
# CONCEPTS IN WAVE ENERGY CONVERSION

# THE SEA TITAN EU-FUNDED PROJECT

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CIEMAT

SeaTitan

wedge

ENGIE Fabricom

HYDROcap renewable energy

UNE Normalización Española

CENTIPOD LTD.

WavEC Offshore Renewables

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CORPOWER OCEAN

OCEM POWER ELECTRONICS

NEWENERGYWORLD

Columbus Superconductors

# Overview

## First Part:

- The energy of the Sea Waves
- Wave Energy Converters (WEC) and their classification
- Point Absorbers as a the most common type of WEC
- The Power Take-Off (PTO) as part of the  WEC
- Why PTO Point Absorbers need to be efficient producing high forces

## Second Part:

- The structure of the Sea Titan Project
- What is a Switched Reluctance Machine (SRM) and how it works
- The Calculation of the Azimuthal SRM
- The Design of the Azimuthal SRM
- The Fabrication of the Azimuthal SRM
- First Tests of the Azimuthal SRM
- Superconducting PTOs for Wave Energy Conversion
- Concluding Remarks

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 764014

# First Part:
# An introduction to Wave Energy

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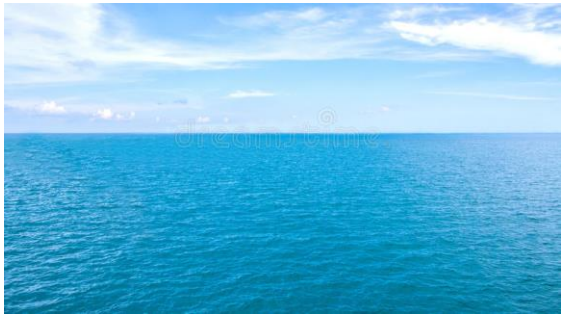
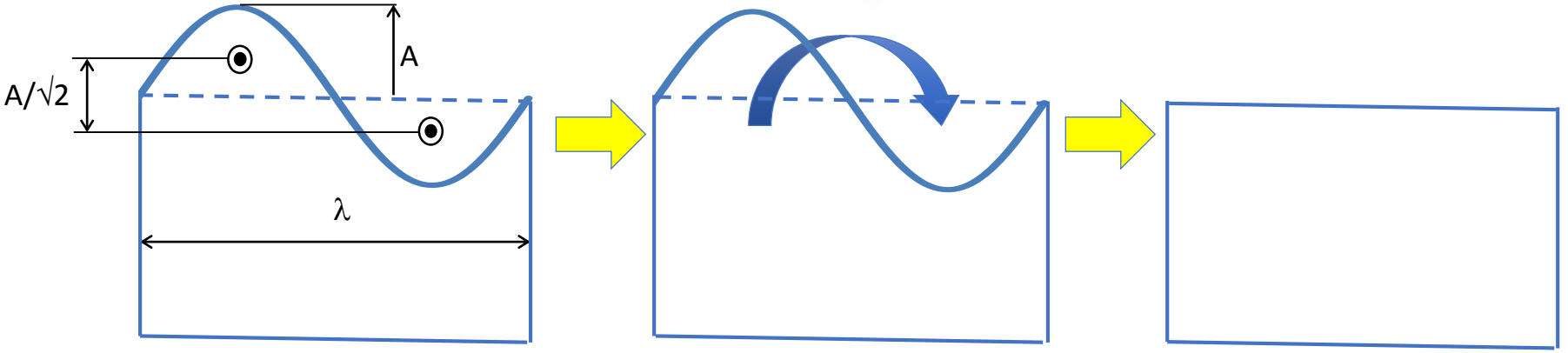
# Sea Waves Contain Energy

IDEAL WAVE ENERGY ABSORBER






A wavy sea is more energetic than a calmed sea. A device able to attenuate a wave, will extract a certain amount of energy that may be converted into electricity.

$$P = \frac{\rho g^2 T A^2}{8\pi} \text{ (Kw/m)}$$

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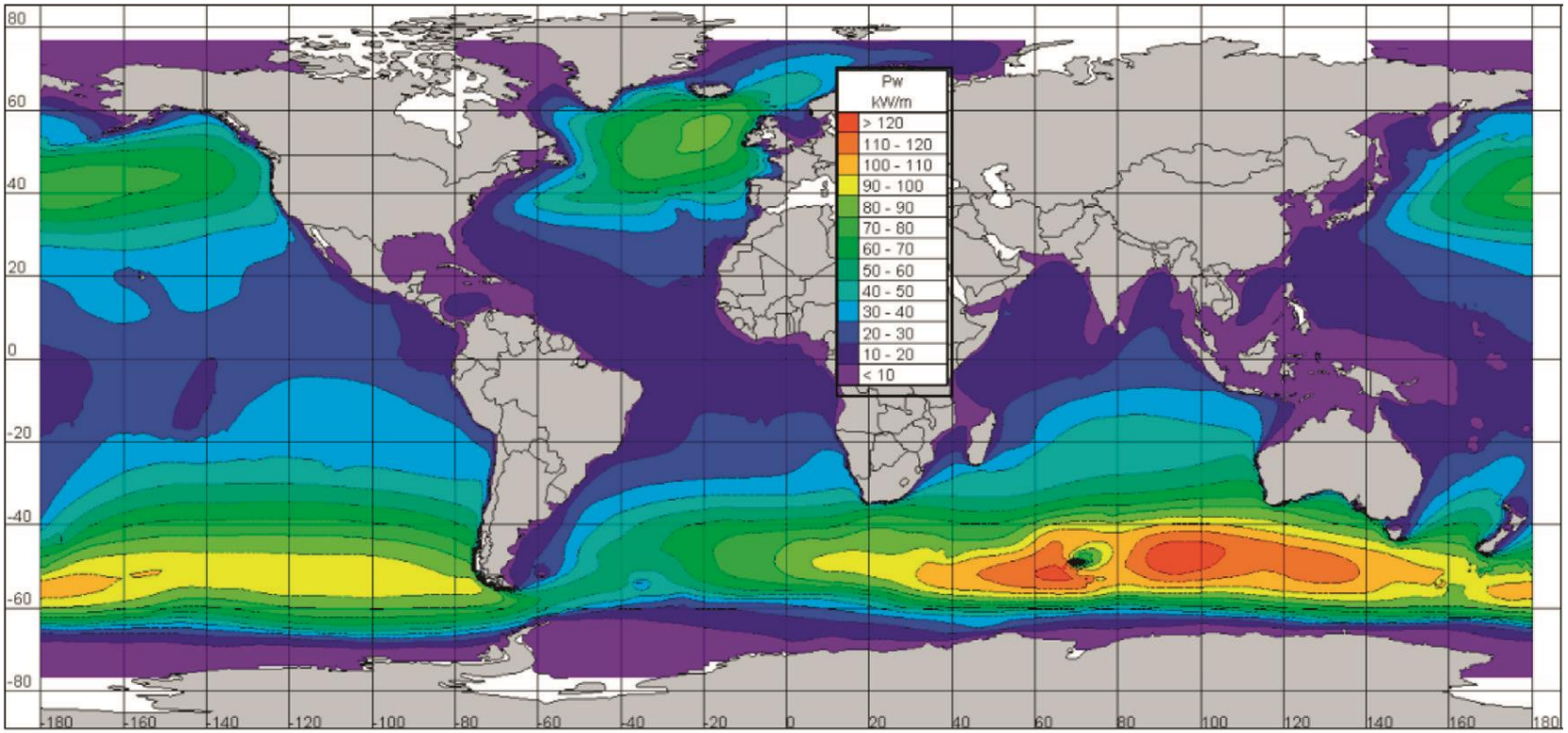
# The Oceans Energy Map




A relevant indicator in Wave Energy Conversion is the available power per meter wave front. It varies very much from site to site but, just as a reference in the Cantabric Coast, extracting the full power corresponding to a 10m long wave can supply the energy corresponding to 100 homes

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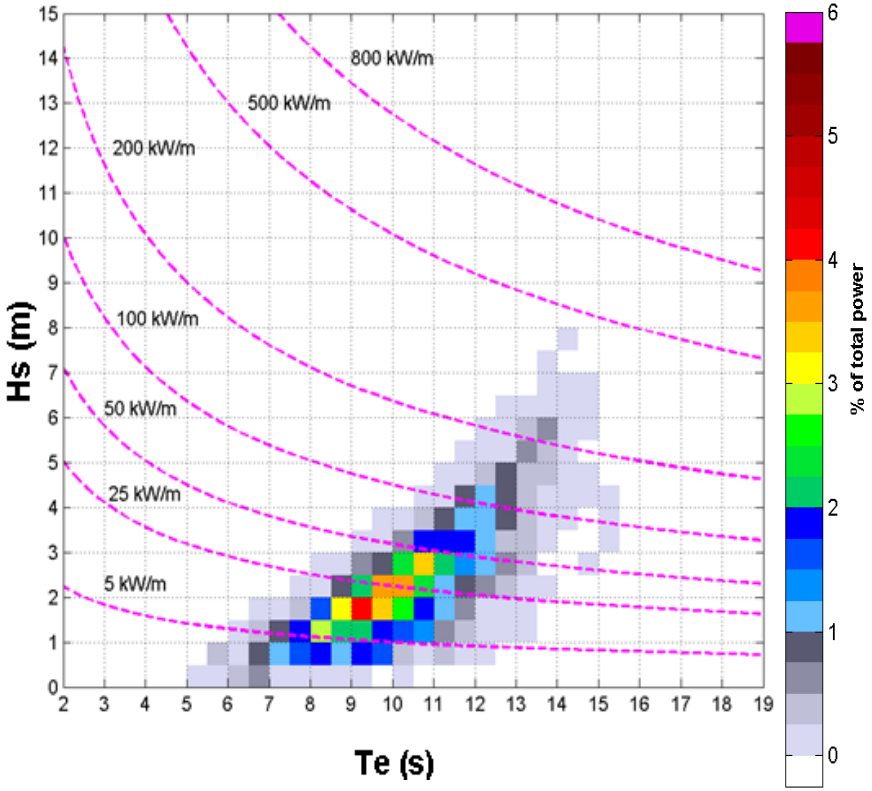
# The Real Available Power at Sea




Each site has associated its own "occurrence matrix" (scatter diagram) that shows the probability of occurrence for a certain sea state (in terms of height and period). The average overall power that can be extracted is the sum of the power associated to each site, weighted by its occurrence:

$$P_E = \frac{1}{100} \sum_{i=1}^{n_T} \sum_{j=1}^{n_H} p_{ij} \cdot P_{ij}$$

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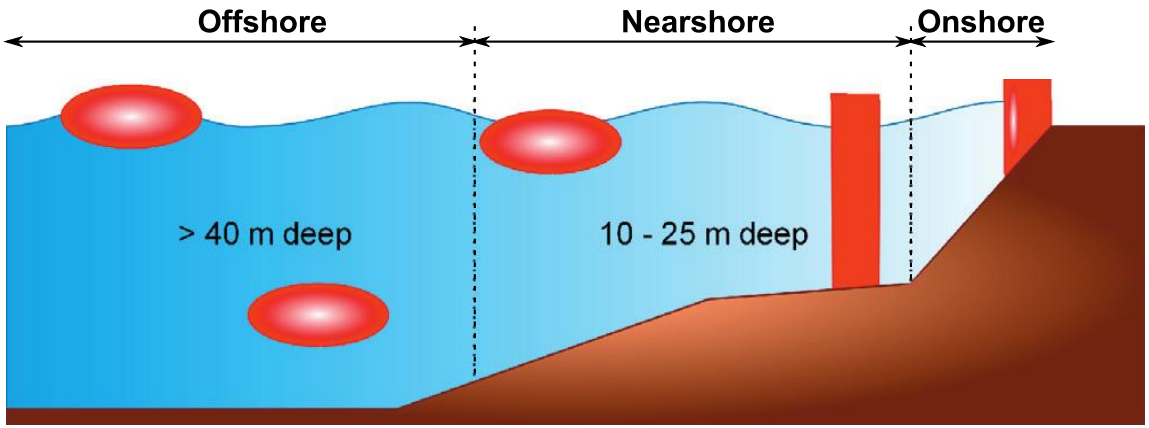
# The First Classification of WECs




A device that extracts energy from the waves is commonly named Wave Energy Converter (WEC)

WEC classification according to its location with respect to the shore

| DEVICE TYPE | DEVICE LENGHT | CAPTURE WIDTH (W) |
|---|---|---|
| Attenuator | L = l | W=0.5 l = 0.5 L |
| L | L=2 l | W=0.73 l = 0.37 L |
| Terminator | L=l | W= l = L |
| L | | |
| Point Absorber | L≈0.1 l | W= l/2p ≈ 0.16 l = 1.6 L |
| l L | | |

WEC classification according the orientation of the device with respect direction of the incoming wave

