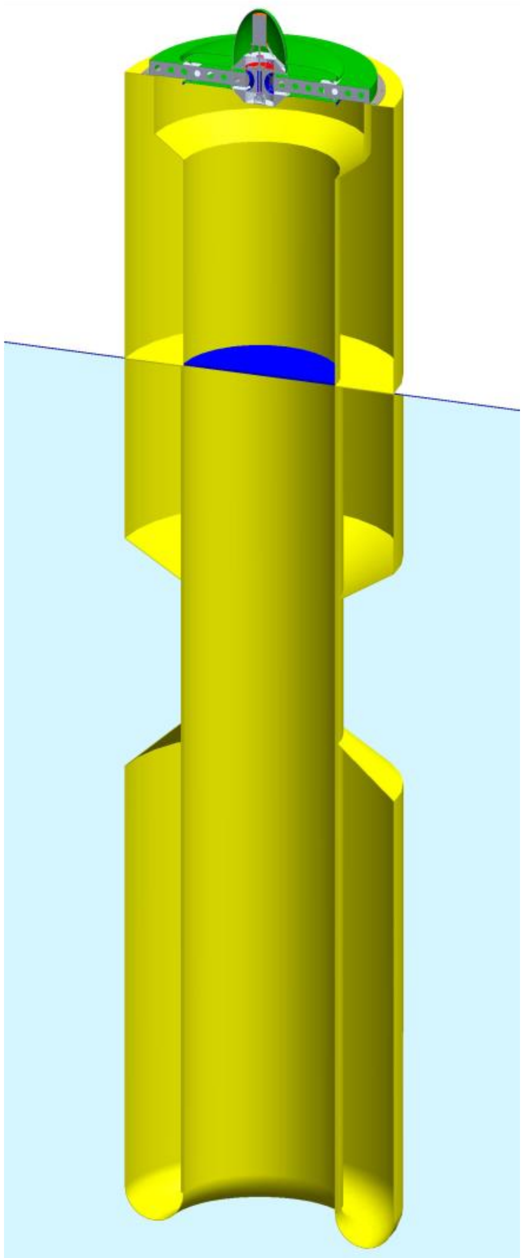
$$\frac{D_{\text{water}}}{D_{\text{air}}} = \left(\frac{\rho_{\text{water}}}{\rho_{\text{air}}}\right)^{1/4} = 5.35 \quad \text{and} \quad \frac{\Omega_{\text{water}}}{\Omega_{\text{air}}} = \left(\frac{\rho_{\text{water}}}{\rho_{\text{air}}}\right)^{3/4} = 0.00653$$

- It is not difficult to find for the torque ratio (for equal power)

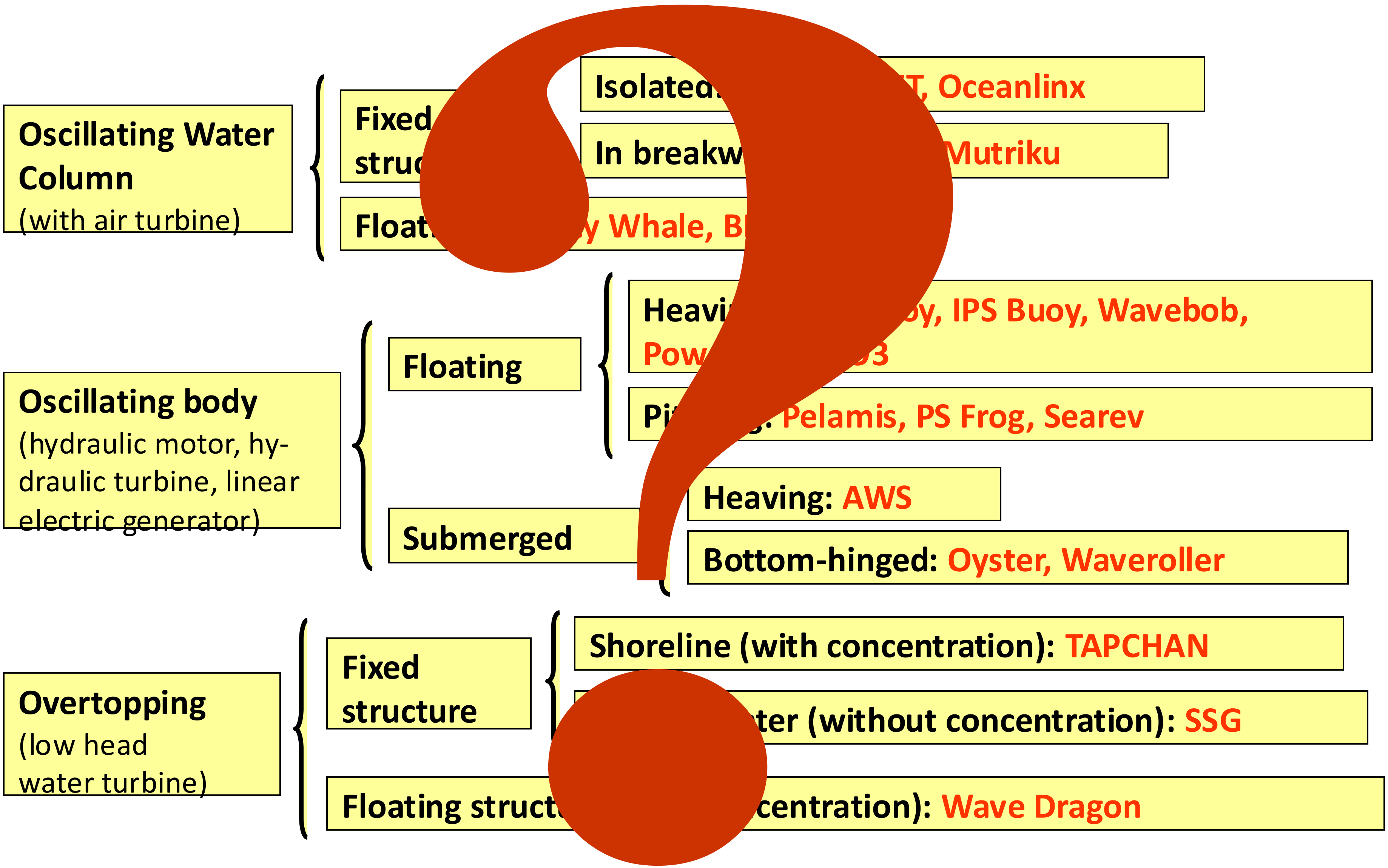
$$\frac{T_{\text{water}}}{T_{\text{air}}} = 153.2$$

- Unlike a PTO with a turbine in air, a PTO with a turbine in water (because of its very low rotational speed) would require a gear box and a flywheel
- NOTE: Cavitation not addressed (installation of the turbine at a higher depth)

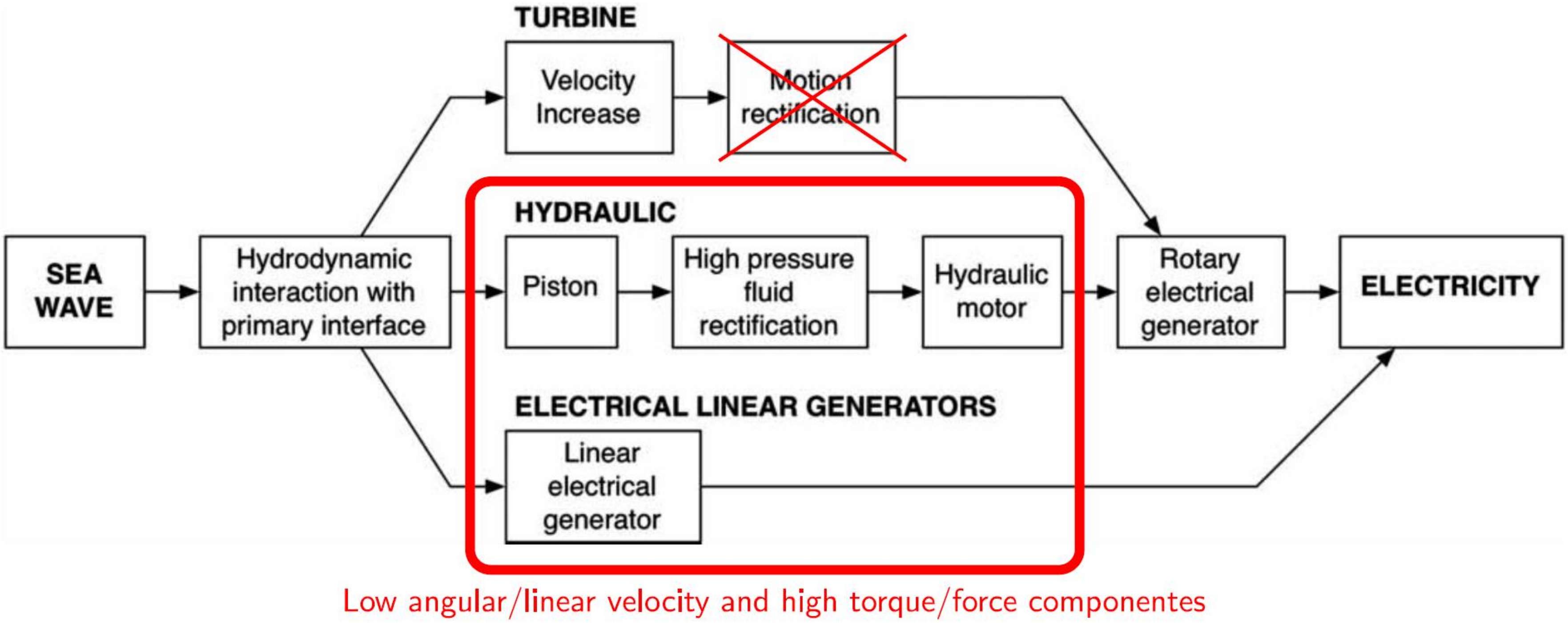
Air turbine on top → Spar-buoy OWC



OWC vs. other systems

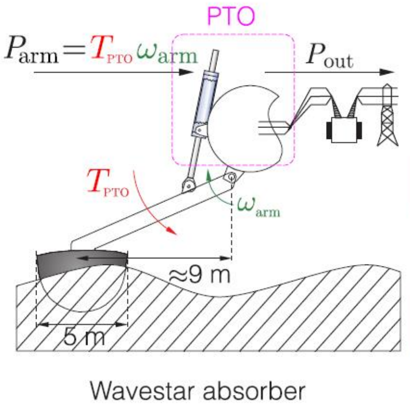


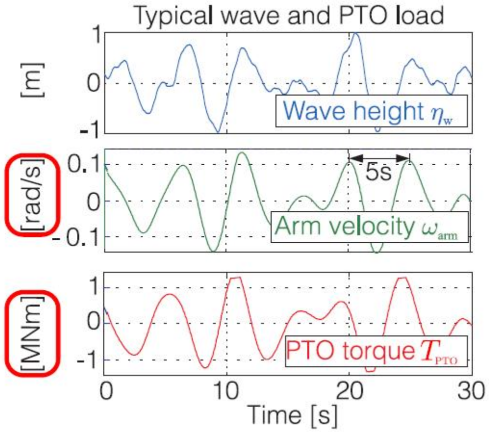
OWC vs. other systems

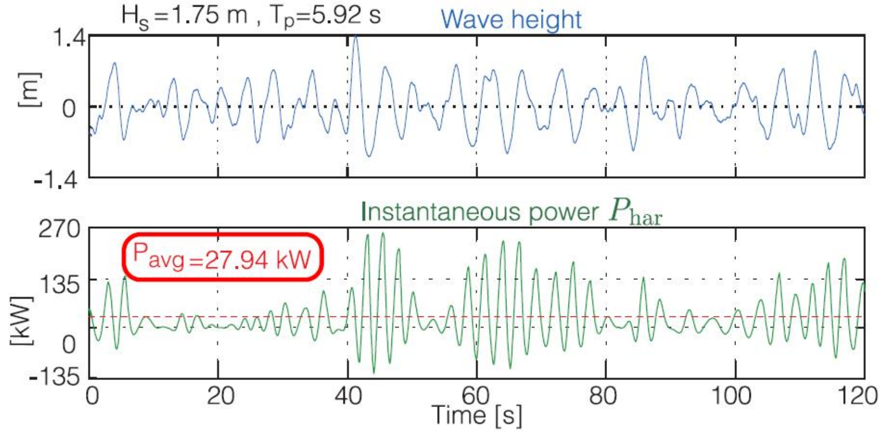


WAVESTAR

For example, using **Wavestar public data**







Fighting the physics?