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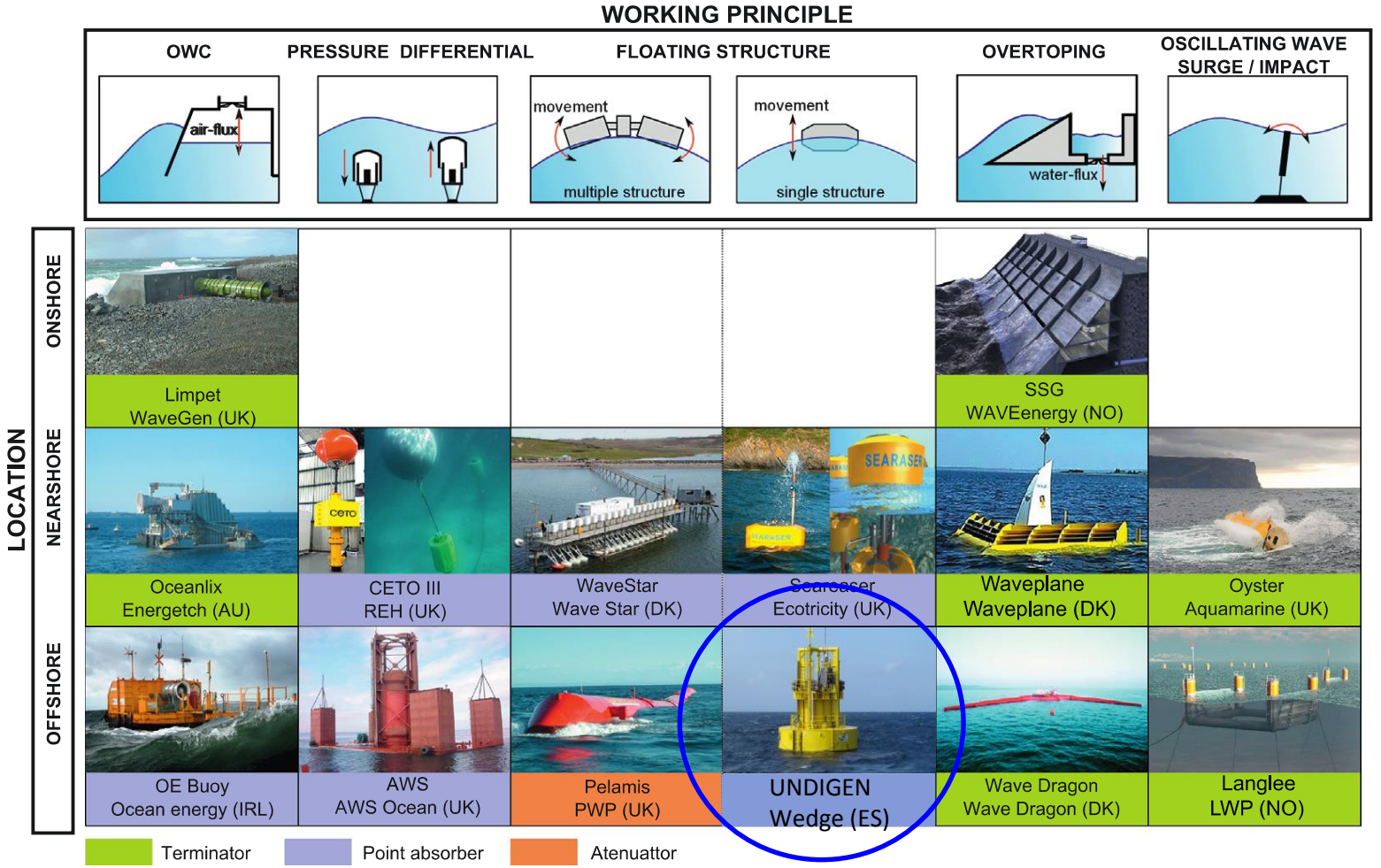
# The Second Classification of WECs (1)




WECs also admit another classification according its working principle. This table shows different realizations sorted by three different criteria: Location, Orientation and Working Principle.

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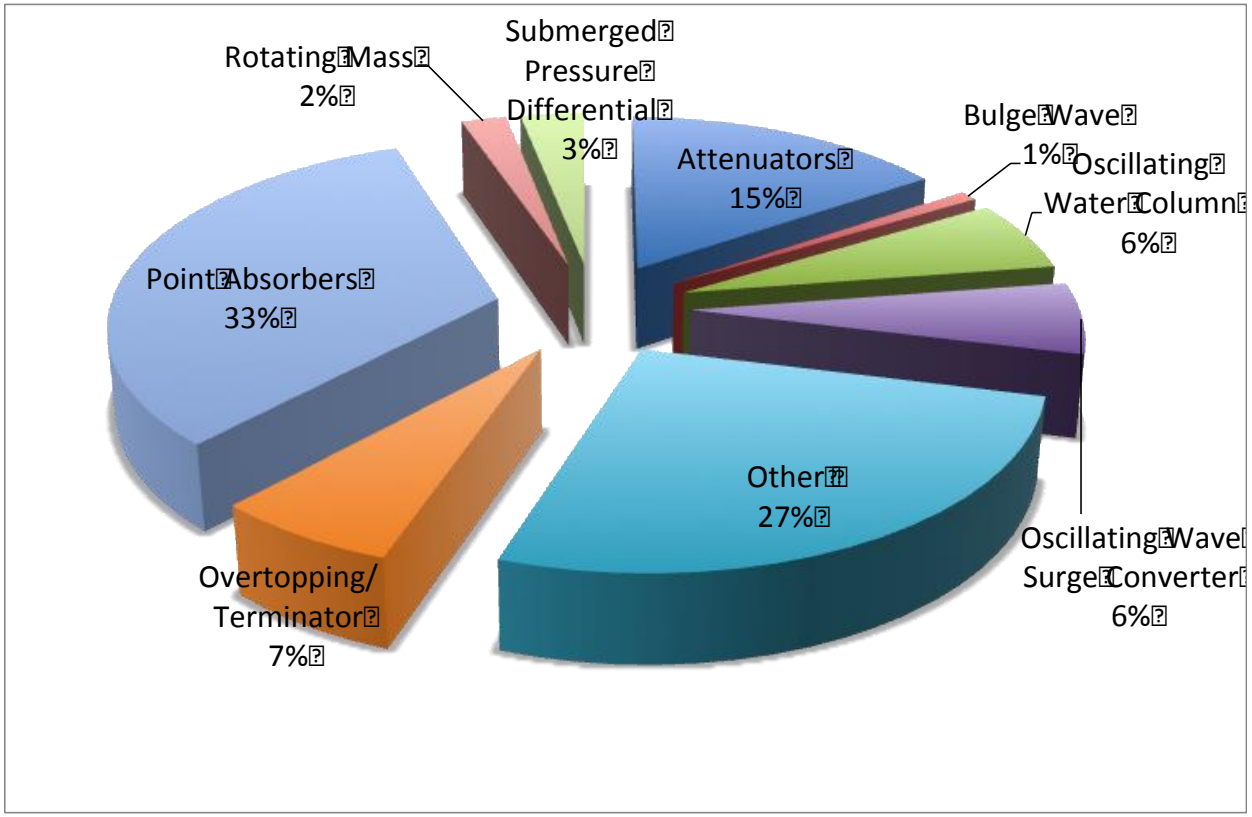
# The Second Classification of WECs (2)




In 2017 CIEMAT performed a classification of 226 WEC projects all over the world according to the technology in which they where based on. The analysis relayed on data from the European Marine Energy Centre (EMEC) concluding that the most dominant solution was the Point Absorber with 1/3 of all the cases.

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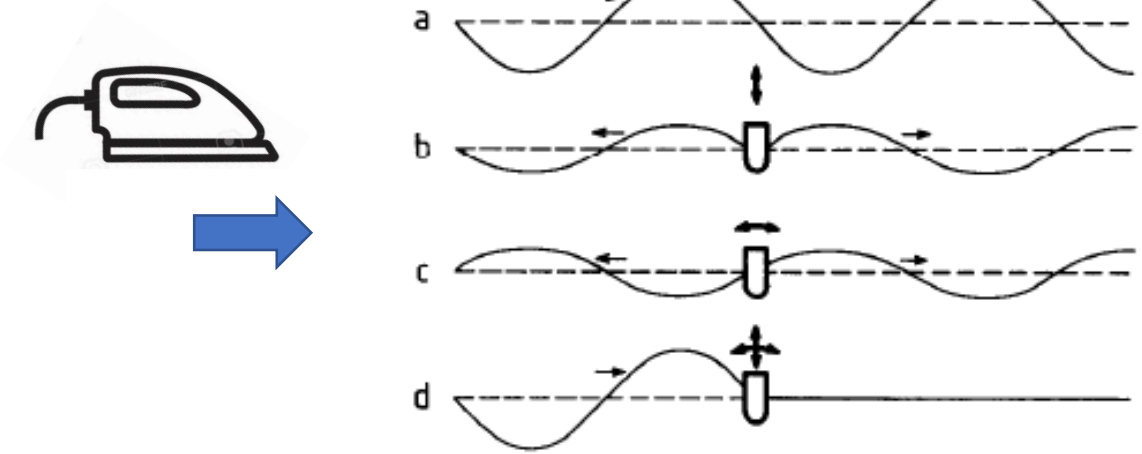
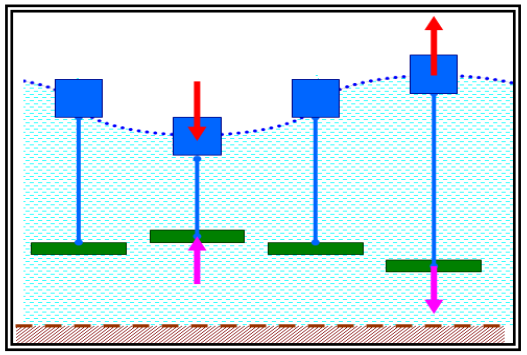
# “To Absorb Waves Means to Generate Waves”

(J. Falnes)



HEAVING POINT ABSORBER

PITCH POINT ABSORBER

Some Point Absorbers generate symmetric waves when they oscillate (heaving) while others generate antisymmetric waves (pitch). A combination of both is able to cancel the incoming wave extracting all its energy.

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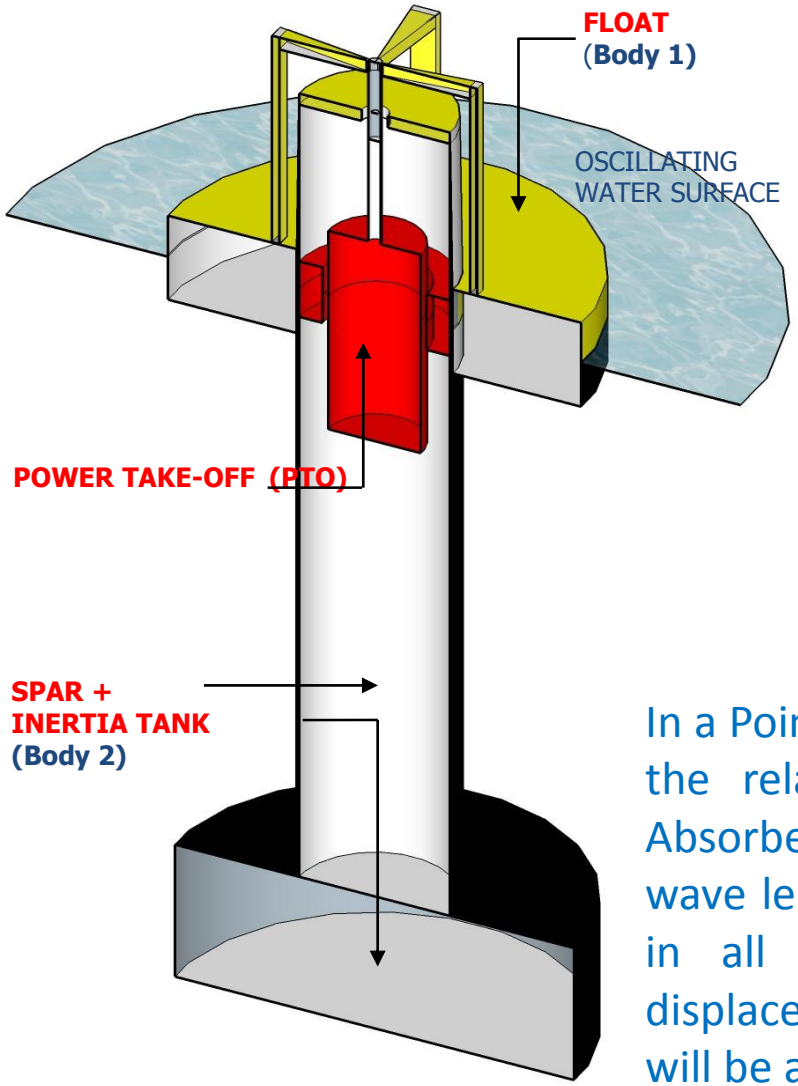
# The Heaving Point Absorber Type WEC





In a Point Absorber, energy is produced in the PTO with the relative displacement of two bodies. A Point Absorber has a small dimension compared with the wave length and it is able to extract the same energy in all directions of the incoming wave. If the displacement is done in the vertical direction, then it will be a Heaving Point Absorber.

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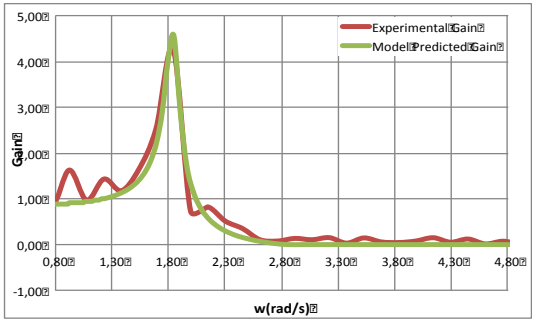
# The Experimental Verification of a WEC Working Principle




Computed & Measured Gain Function of the W1 HPA

This video shows the operation of the UNDIGEN WEC at Las Palmas Harbour. It becomes very illustrative of how the movement of the Float is amplified with regard the wave motion since it is close to resonance, while the spar hardly moves since it resonant frequency is very far away from that of the waves

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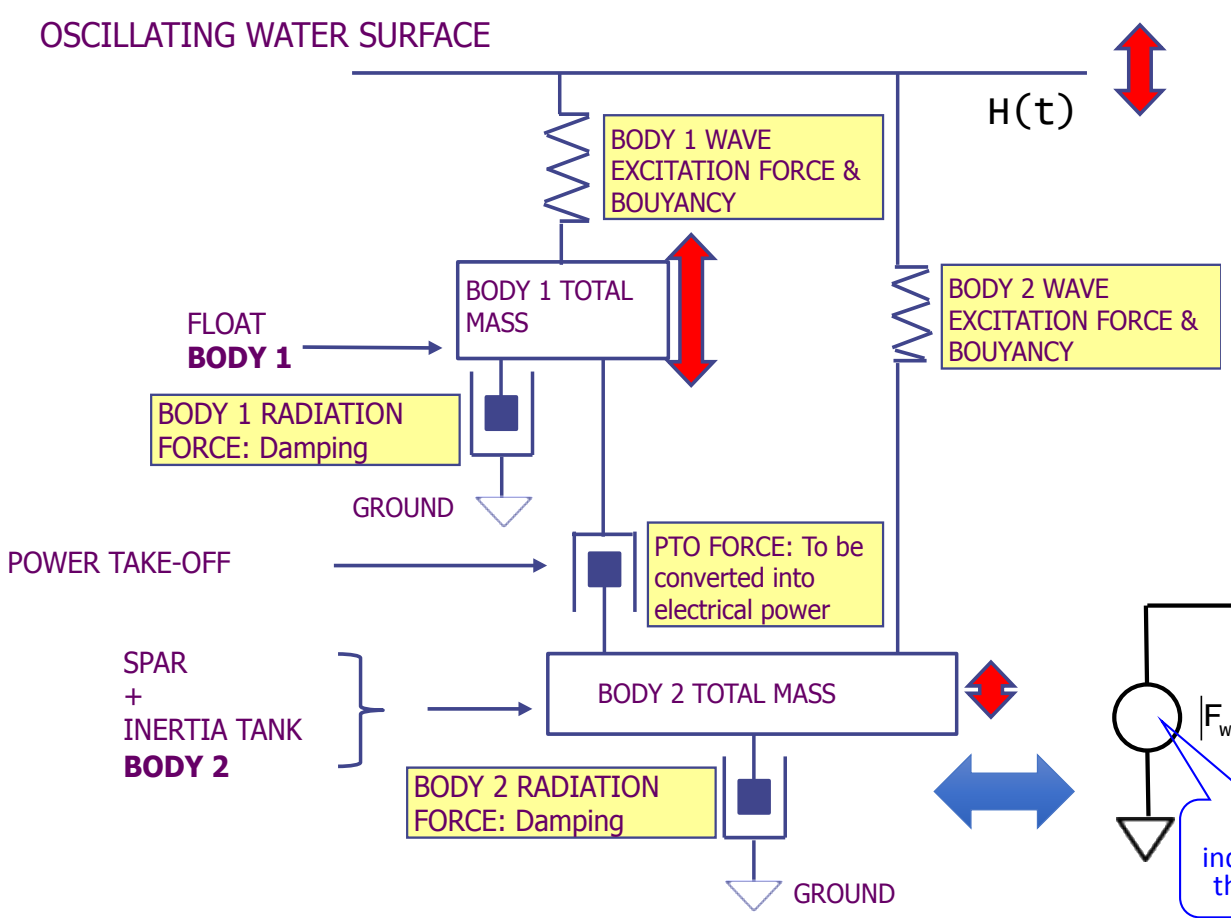
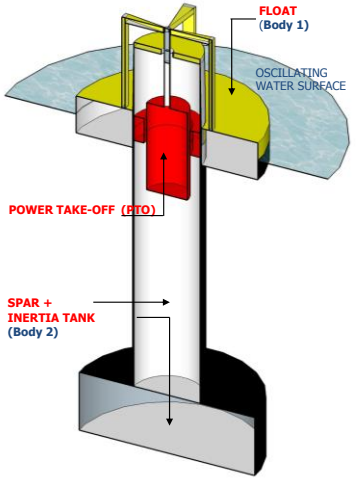
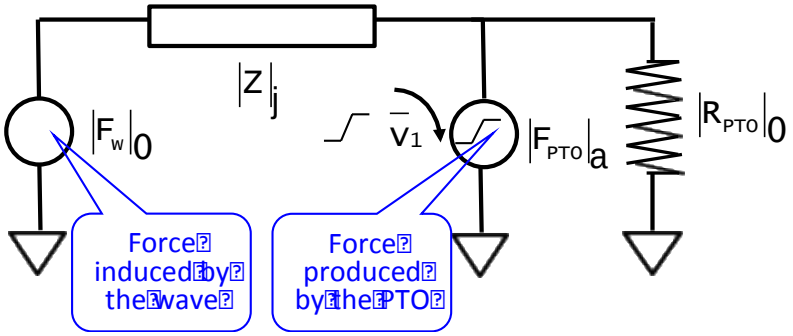
# The Physics of a Heaving Point Absorber




A Point Absorber is an oscillating system with its corresponding mechanical model. Alternatively it can be represented by an equivalent electric circuit that allows to find the optimum force to be exerted by the PTO.

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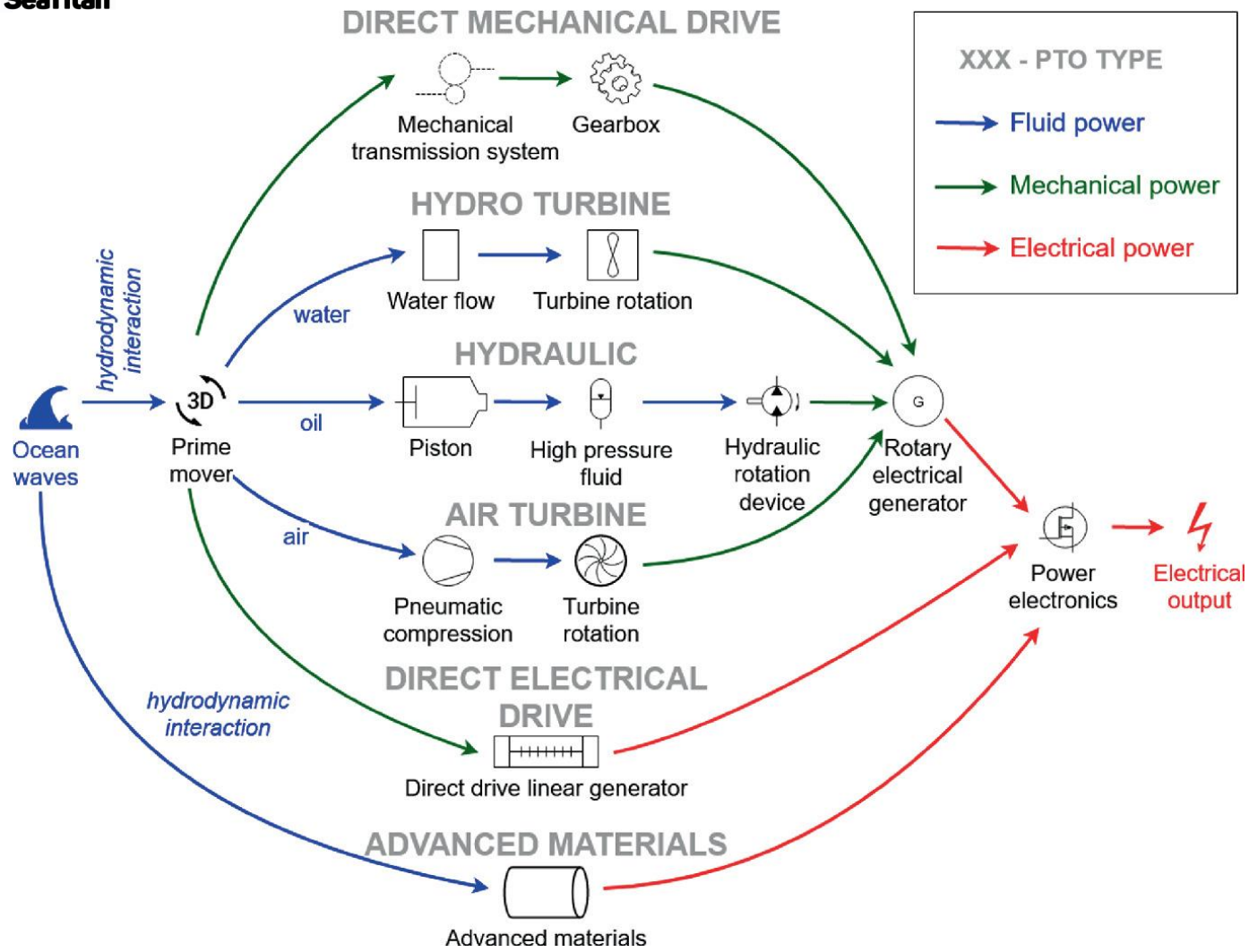
# What is a PTO and How They are Classified




The PTO is the WEC component in charge of transforming the mechanical energy of the wave into electricity.

There are different types of PTOs , but only electric ones perform a direct conversion of energy which means a better efficiency and a higher simplicity

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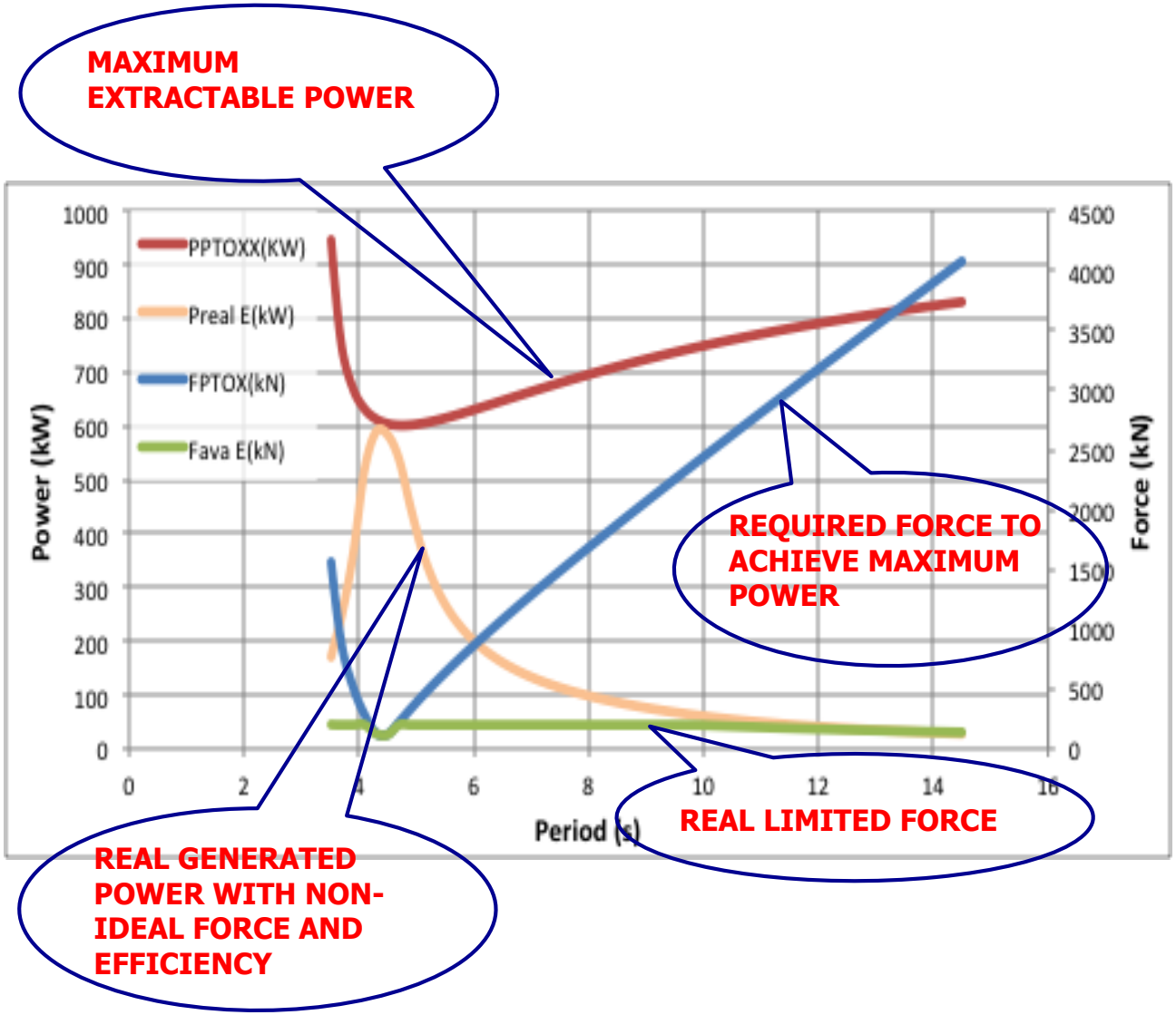
# ¿What is the Force that a Point Absorber Must Produce?