$$P_{arm} = T_{PTO}\,\Omega_{arm}$$

if $\Omega_{arm} \sim 0.1\,\text{rad/s}$

$$\Rightarrow T_{PTO} \sim 10^6\,\text{Nm}$$

for a $P_{avg} = 28\,\text{kW}$!!!

Spar-buoy OWC vs WAVESTAR

- The OWC devices have a "componentless gear box"
- Typical ratio of turbine inlet area to the OWC water plane area

$$\frac{S_{\mathrm{turb}}}{S_{\mathrm{OWC}}} \sim 0.02$$

- For a OWC velocity of

$$v_{\mathrm{OWC}} \sim 1\,\mathrm{m/s}$$

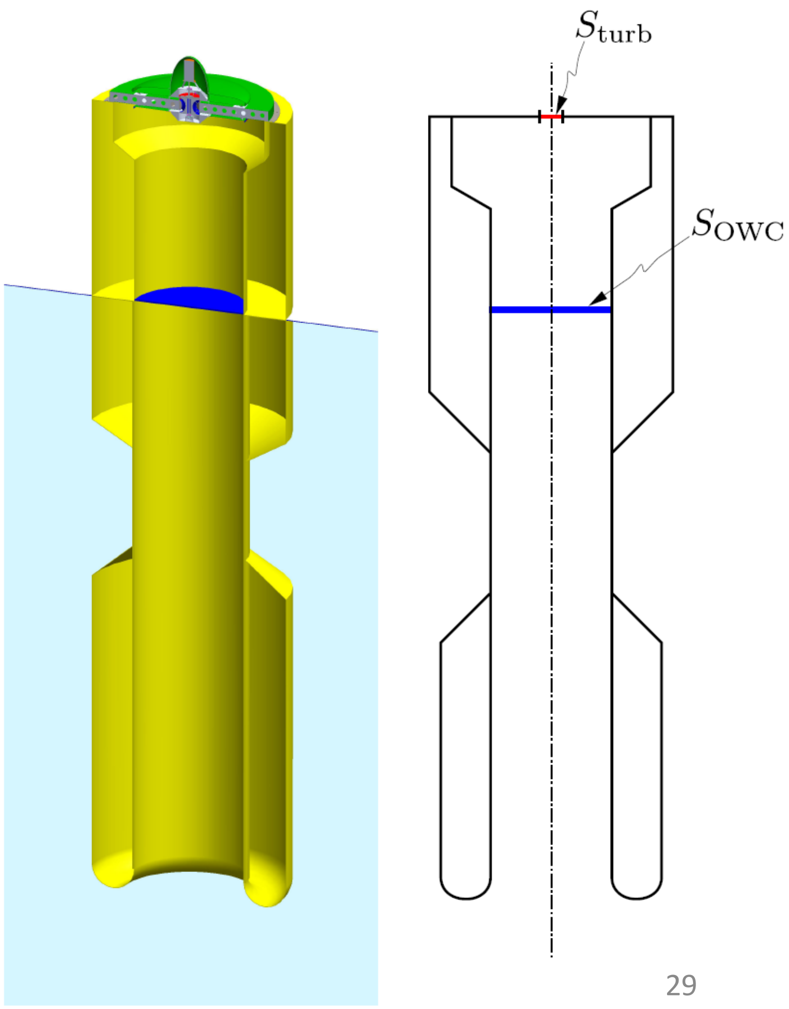
the turbine inlet velocity is

$$v_{\mathrm{turb}} = \frac{S_{\mathrm{turb}}}{S_{\mathrm{OWC}}} v_{\mathrm{OWC}} = 50\,\mathrm{m/s}$$

- Typical torque for 28 kW

$$T_{\mathrm{turb}} \sim 10^2\,\mathrm{Nm}$$

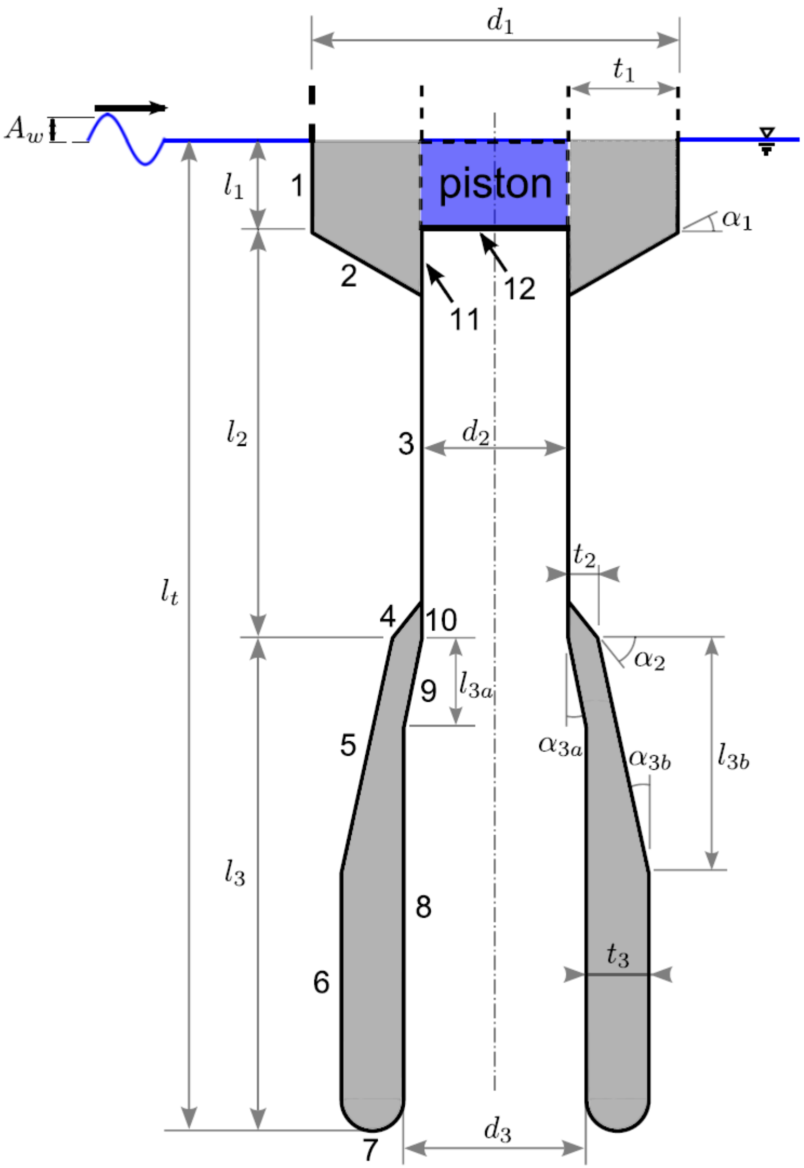
- Torque ratio $\frac{T_{\mathrm{turb}}}{T_{\mathrm{Wavestar}}} \sim 10^{-4}$



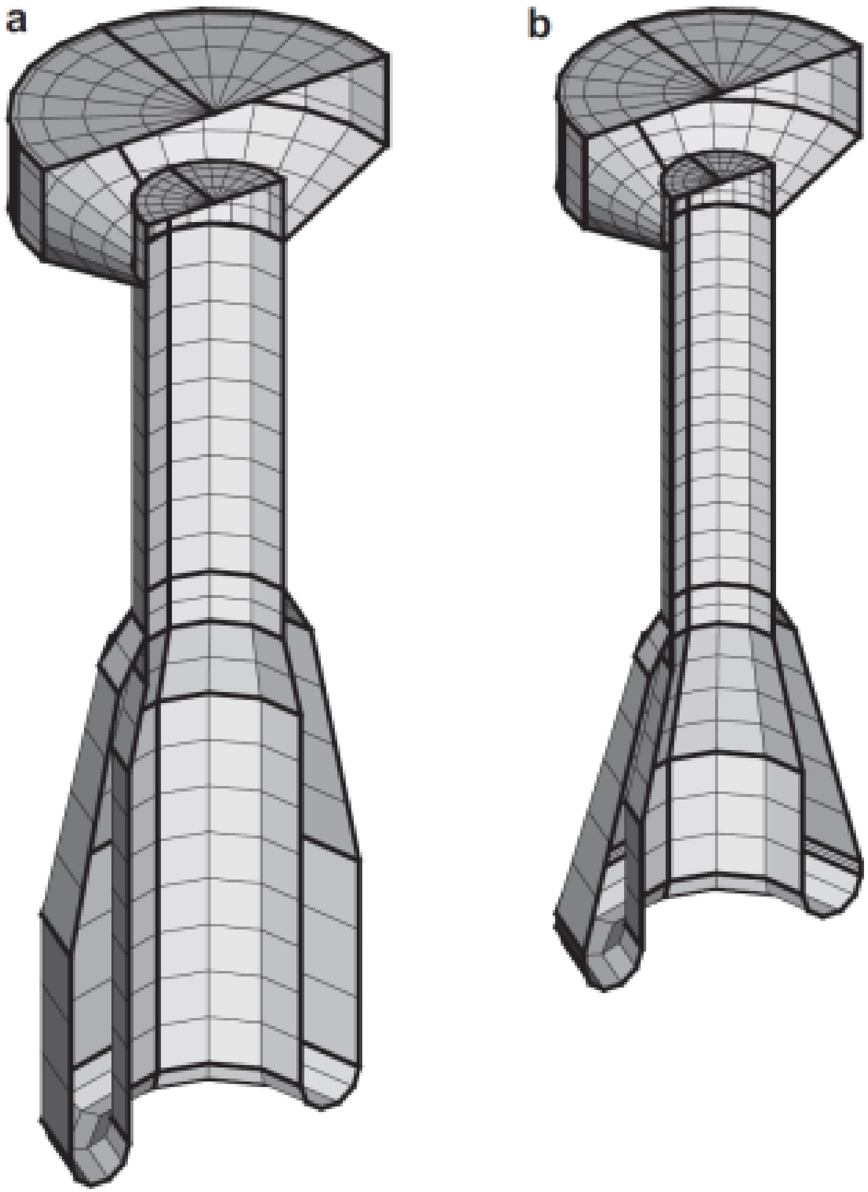
Spar-buoy OWC and biradial turbine (integrated) development