It is clearly necessary to use high-force and high-efficiency PTOs to improve the capture capacity in real seas.

Alternatively there are other means to always extract the maximum power, like modifying the float mass or wet surface so that the resonant frequency matches the wave frequency.

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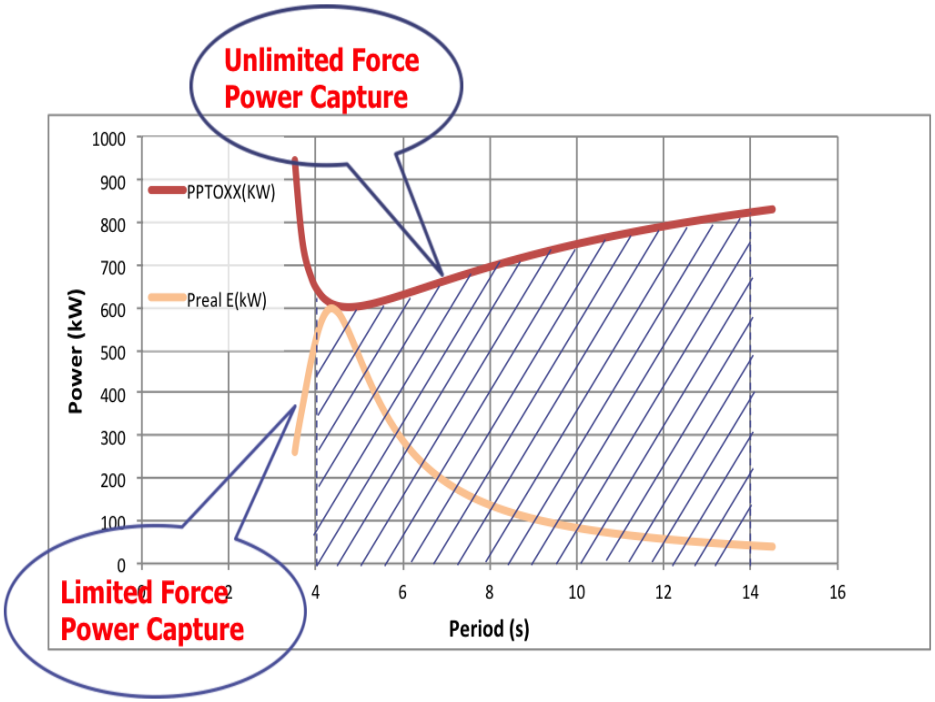
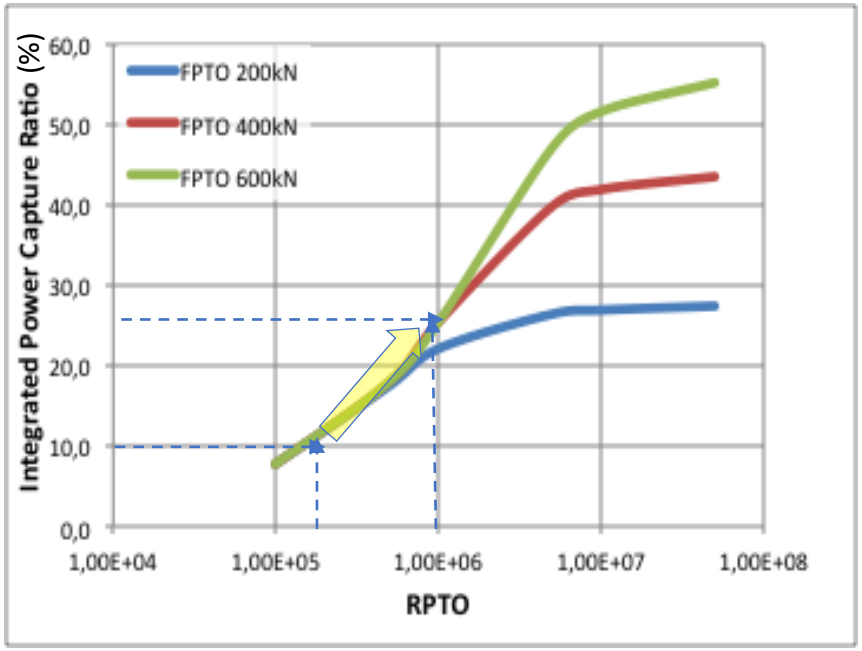
# The Concept of IPCR
## (Integrated Power Capture Ratio)




The IPCR (Integrated Power Capture Ratio) is the ratio between the overall area of the extractable power in a range of periods using a force-limited WEC with a certain efficiency and that corresponding to a WEC without force limitation and a 100% efficiency. The higher the IPCR, the bigger the amount of energy that can be extracted.

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# Second Part:
# The SEA TITAN Project

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# The SEA TITAN Project

## Surging Energy Absorption Through Increasing Thrust And efficieNcy

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### GOALS:

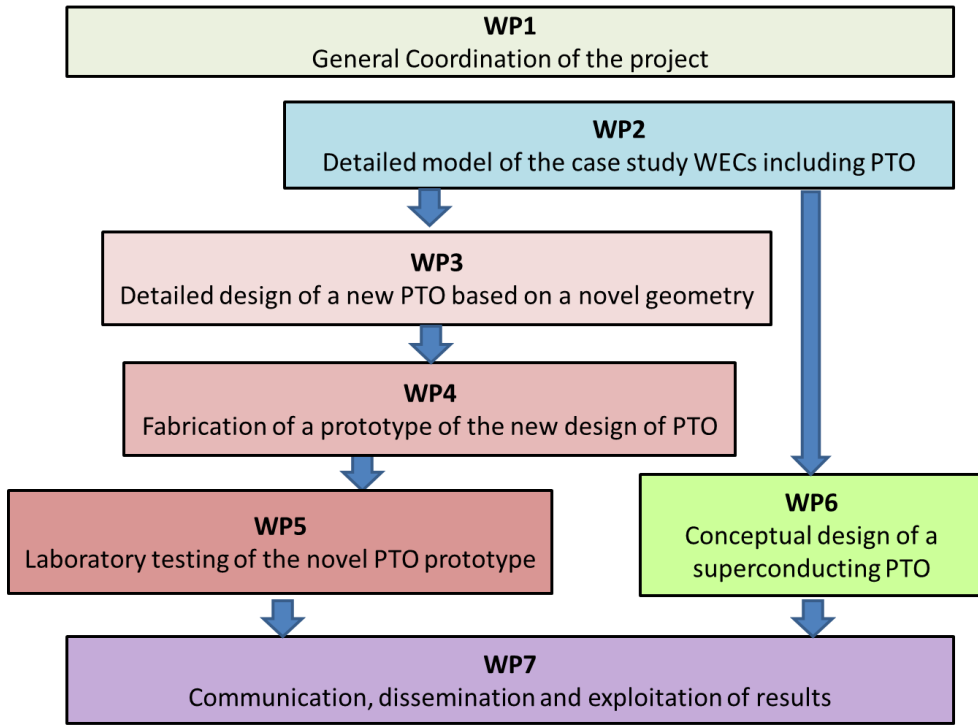
**- Developing a new PTO based on a Linear SRM**

- Force Density x 2
- IPCR x2
- Increasing the FtWE up to 80%
- Reducing Capex/kW down to 25%
- Reducing LCoE in about 30%

**- Modular & Cross Cutting up to 500 kN & 3m/s**

**- 3ª Generation based on a Superconducting PTO**

TYPE OF ACTION: RESEARCH & INNOVATION ACTION (RIA)




| | Participant Organization name | Type | Country |
|---|---|---|---|
| 1 (C) | Wedge Global S.L. | WEC Developer | Spain |
| 2 | CIEMAT | Pubilc R&D Center | Spain |
| 3 | WavEC - Offshore Renewables | R6D Center | Portugal |
| 4 | CorPower Ocean | WEC Developer | Sweden |
| 5 | Centipod LTD | WEC Developer | UK |
| 6 | Hydrocap Energy SAS | WEC Developer | France |
| 7 | OCEM Energy Technology srl | Power Electronics | Italy |
| 8 | Columbus Superconductors (AGS) | Superconductors | Italy |
| 9 | Engie Fabricom | Installation & Services | Belgium |
| 10 | EDP Center New Energy Technologies | R&D Center | Portugal |
| 11 | Asociación Española de Normalización | Regulatory Body | Spain |

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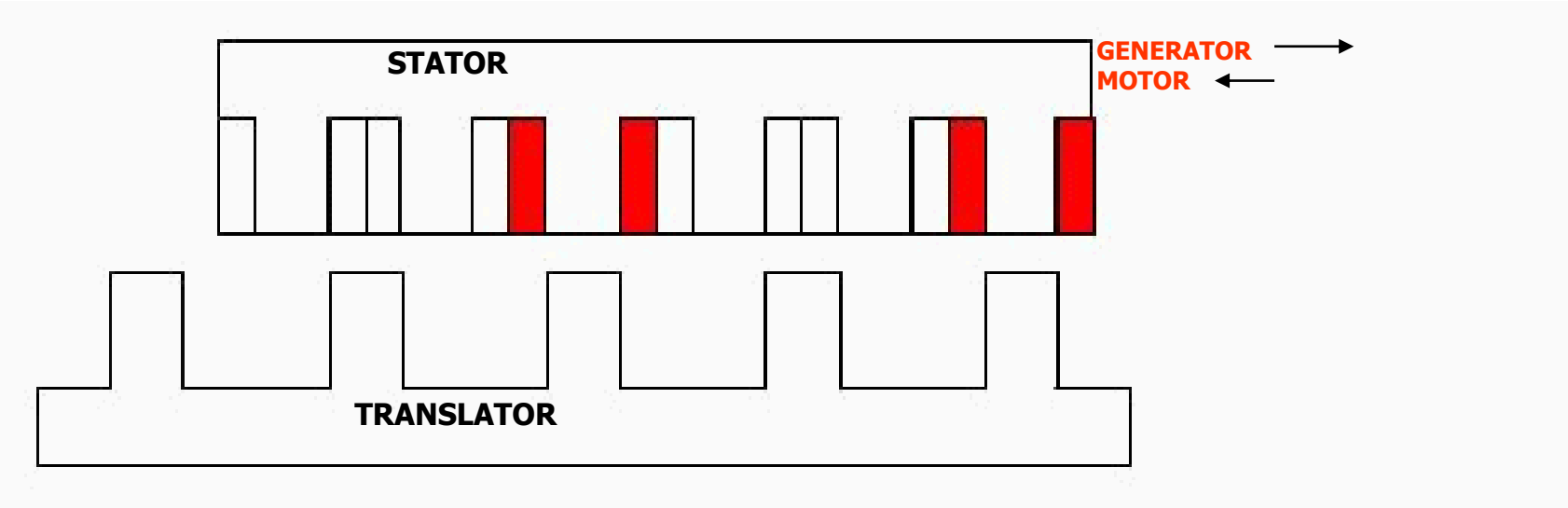
# The Principle of the Linear Switched Reluctance Machine (SRM)




In a Switched Reluctance Machine, Stator phases are sequentially switched on and off. Passive Side is attracted by the Active one in order to minimize the Reluctance of the Magnetic Circuit (Motor Mode) or it is driven by an external force to maximise the Reluctance (Generator Mode).