Spar-buoy OWC hydrodynamic optimization

- Parametric modelling of the hull shape
- Constrained optimization
  - Not all values are allowed for the parameters
- The objective function is (typically) not smooth
- Use of derivative-free optimizers
  - COBYLA
  - Differential Evolution Genetic Algorithm
    - Brute force but easily parallelized



The spar buoy OWC hydrodynamic optimization

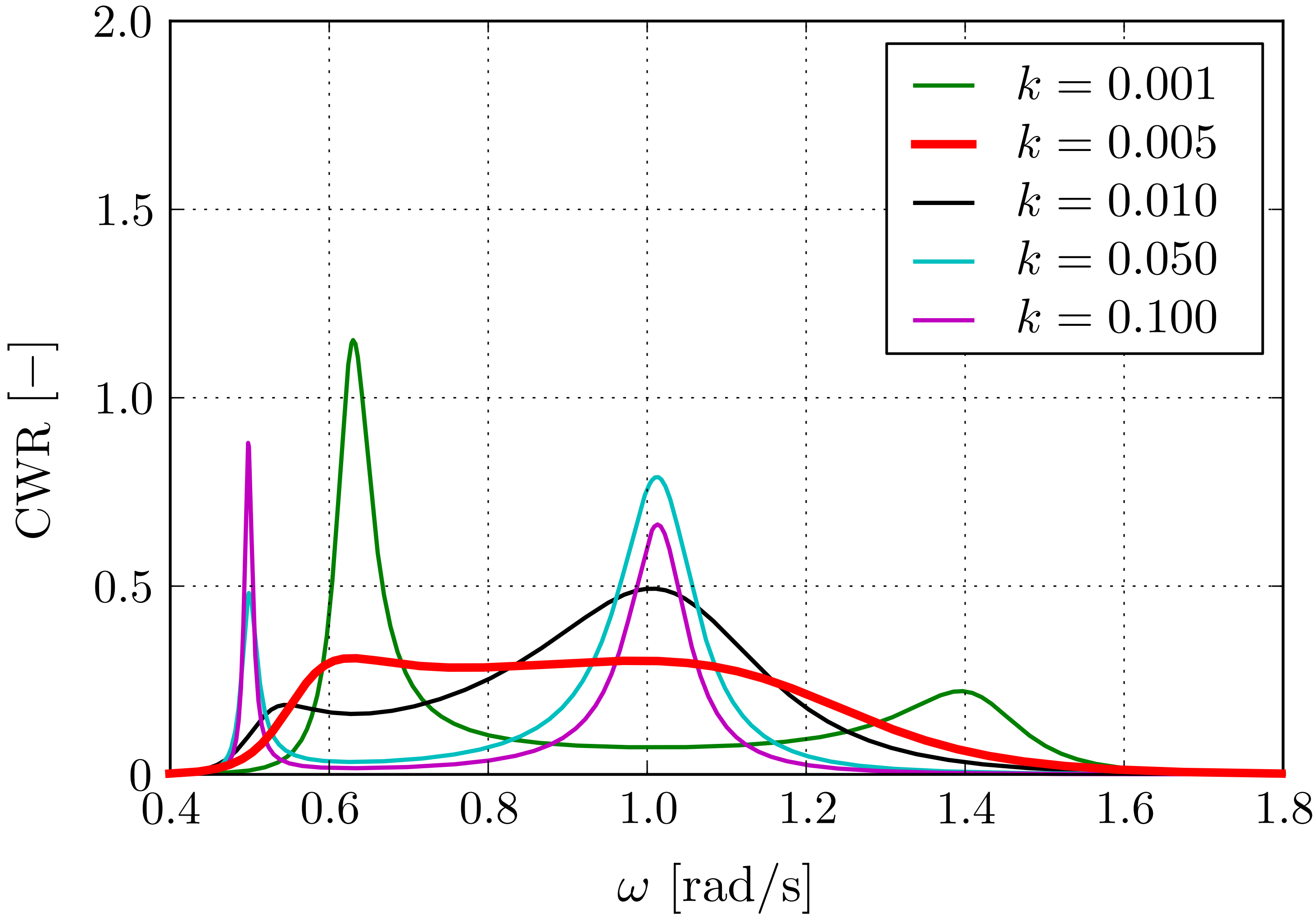


- Tube length increases the OWC mass, m
- Bell shape at the bottom increases the added mass, A

$$T_{\mathrm{OWC}} \propto \sqrt{\frac{m + A}{\rho g S}} \in [8\mathrm{s}, 12\mathrm{s}]$$

- System resonance period should match the waves period

The spar buoy OWC hydrodynamic optimization

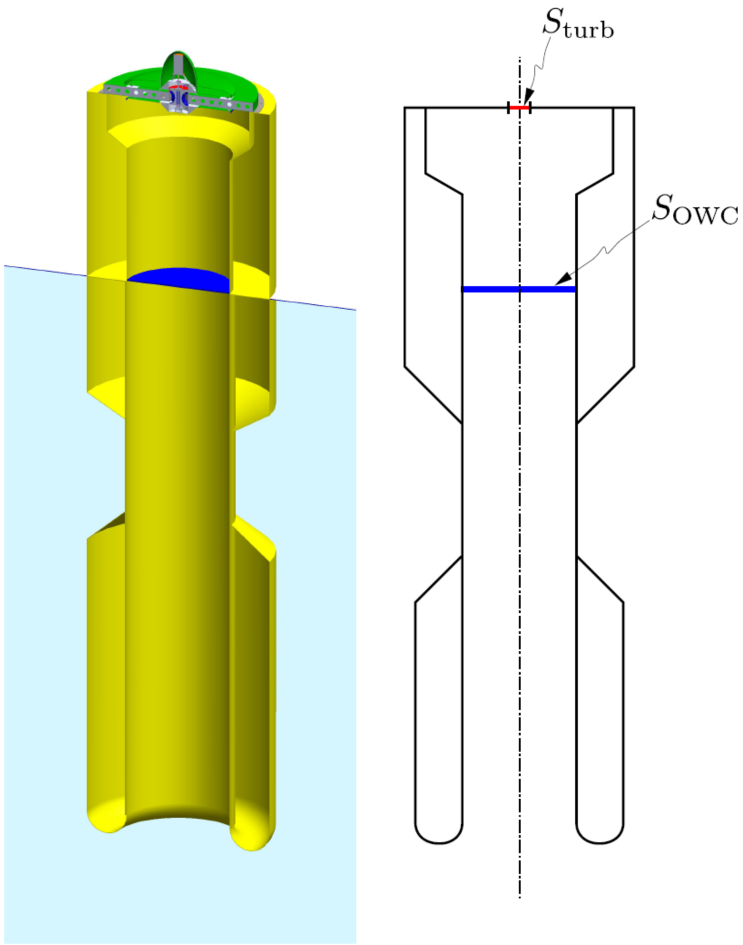


- **Flat response to cope with the waves randomness**

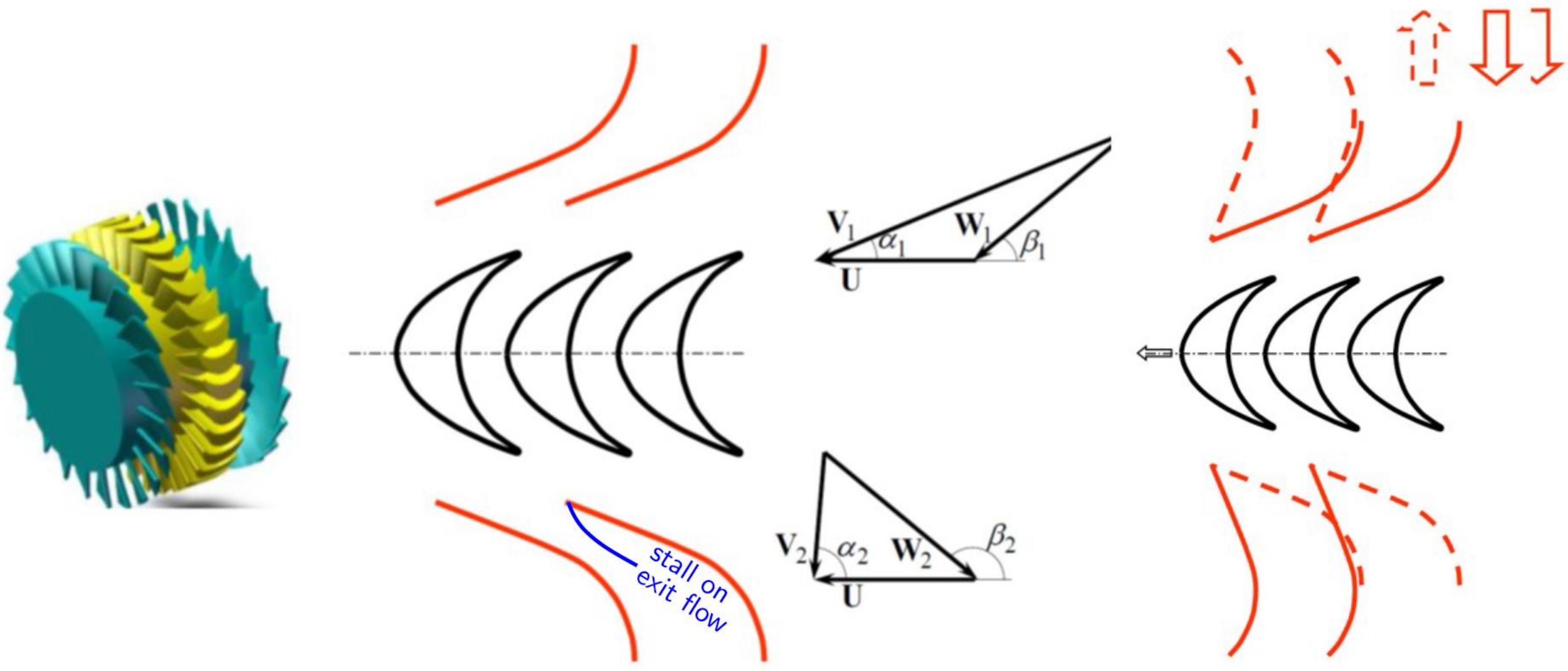
Spar-buoy OWC

- **The system has also drawbacks**
  - High-cost of the buoy
  - High pressure heads are **not** suited for Wells turbines
  - The axial impulse turbine had low efficiency

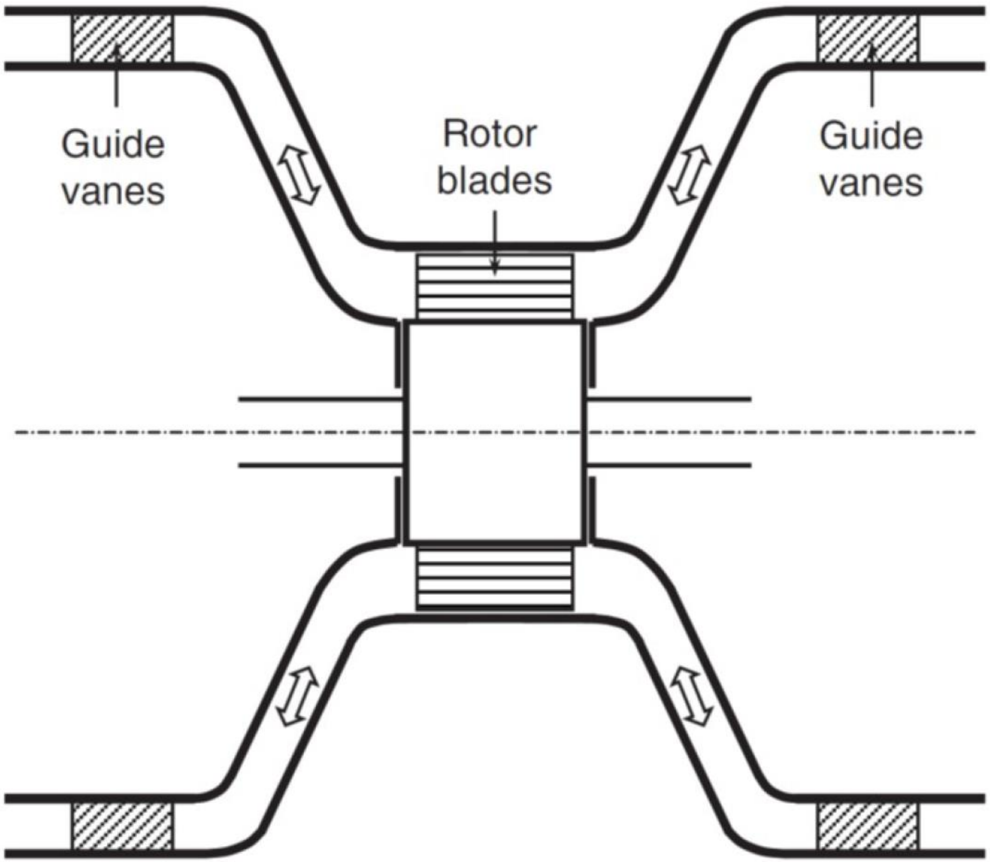
- **We needed a new type of turbine!**



Axial impulse turbine (CORES project)

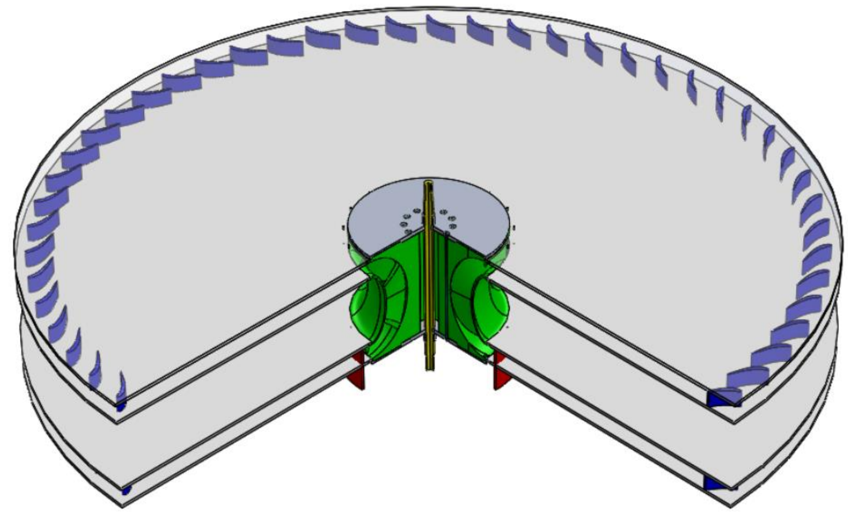


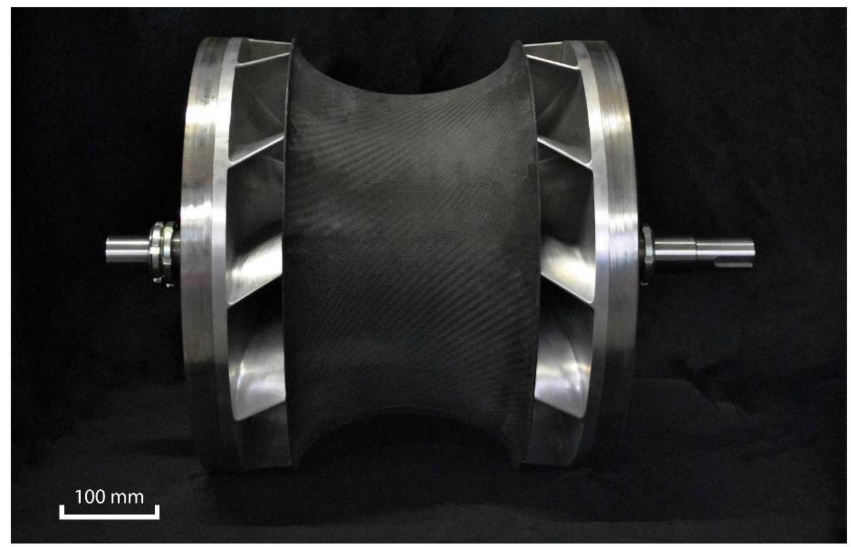
The first idea – conical entrance/exit



- The HydroAir concept to reduce the pressure losses at the exit stator
- IST had the same idea but did not patented or published the results