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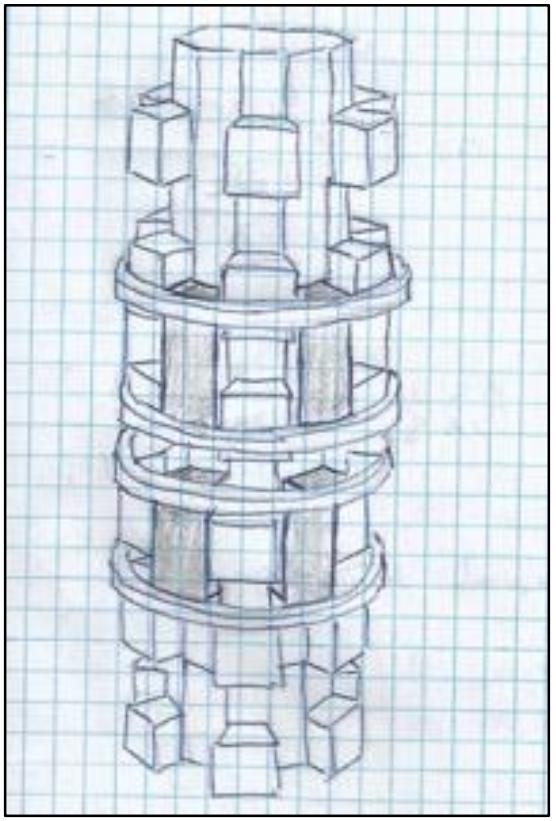

# The development of WP3 WP4 & WP5

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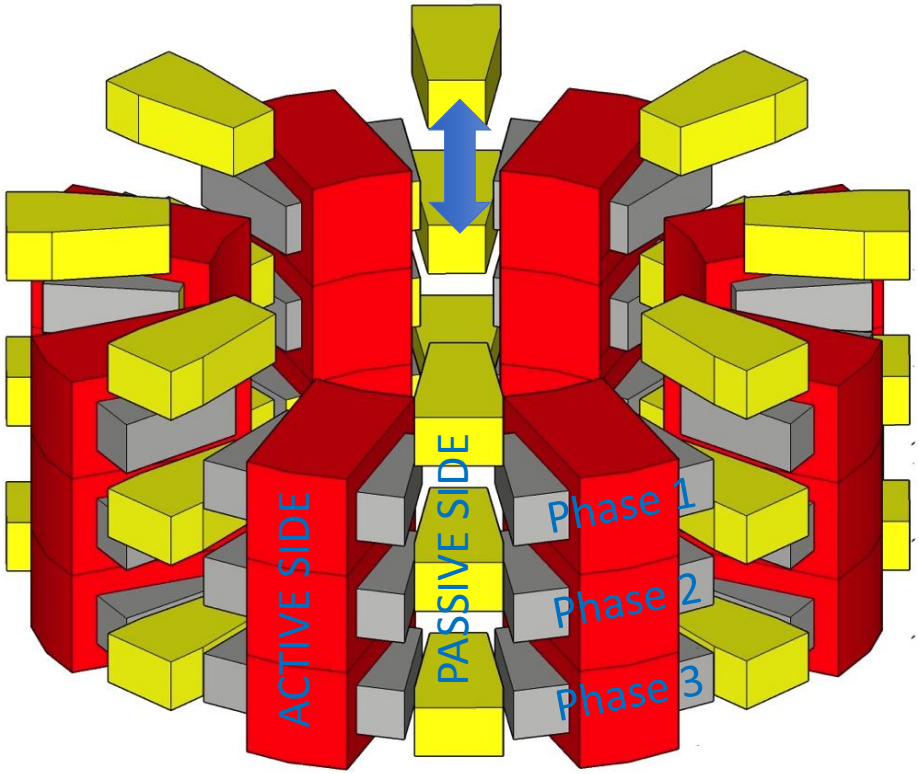
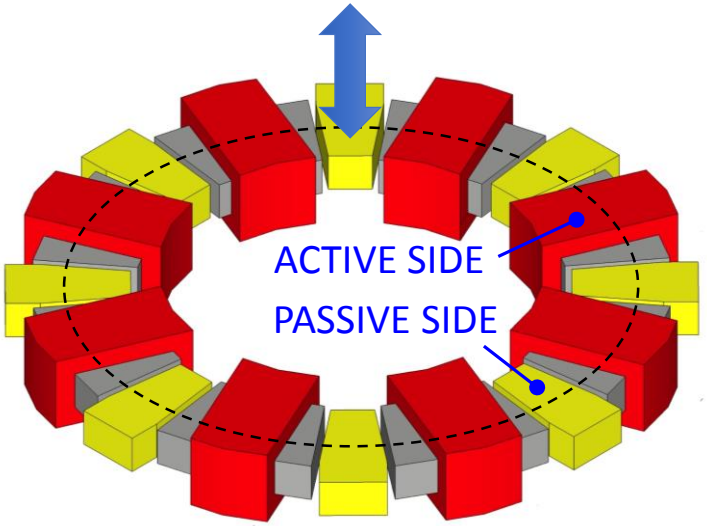
# The Concept of Azimuthal SRM

The SEA TITAN Project is based on a new type of Switched Reluctance Machine with a topology that allows a significant increasing of the force density and consequently the net force produced by the PTO.




**The Azimutal SRM (3 Phase Arrangement)**




**1 Phase of the Azimuthal SRM**

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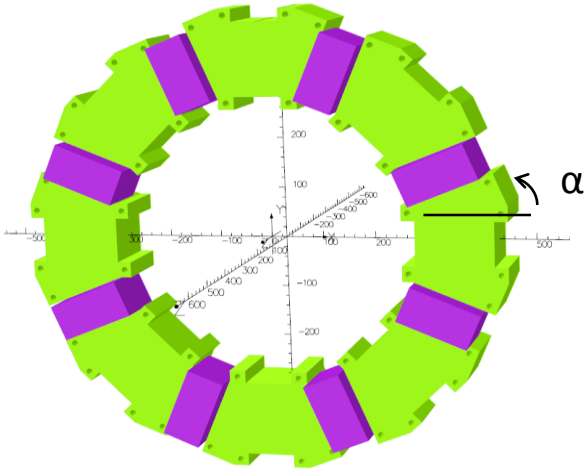
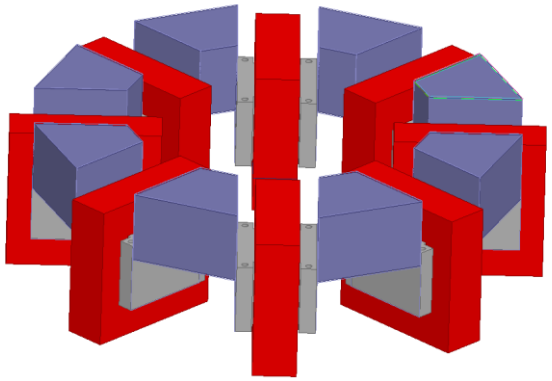
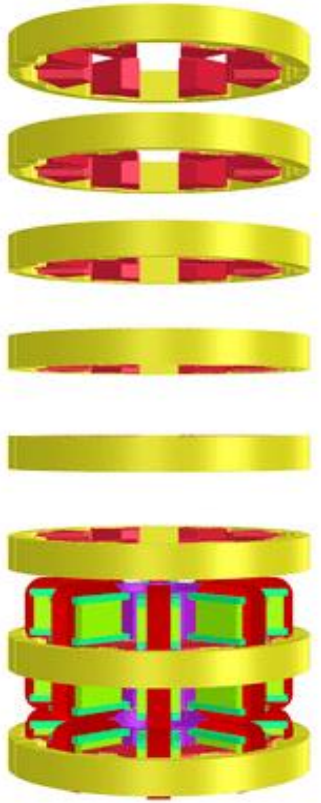
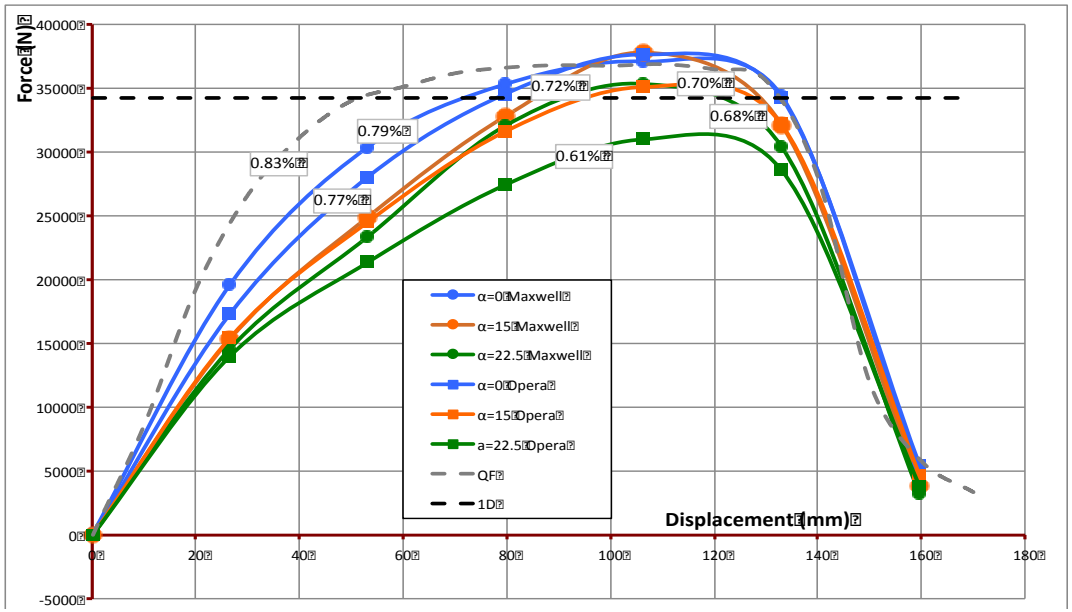
# Magnetic Calculations for the Sea Titan Azimuthal SRM








Analitycal and FEM (Opera & Maxwell) models have been used to calculate and optimise the Switched Reluctance Machine.

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# The Full Simulation Process of the Azimuthal SRM

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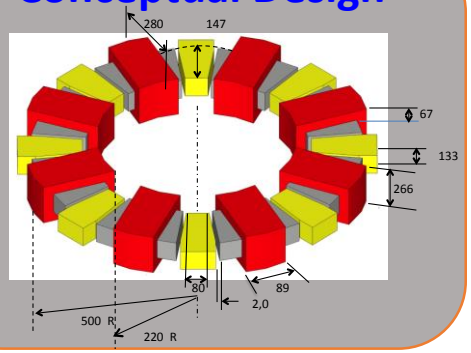
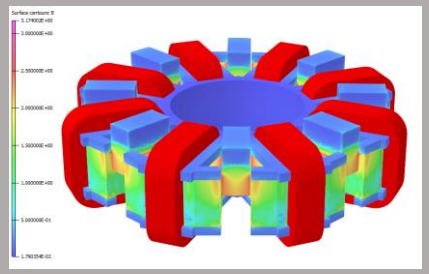
**Conceptual Design & FEM** → **Flux & Force Tables** → **Matlab-Simulink Model**

## Conceptual Design



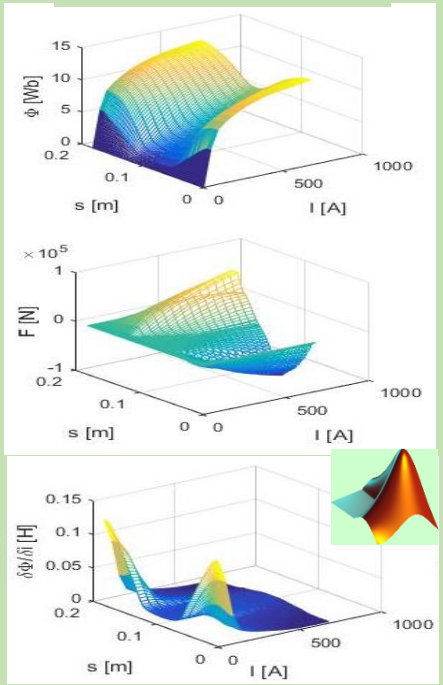

&

## FEM Modelling

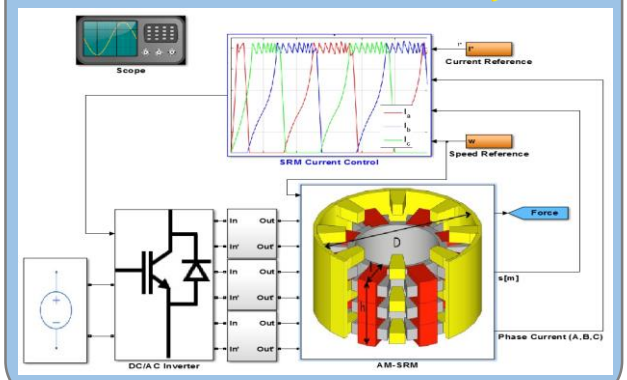


Opera Simulation Software COBHAM | ANSYS

## Postprocessing




## SRM Model




From the last model, waveforms of the electrical magnitudes can be calculated to allow designing the Power Converter and evaluate the losses.