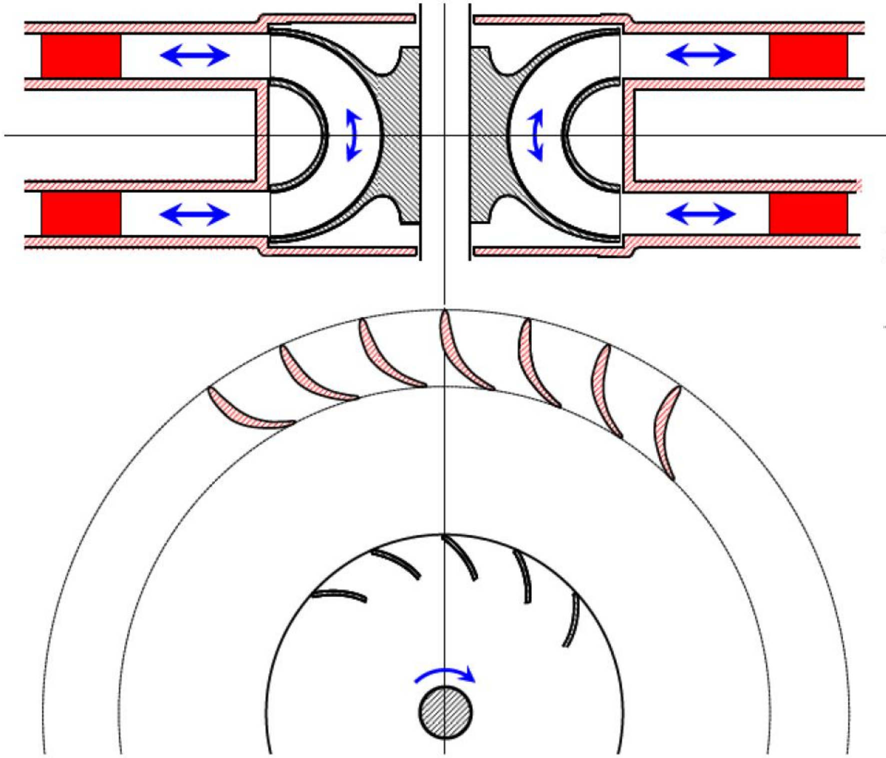
Biradial turbine

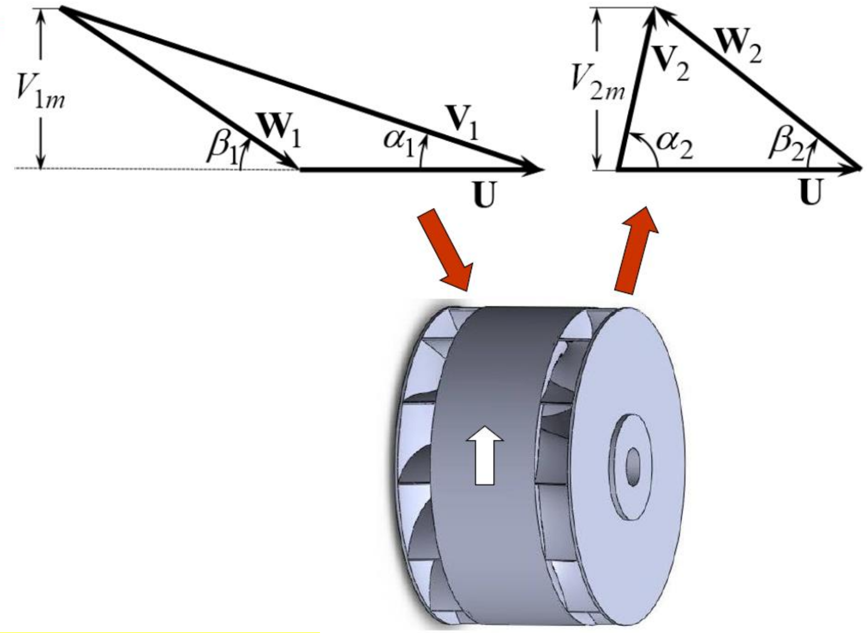




- The biradial turbine at the original IST test rig

Biradial turbine

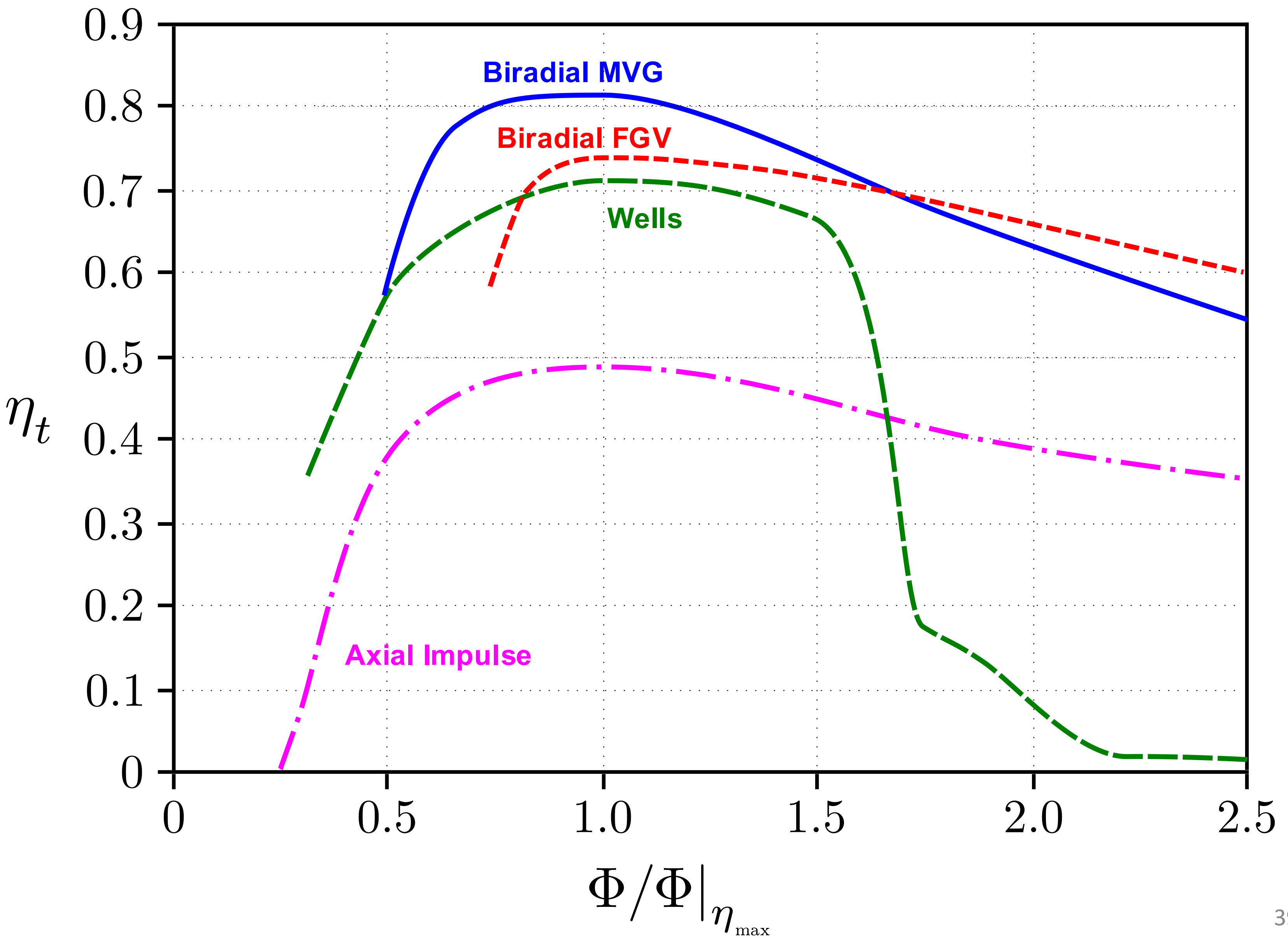




Reduces swirl and losses on the exit stator

$$\left.\begin{array}{ll}\textbf{Mass balance:} & V_{r_{\mathrm{stat}}} = V_{r_2}\dfrac{r_2}{r_{\mathrm{stat}}} \\[2ex] \textbf{Angular momentum:} & V_{t_{\mathrm{stat}}} = V_{t_2}\dfrac{r_2}{r_{\mathrm{stat}}}\end{array}\right\} \Rightarrow V_{\mathrm{stat}}^2 < V_2^2 \Rightarrow \text{lower losses}$$

Need a better turbine? Problem solved!



No more mistakes: Patent filled

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European Patent Office
Office européen des brevets

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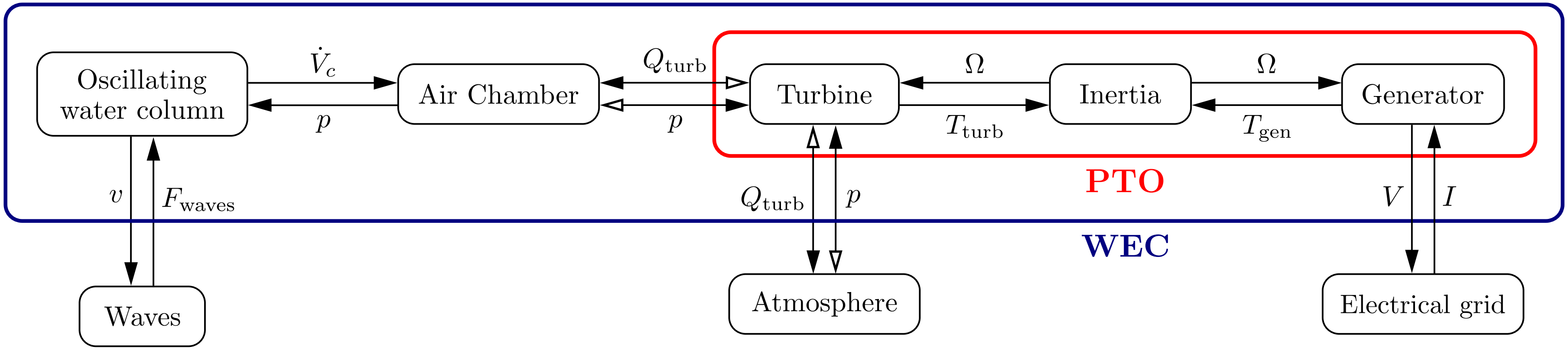
(54) **TURBINE WITH RADIAL INLET AND OUTLET ROTOR FOR USE IN BIDIRECTIONAL FLOWS**

(57) The present invention relates to a turbine which can absorb energy from bi-directional reversing flows, as is the case of ocean wave energy converters. In the periphery of the bladed rotor (2) of the turbine there are two

ments are considered. In both arrangements, the inlet guide vanes deflect the inward flow and impart a circumferential swirl component in the same direction as the normal rotational direction of the rotor. In one of the ar-

Small-scale experimental testing of the spar buoy OWC



- Different physical systems
  - Spar buoy OWC
  - Air chamber
  - Turbine
  - Generator
- **How to scale the different systems respecting the physics?**

Before go to an expensive facility…

- **Test, test, test… all components and extreme behaviour until no failures are found**

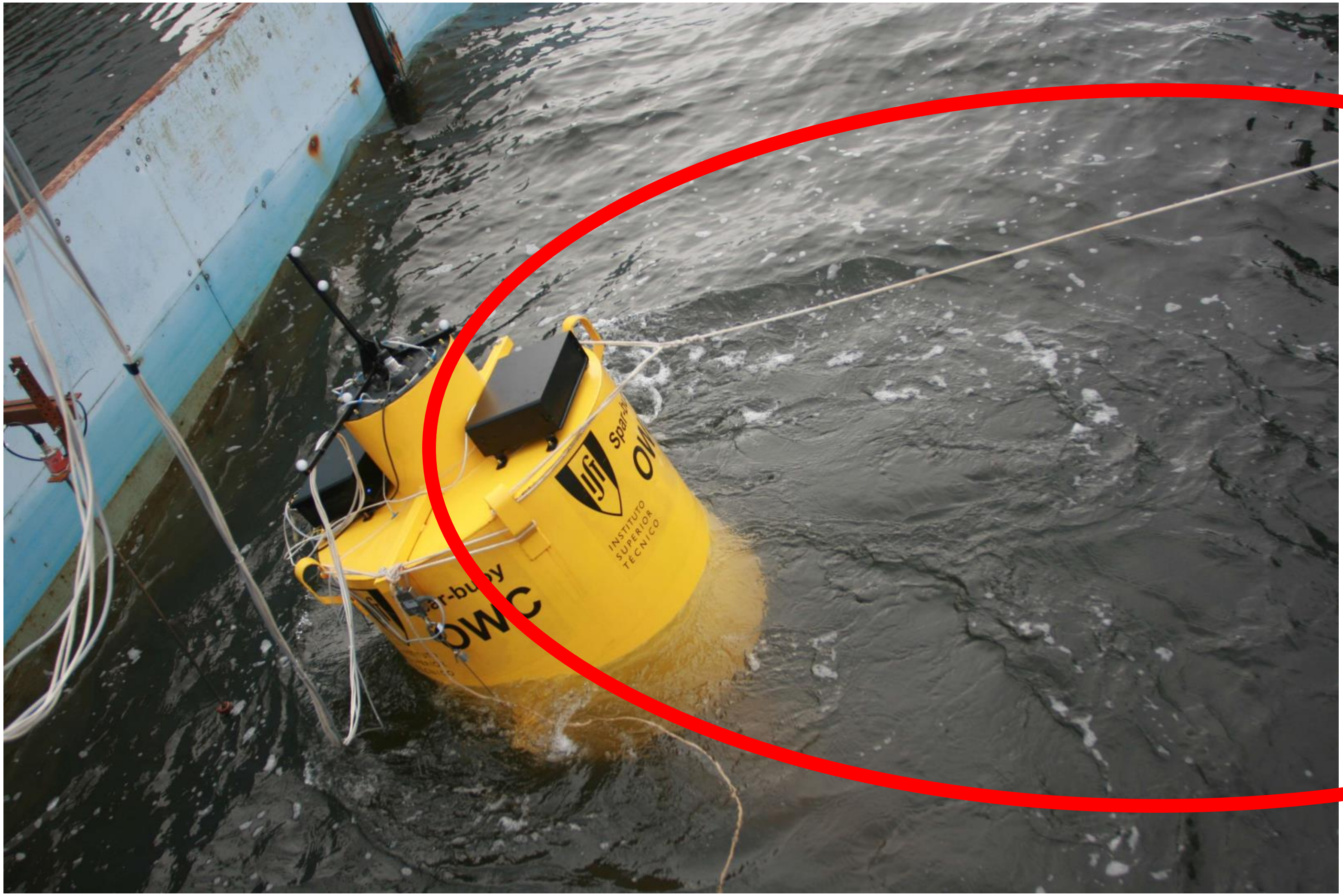
NAREC, UK

Isolated spar-buoy OWC tests at a scale of 1:16, 2012

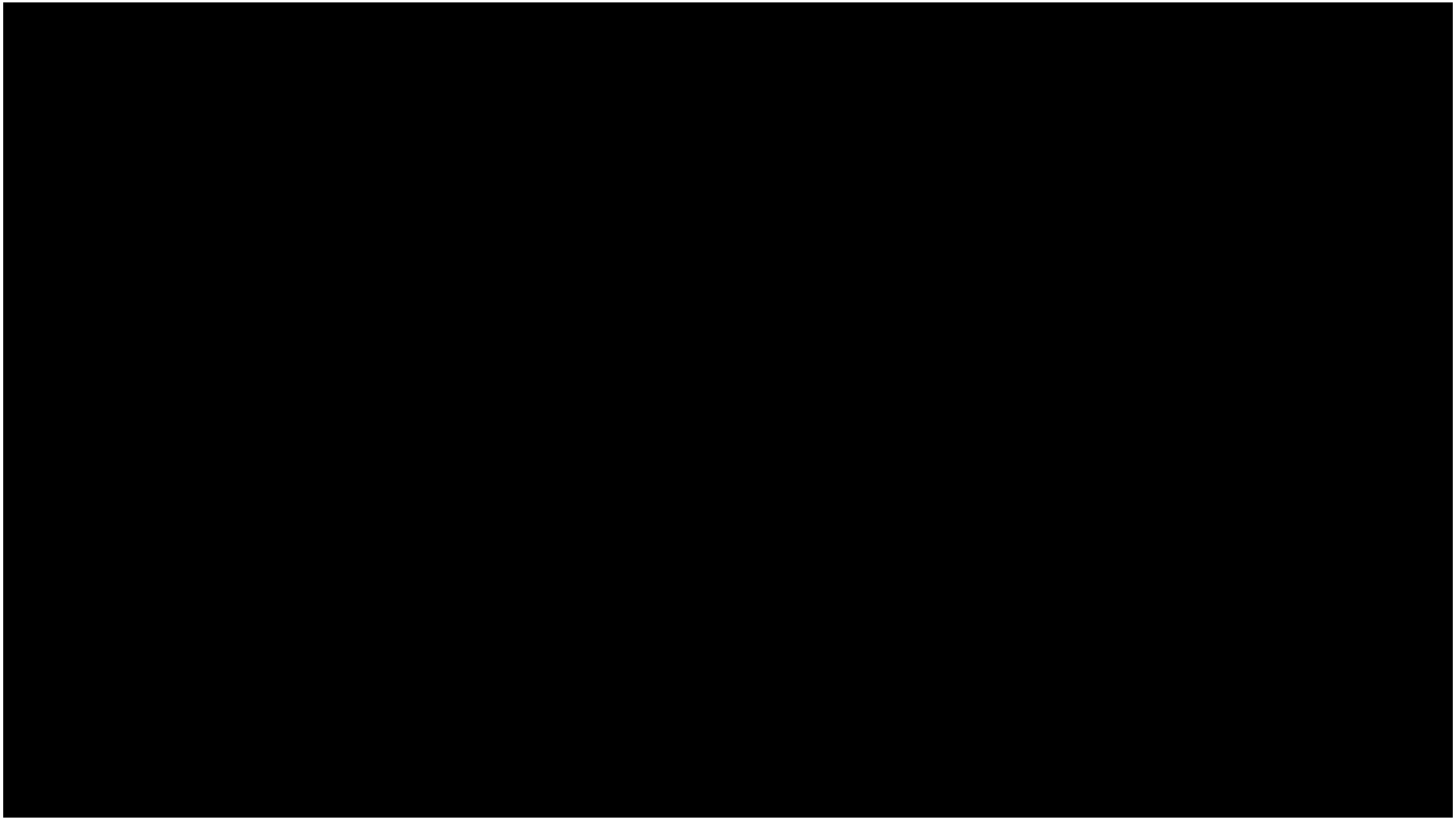
- We did not simulate the compressibility
  - Connecting rigid pipe could affect the dynamics
  - Results were used to calibrate numerical model at the scale of the experiments

Small-scale experimental testing of the spar buoy OWC

- Undesirable property of the spar buoy OWC: **parametric resonance**



Small-scale experimental testing of the spar buoy OWC



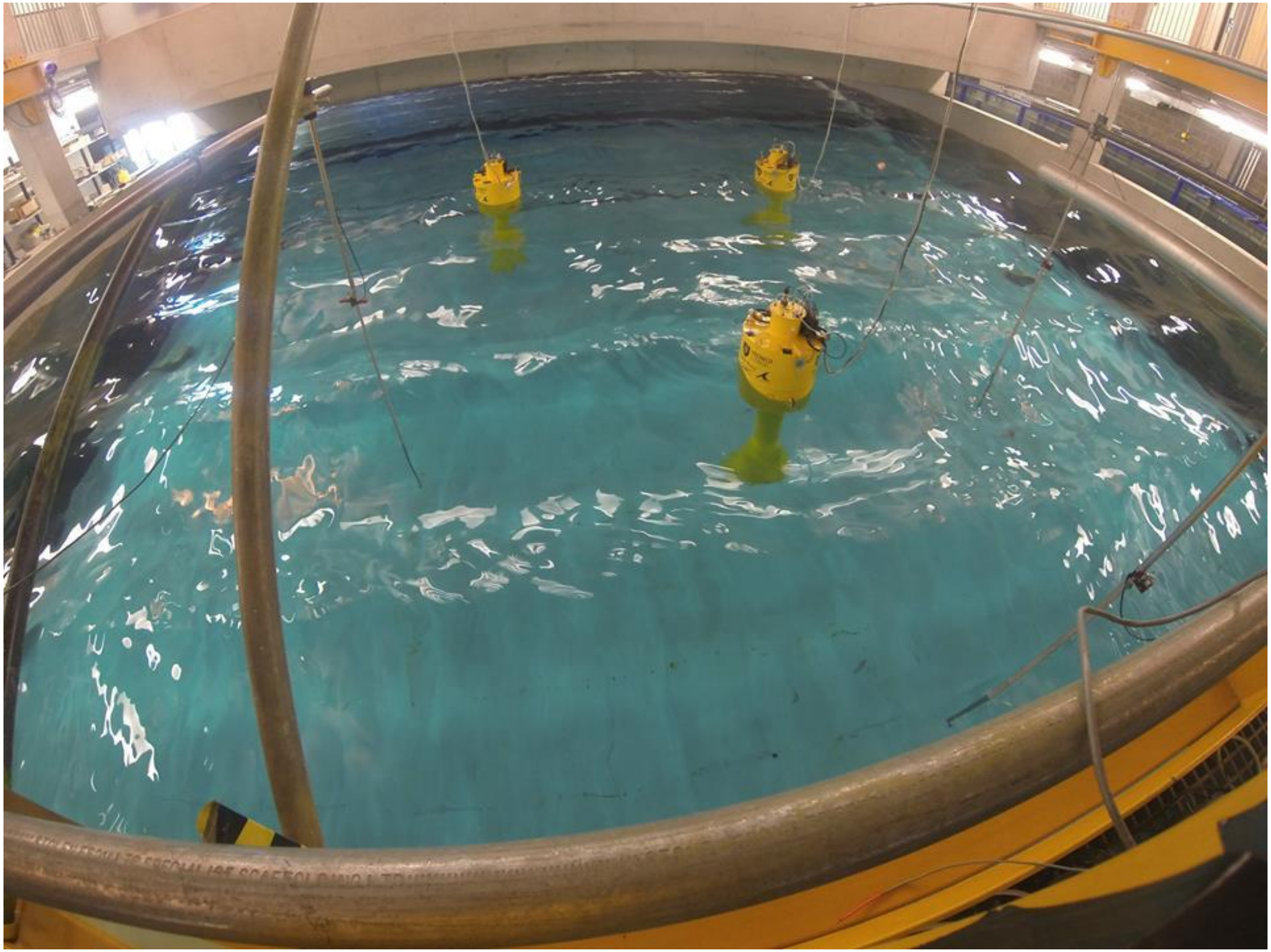
Meanwhile…

- The spar-buoy OWC Portuguese patent was filled

- **Worldwide patente is too expensive and time consuming**
  - use it wisely!
  - Universities and small companies can not afford to make worldwide patents for all ideas

- **Portuguese patente**
  - a simple protection against tentatives of patenting similar concepts
  - IST does not aim to sell buoys

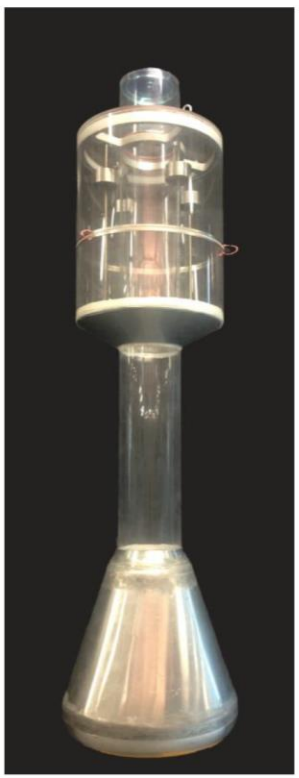
MARINET project funding



Array and extreme conditions tests, scale 1:32, COST Lab, University of Plymouth2014

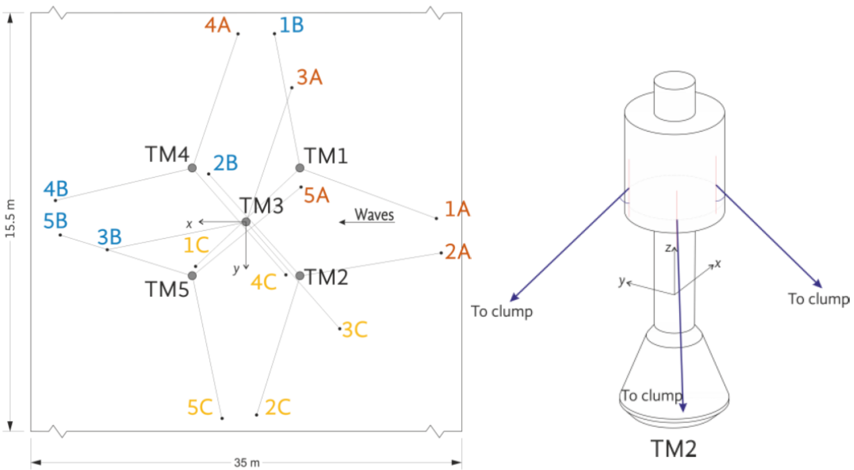
WETFEET H-2020 project

- Study of arrays and a new type of mooring lines to mitigate parametric resonance
- Test performed at a scale of 1:40 at COAST Lab, University of Plymouth

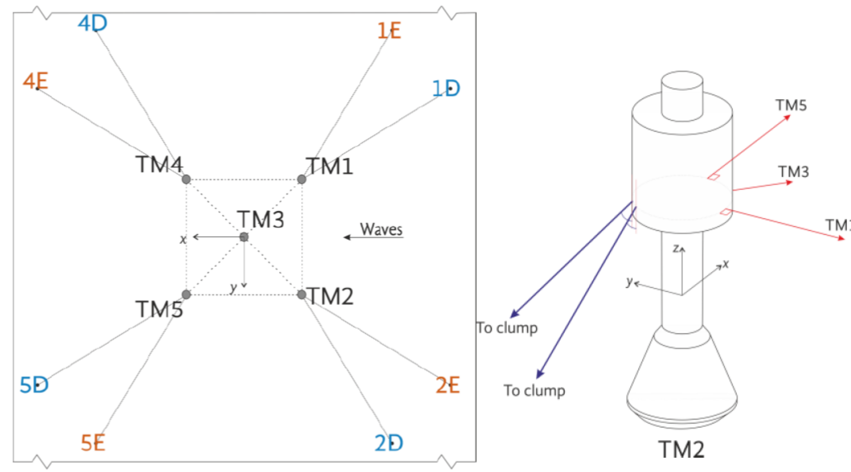


WETFEET H-2020 project

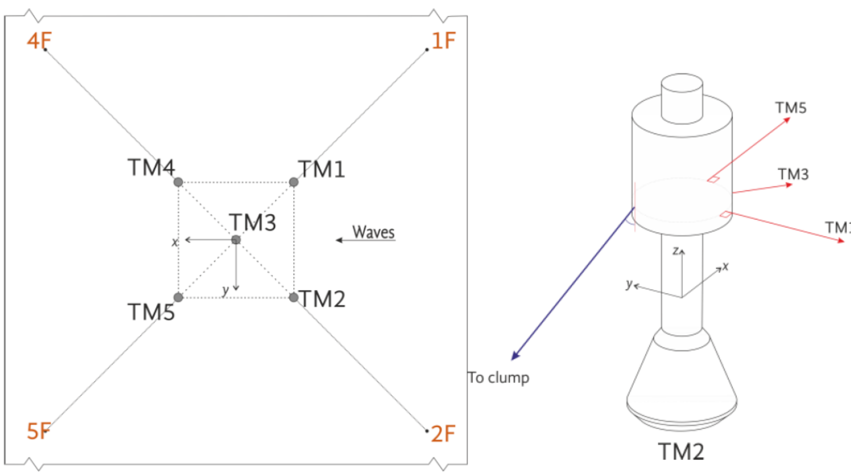
- New array configurations to reduce costs
- Test performed at COAST Lab 2017