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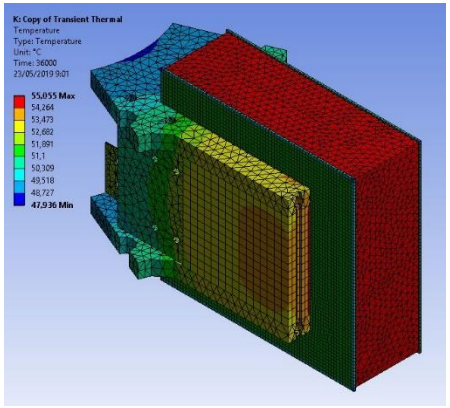
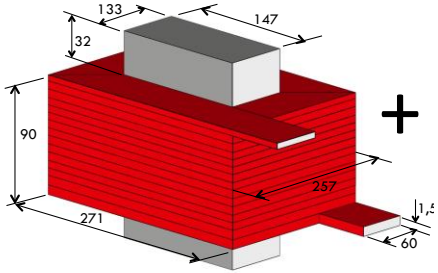
# Additional Calculations for the Azimuthal SRM

THERMAL CALCULATIONS

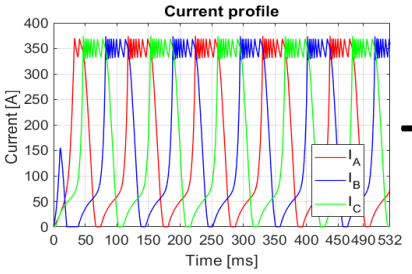
MECHANICAL CALCULATIONS



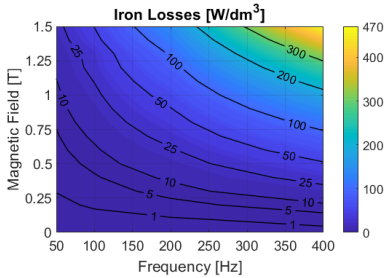

Joule Losses DC

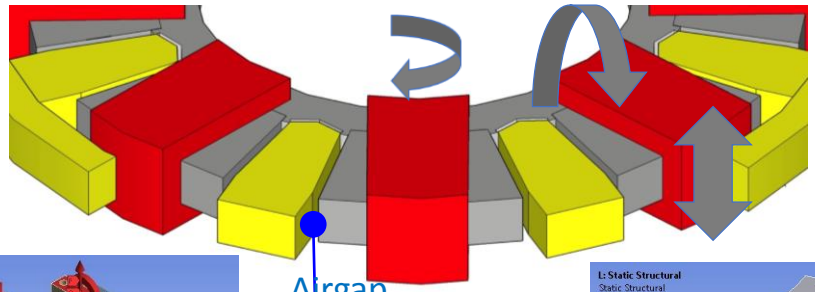



Losses AC

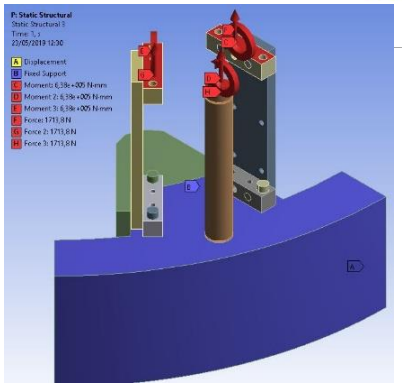



Iron Losses

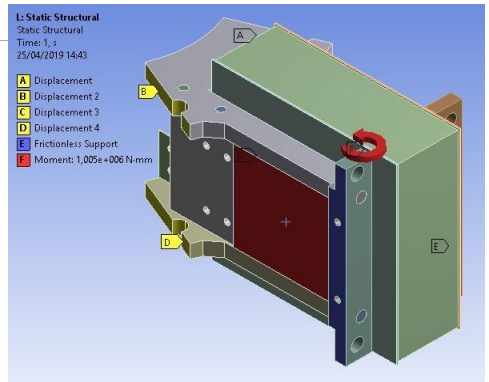


Airgap missaligmnet




Passive Side Stresses




Active Side Stresses

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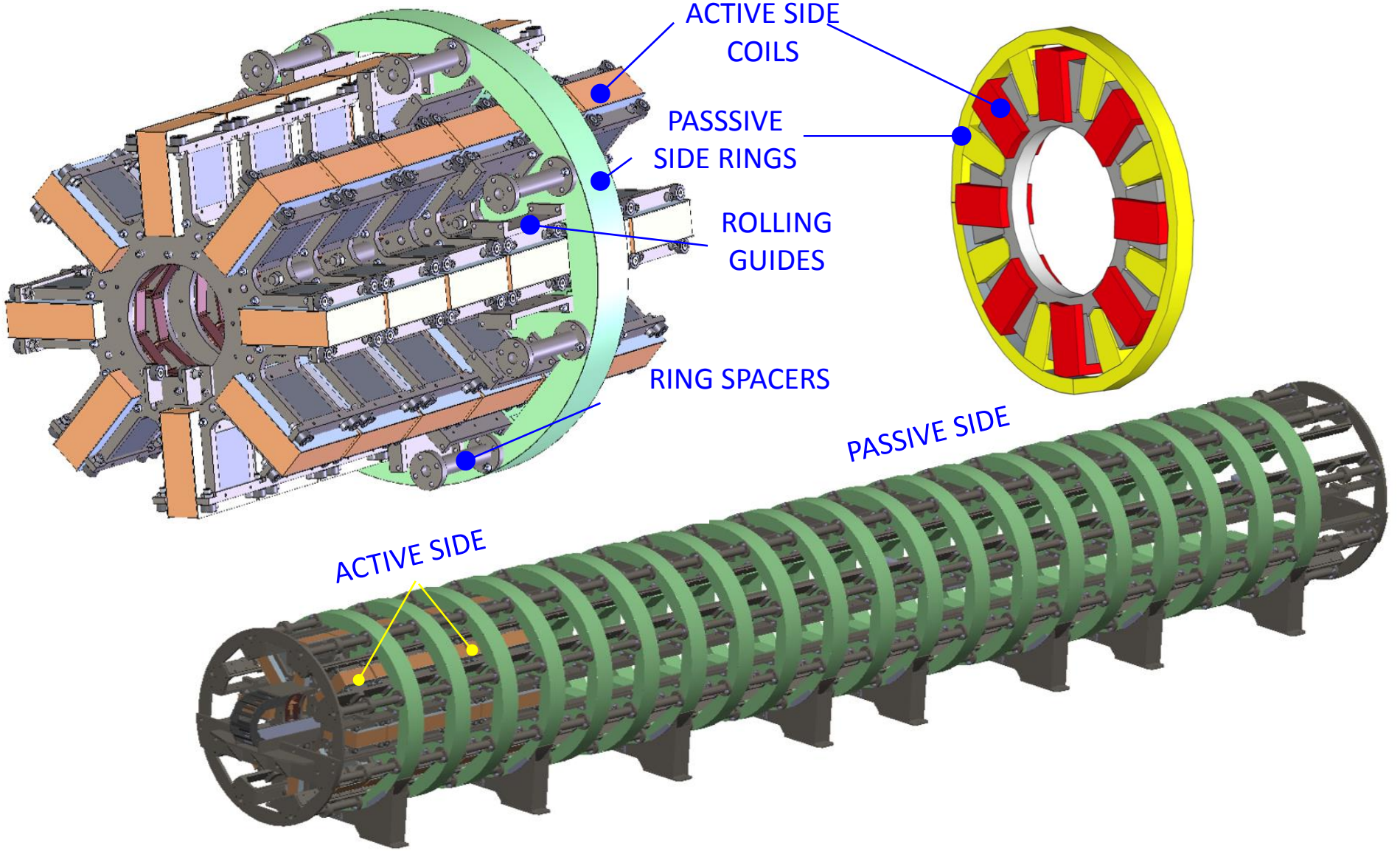
# Global Design of the Azimuthal SRM

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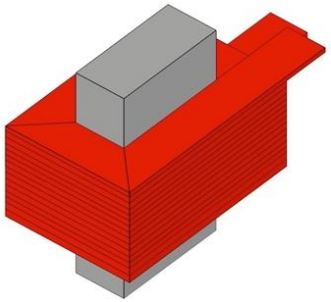
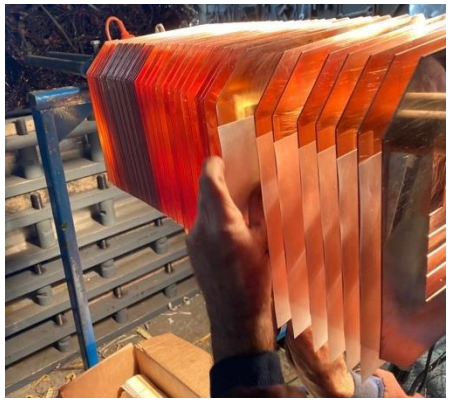
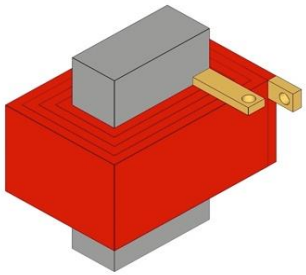
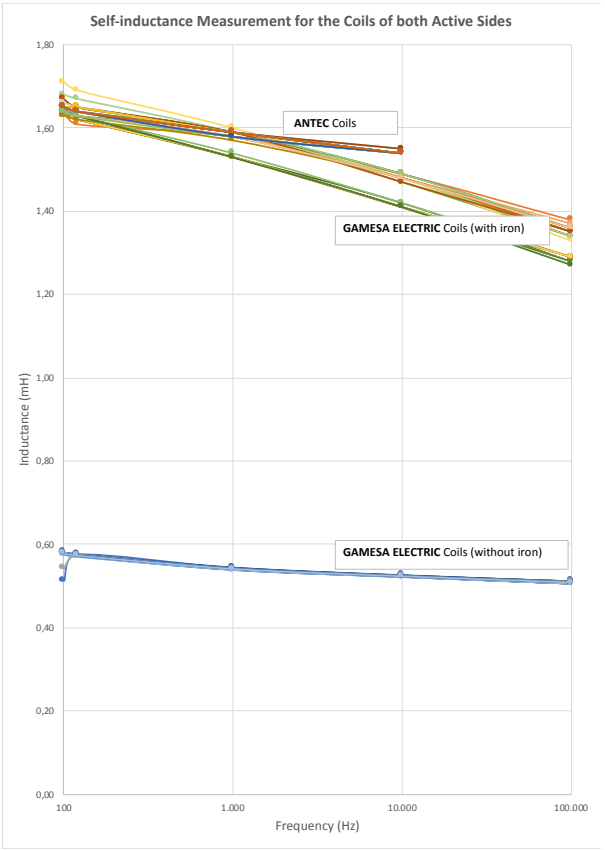
# Two Technologies for the Active Side Coils










Each of the two Active Sides are based on two different type of coils: One is based on copper laminations which are cut and welded to conform a winding. The other consists of winding a copper tape with the corresponding insulation around a mandrel

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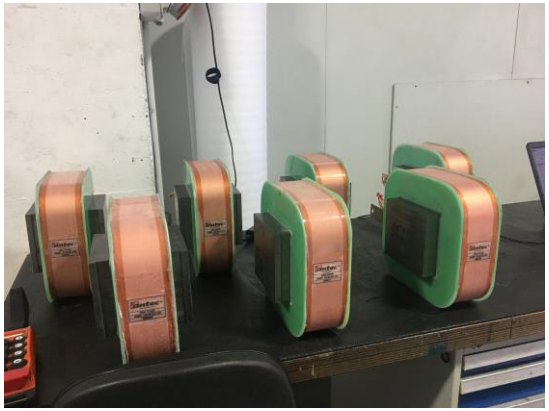
# Assembly of the Active Sides




Once the two types of coils were fabricated and accepted, they were assembled to constitute each corresponding Active Side

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# Full Assembly of the Machine & First Runs

The Actives are inserted inside the Passive Side moving along rolling guides. They can be configurated to act as Motor/Motor, Motor/Generator or Generator/Generator