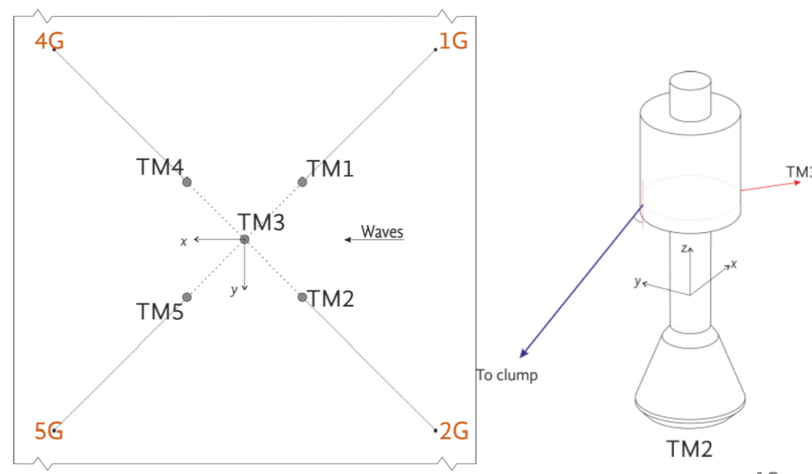
Configuration A



Configuration B



Configuration C



Configuration D

OPERA H-2020 Project

(Open Sea Wave Operating Experience to Reduce Energy Cost)

OPERA H-2020 project aims

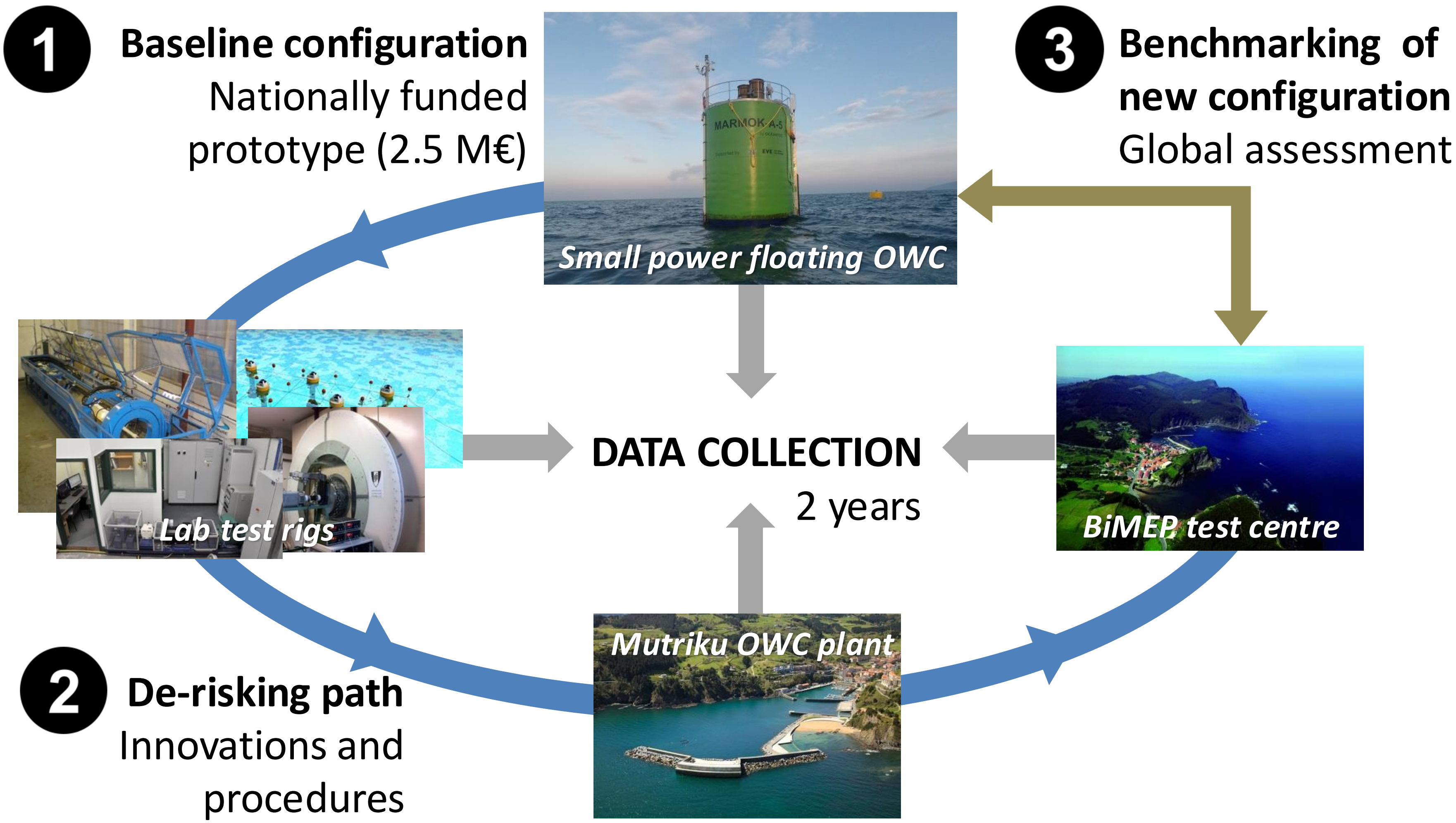
Collect, analyse and share for the first time high-quality **open-sea operating data and experience**

Validate & de-risk **4 industrial innovations** for wave energy

Innovation	Target	LCOE impact
Novel biradial air turbine	50% higher annual efficiency compared to Wells turbine	33%
Advanced control strategies	30% increase in energy production	23%
Elastomeric mooring tether	Reduce peak loads by 70%	7-10%
Shared mooring configuration	50% reduction in overall mooring costs in arrays	5-8%

Reduce the **cost of wave energy** by 50% in the long term

OPERA H-2020 project methodology



OPERA H-2020 project

- **IST - Aerodynamic design the biradial turbine for the OCEANTEC's Marmok A5 buoy**
  - Rotor diameter 0.5 m
  - Rated power 30 kW
- **Kymaner – mechanical design and construction of the turbine**

OPERA H-2020 project

- Buoy: 5m diameter, 42m in length, 80 tonnes weight and about 83 tons of ballast
- To be deployed at BIMEP testing site, Basque Country

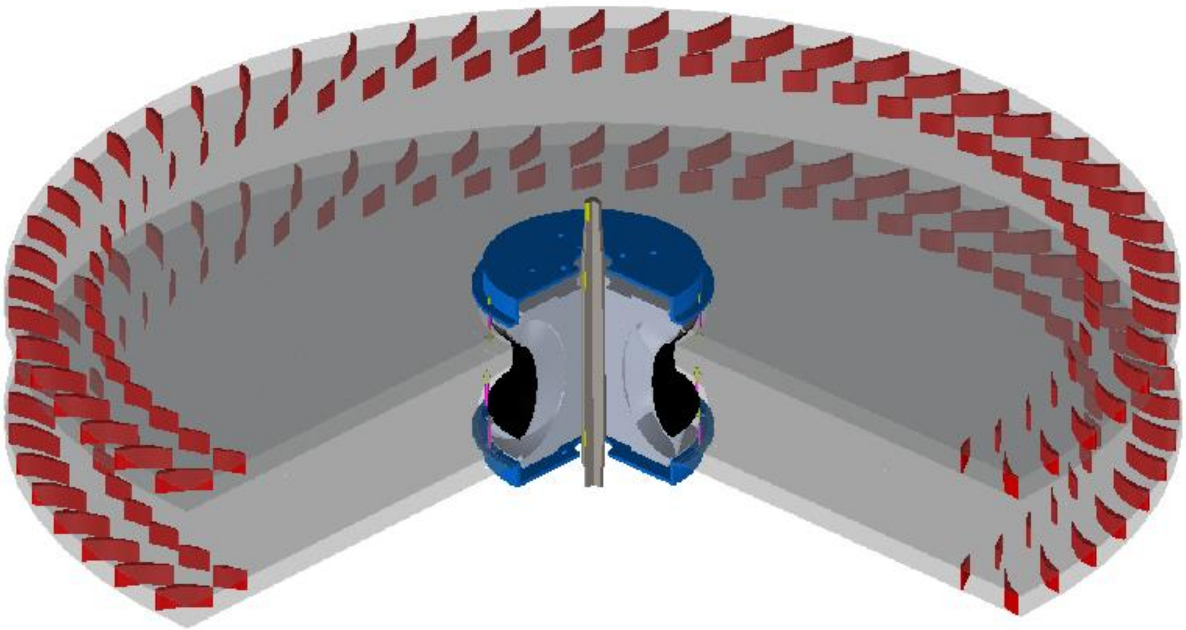
OPERA H-2020 project

- The new variable flow dry test rig for air turbines

New high-speed valve

OPERA H-2020 project

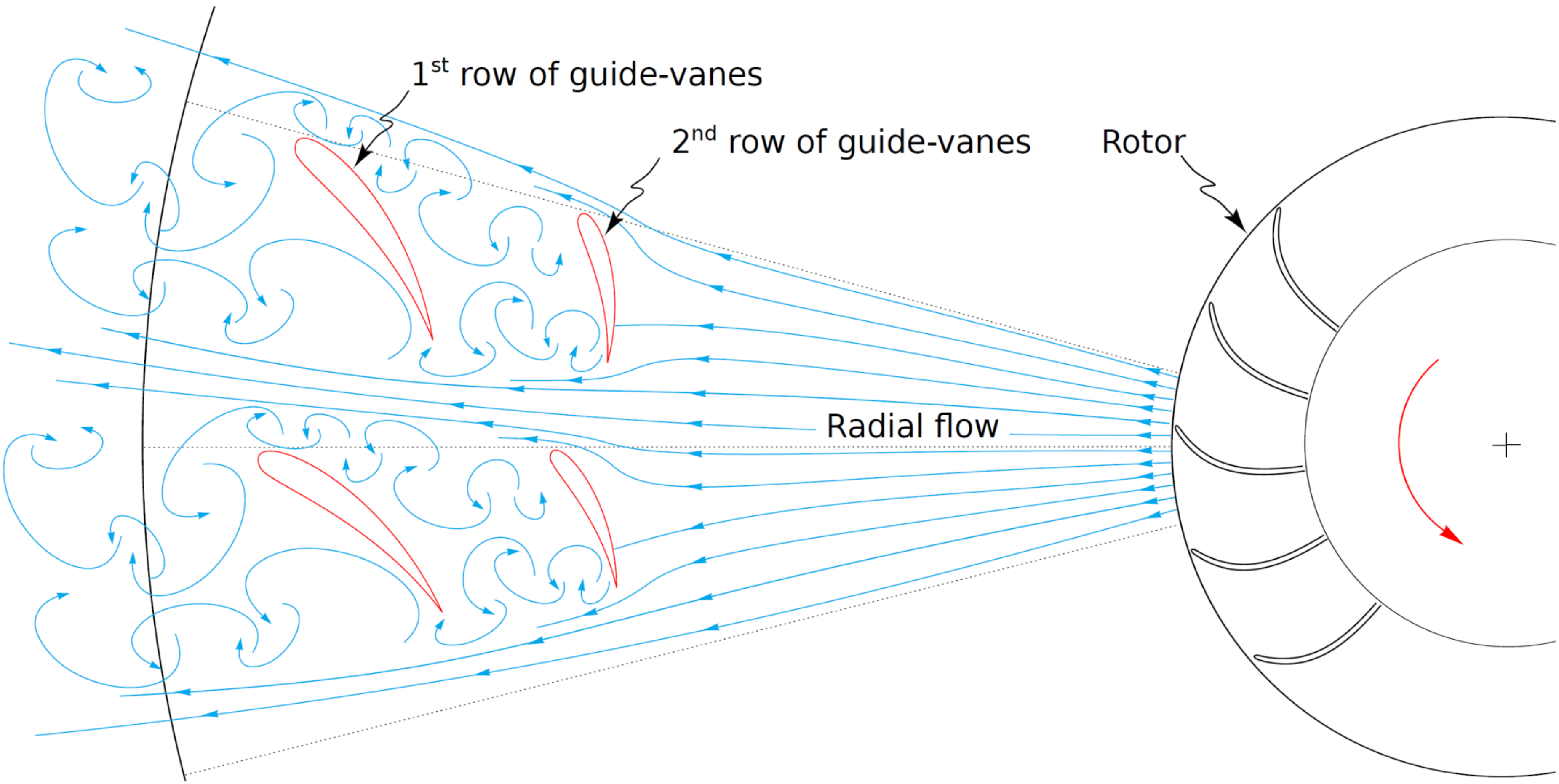
biradial turbine
Kymaner/IST patent WO/2011/102746



rotor

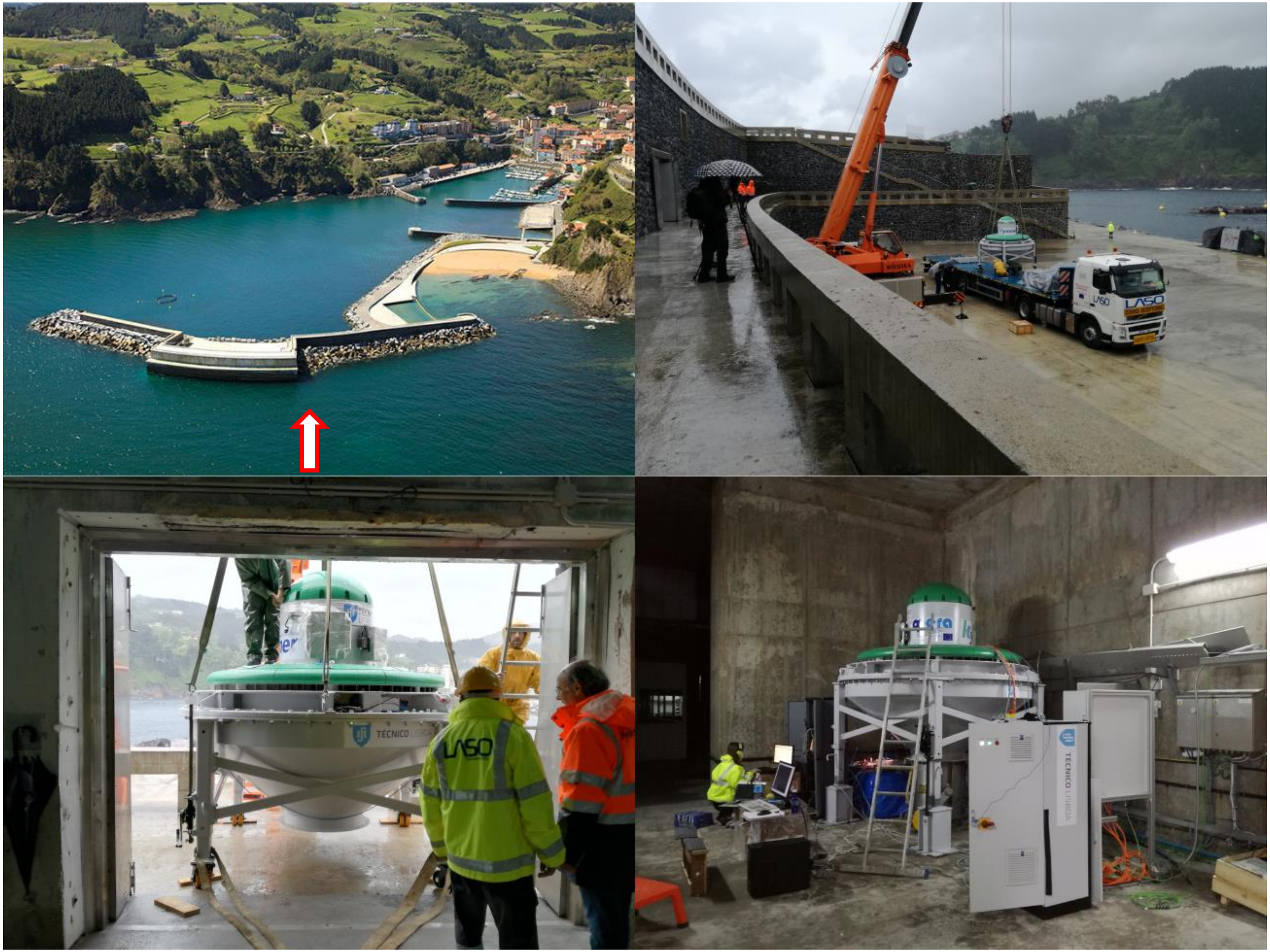
Biradial turbine exit guide vane system

- At the exhaust conditions, the 1st row of GV is in the wake of the 2nd row GV



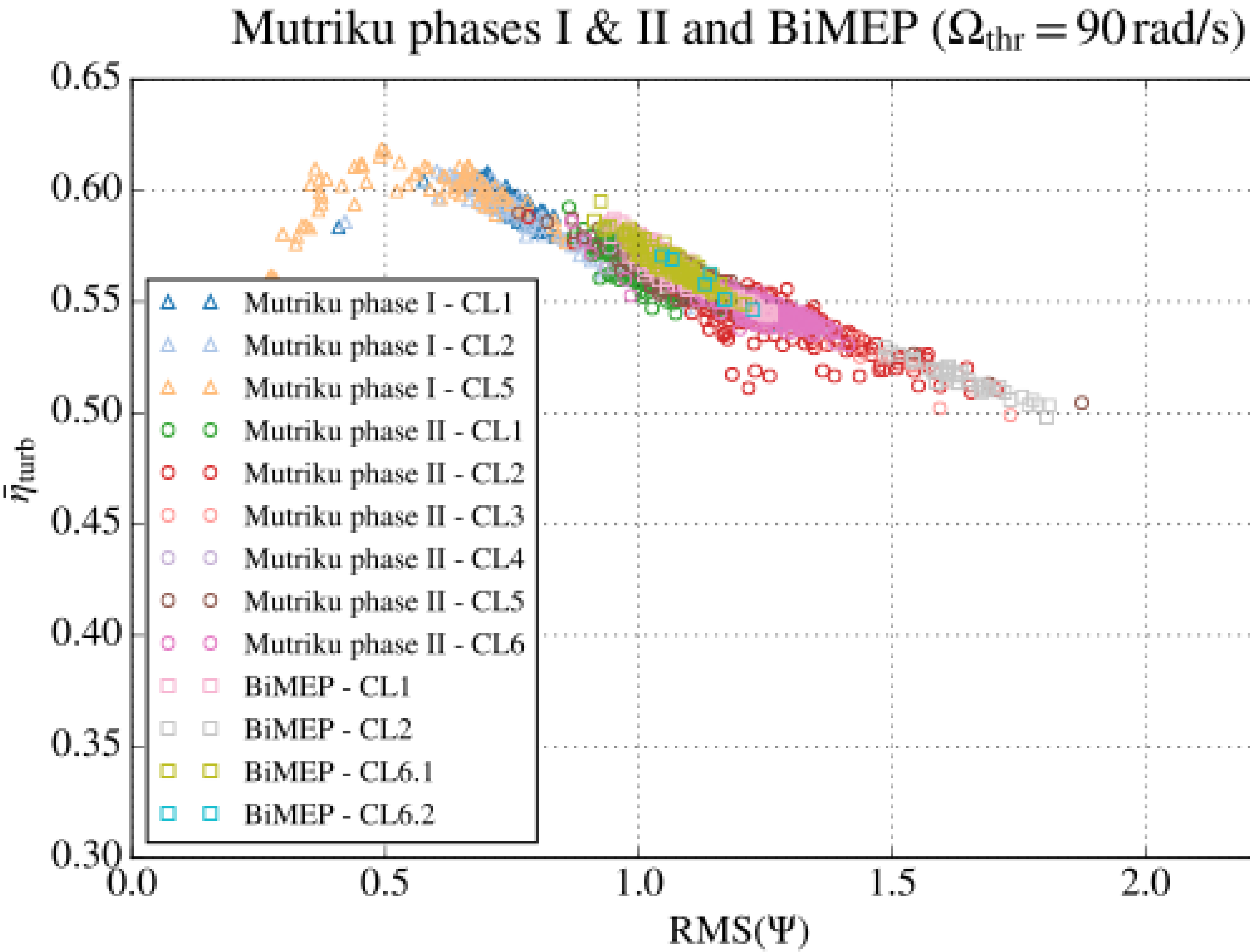
OPERA H-2020 project

Installation of biradial turbine at OWC-breakwater, Mutriku, Northern Spain



OPERA H-2020 project

OPERA H-2020 project



Final comments

- Wave energy harvesting is a **multi-disciplinary** problem
    - Requires teamwork!
    - Ideas usually come from discussions and brainstorming
- To go beyond the theoretical studies
    - Criticize your work!
        - Does the system make any sense from the points of view of:
            - Physics, fluid mechanics, mechanical and electrical design?
    - Integrated development
        - The team needs to understand the overall system even if using commercial off-the-shelf components
    - Create a consortium and apply to national/European projects
        - Gives funding and the challenges (lots of action!)

Final comments

- Intellectual property is important for **investors** but
  - Patents are used for protection not to constraint the work
  - If an idea is not good enough
    - Do not continue the development of a bad idea just because you have a patent
    - Stop before is too late
  - Apply for an international patent only if you have strong evidence of the commercial value of the idea
    - International patents are costly and time-consuming

- **In the end, the only thing that will matter is the commercial revenue!**

Funding...

- CORES FP7 Project partners
- WETFEET H-2020 Partners
- OPERA H-2020 Project partners


Questions?
Disclaimer - This Presentation reflects only the author's views.