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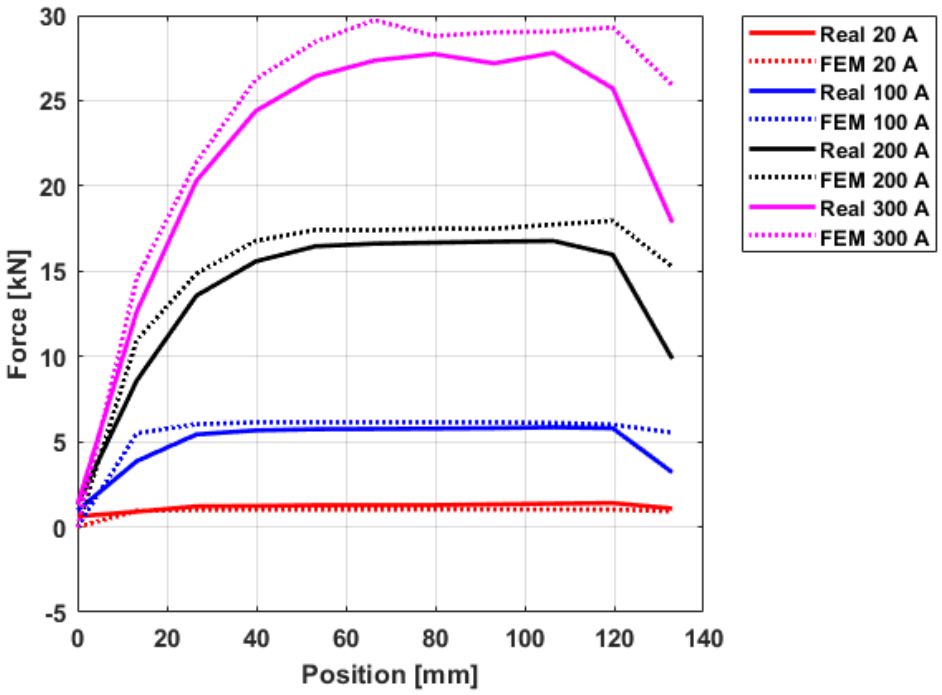
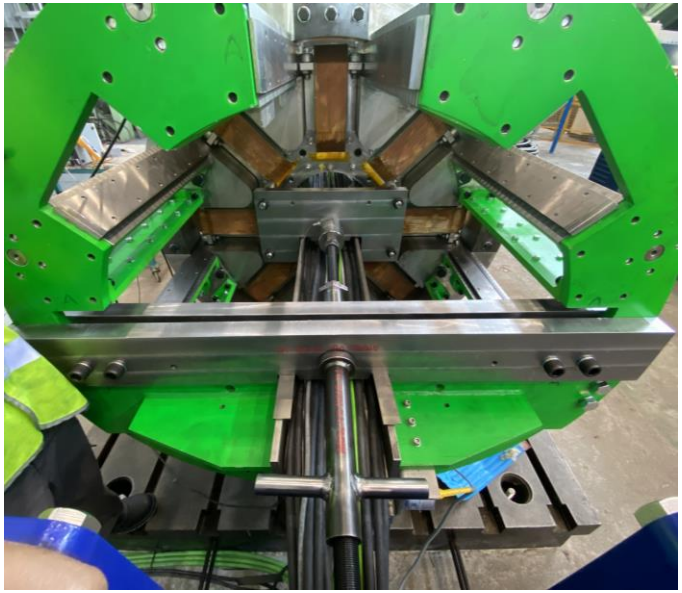
# Static Testing of the Azimuthal SRM



Static measurements of the pulling force have been carried out at the Factory. Coils are energized producing a force against the Passive Side. The movement is blocked and the force measured using a strain gage.

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# The development of WP6 : The Superconducting PTO Concept

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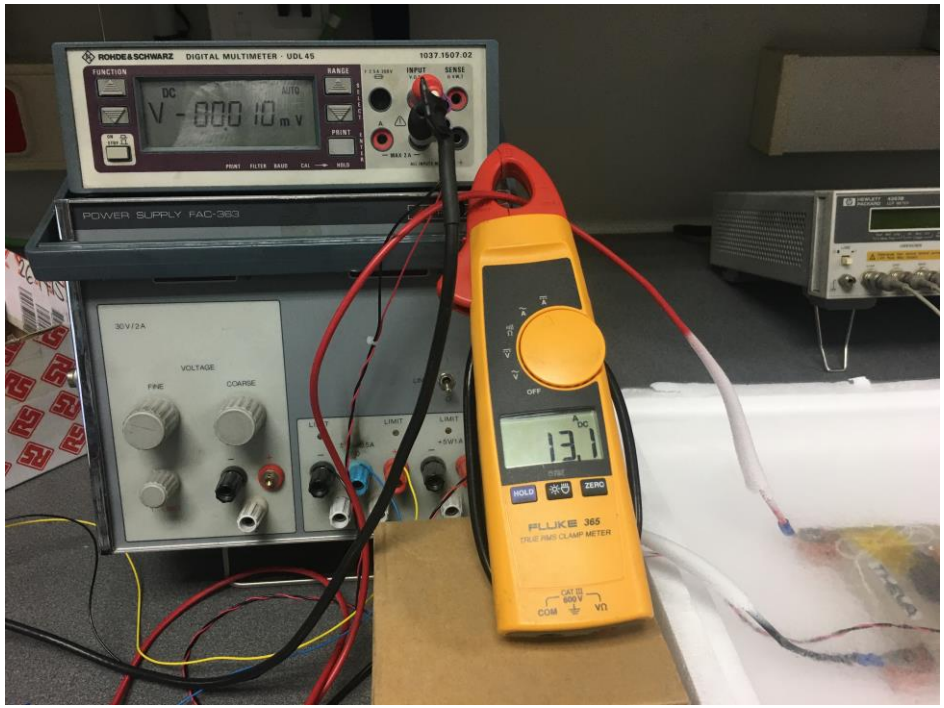
# Why using a Superconducting PTO?

In slide 13, it was demonstrated that a big force and a high efficiency were required to harvest the maximum amount of energy along all the wave period range.




In principle, the force produced by an electrical machine is proportional to the current, while the losses are proportional to the second power of the current. As the force (current) is increased, the machine becomes less efficient. The only solution for that is **using a Superconducting Machine.**

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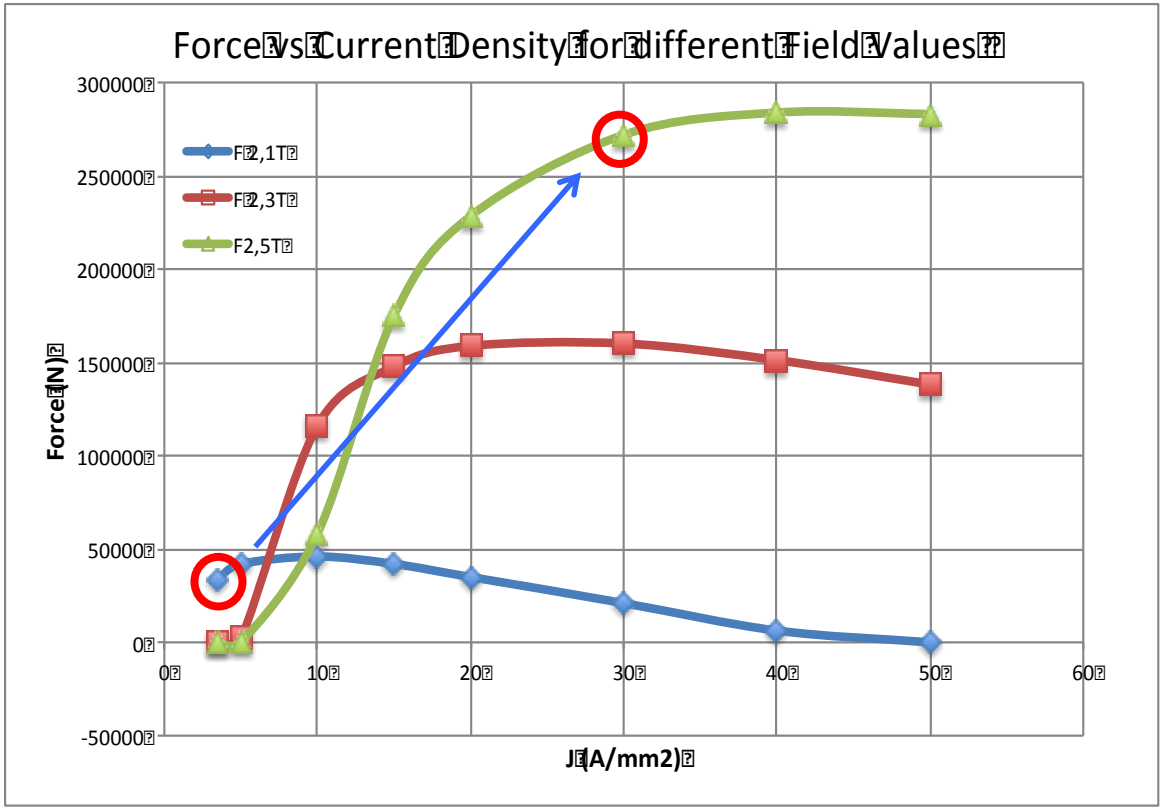
# The Superconducting version of the ASRM




The benefit one gains by using a superferric electrical machine (Iron & Superconducting windings) is that you can increase tremendously the current density and consequently the force. The price one must pay for it is that it must work at very low temperatures (>10 K) with all the associated complexity.

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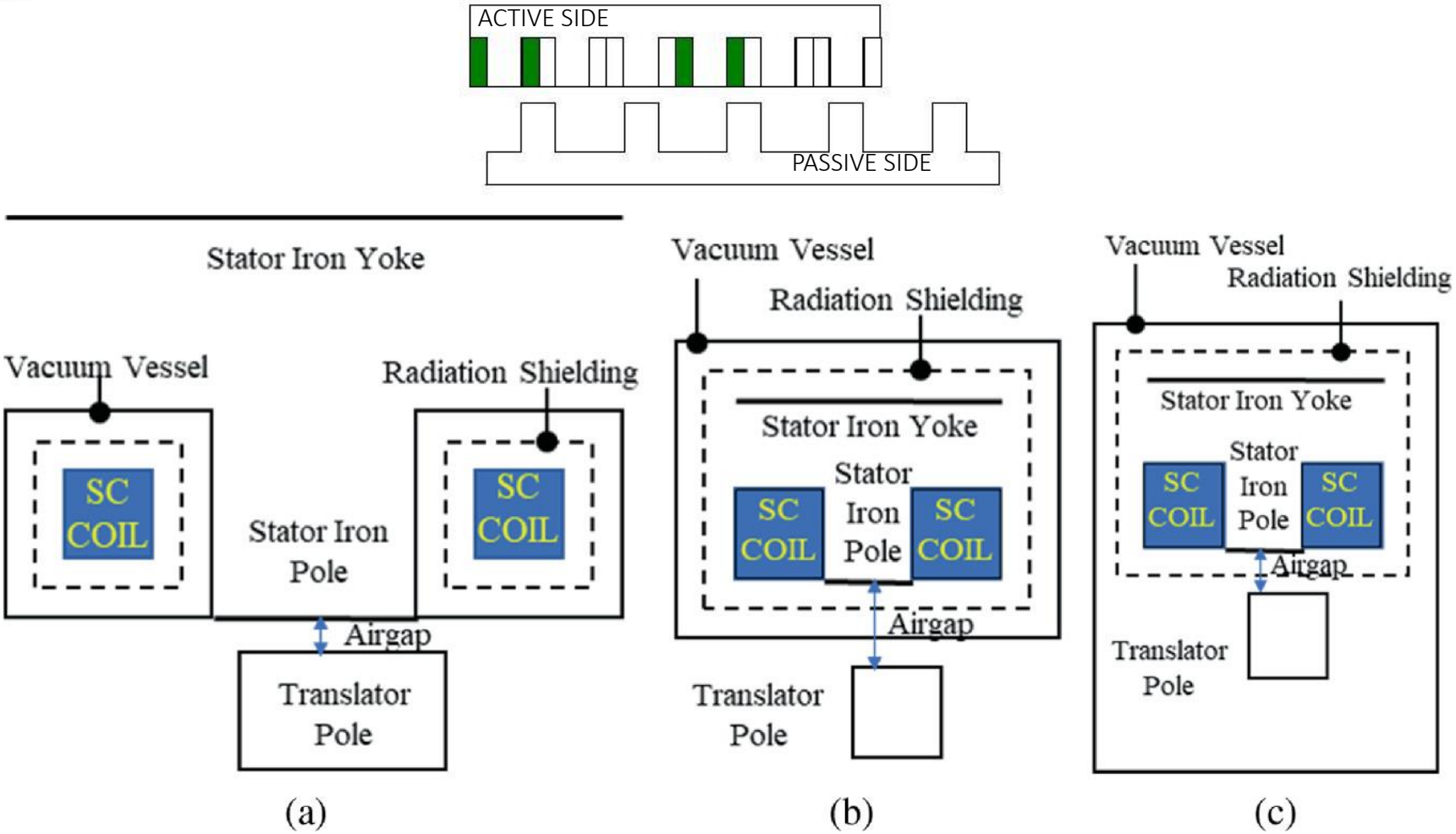
# The Superconducting version of the ASRM




There are, basically, three configurations for a Superferric Switched Reluctance Machine: a) Warm Iron for both Sides b) Warm Iron for the Translator and Cold Iron for the Stator c) Cold Iron for Translator and Stator

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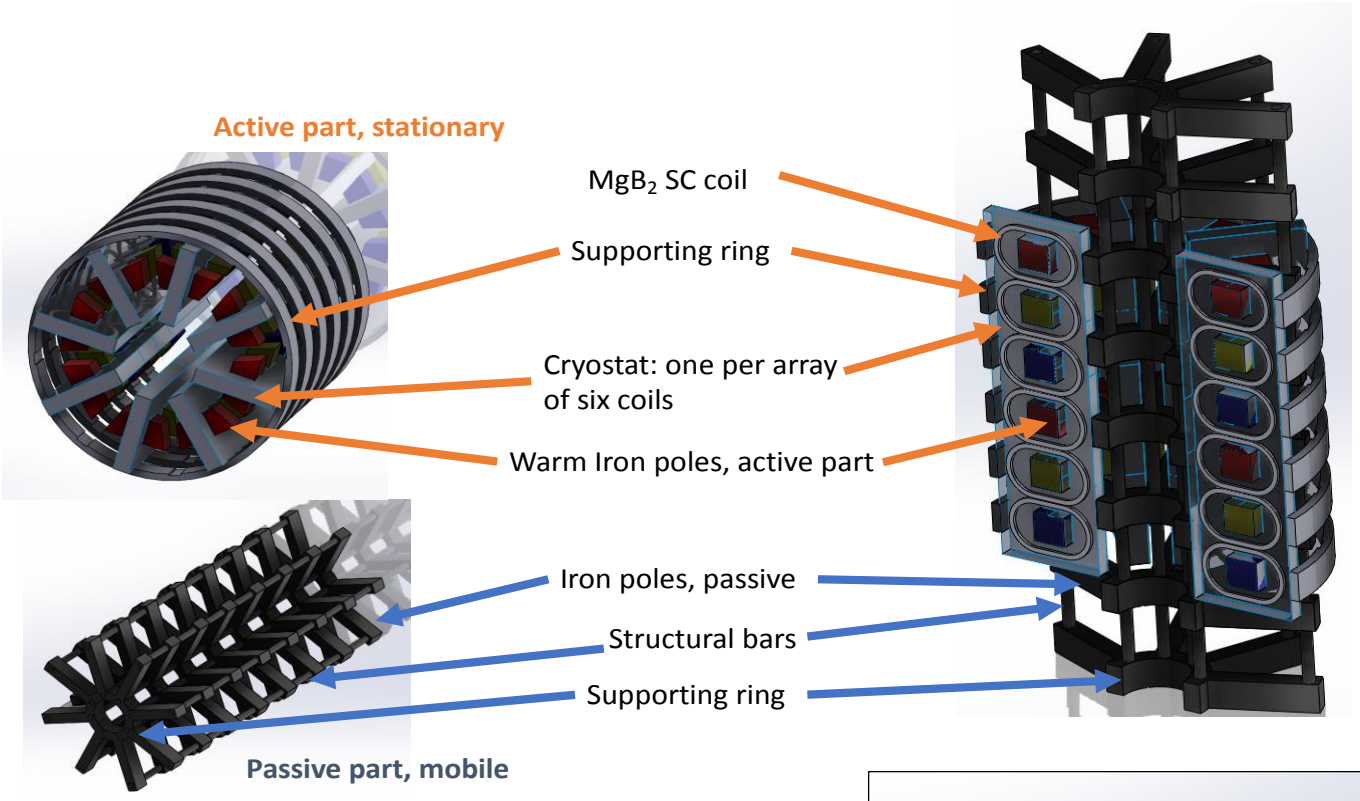
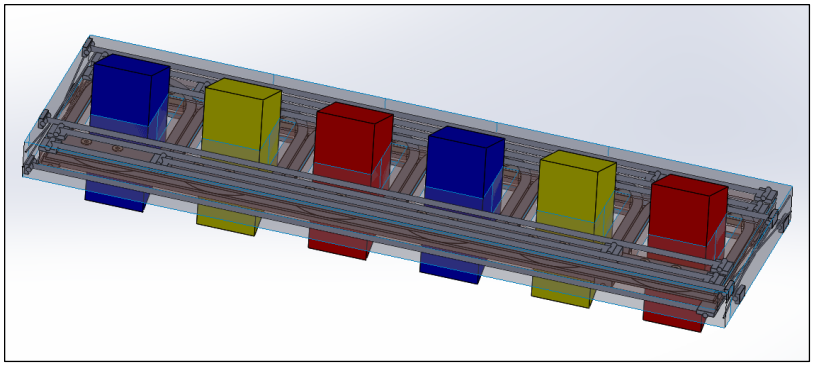
# The Superconducting version of the ASRM




According to the first configuration presented in previous slide, a concept design translation of the resistive ASRM version into a superconducting one was realized. Its complexity makes it unfeasible.



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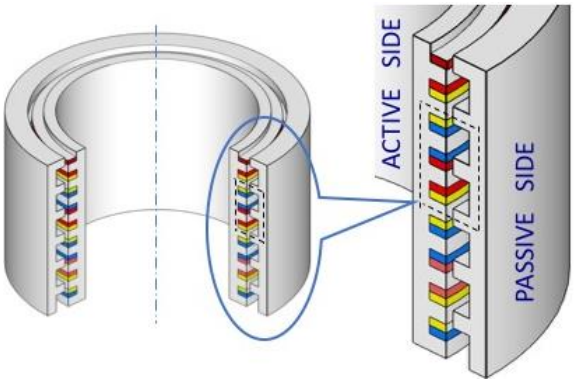
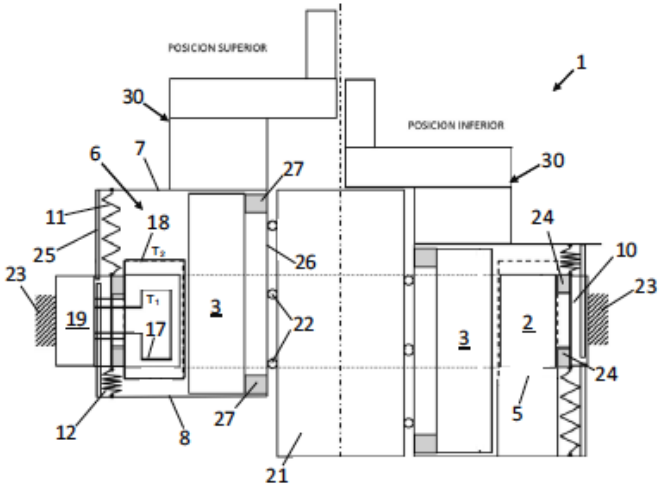
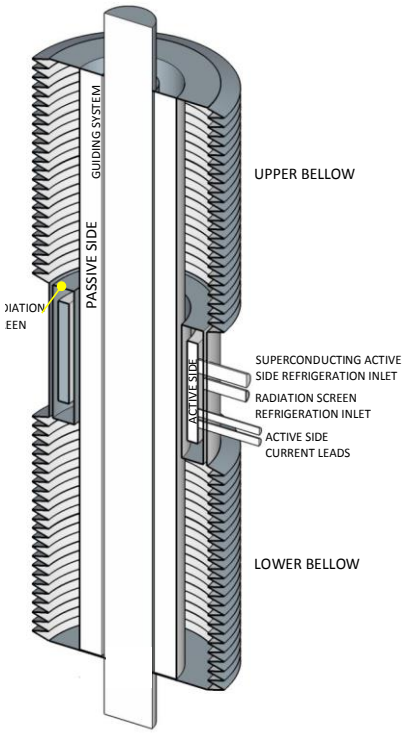
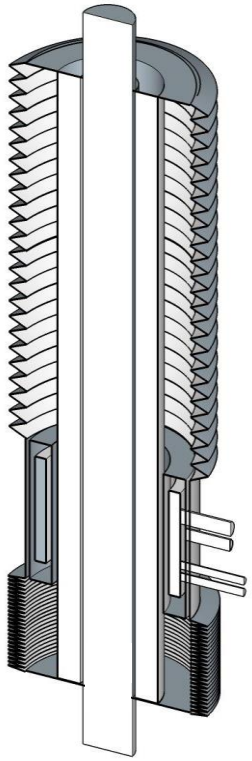
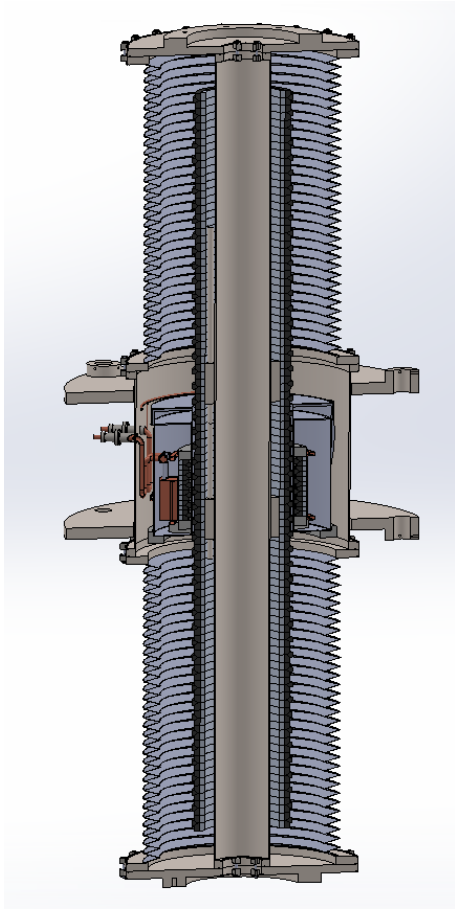
# Better a Superconducting Cylindrical SRM





Based on a modified version of the second configuration and a cylindrical topology of the SRM, a new extremely compact concept was designed, analysed and patented. It is based on the idea of a deformable cryostat.

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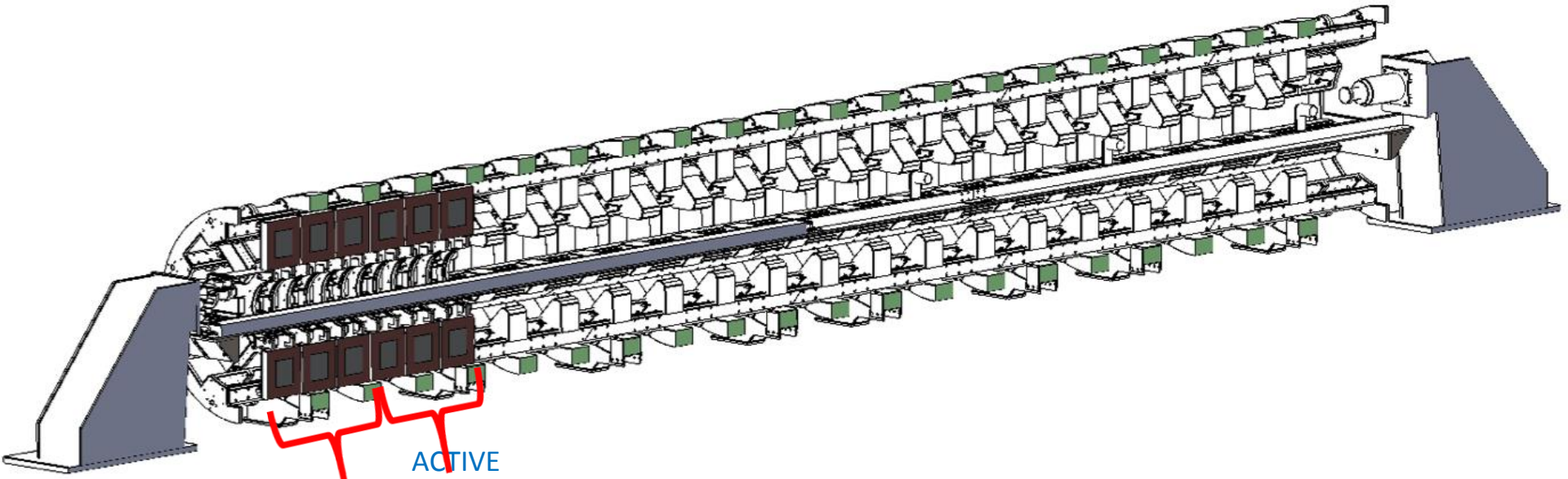
# Dynamic Testing of the Acimuthal SRM




The PTO will be dynamically tested using a Back to Back Configuration in which one Side acts as a Motor and the other one as a Generator.

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# Concluding Remarks

- Wave Energy represents an alternative source of clean energy with better predictability and regularity than other green energies
- According to the Ocean Energy Strategic Roadmap, 100 GW of Ocean Energy should be deployed in Europe by 2050, producing around 350 TWh, meeting up to 10% of Europe´s demand
- As for the rest of Renewables, one main issue of this type of energy is its high Levelized Cost of Energy (LCoE). The goal for the coming years is to reduce it to 20c€/kWh
- Wave energy is not only conceived for Power System Generation but also for small scale applications like autonomous marine vehicles, instrumented buoys, power generation for islands, etc.
- There are different types of competing technologies for WECs . The Point Absorber type, seems to be the most extended one. In any case, reliability and survivability are crucial for the success of this type of energy
- The PTO is a key element of the WEC. Powerful and efficient PTOs are required to maximize their harvesting performances

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