# GDR houlomoteur
## SBM S3

## 21 October 2016

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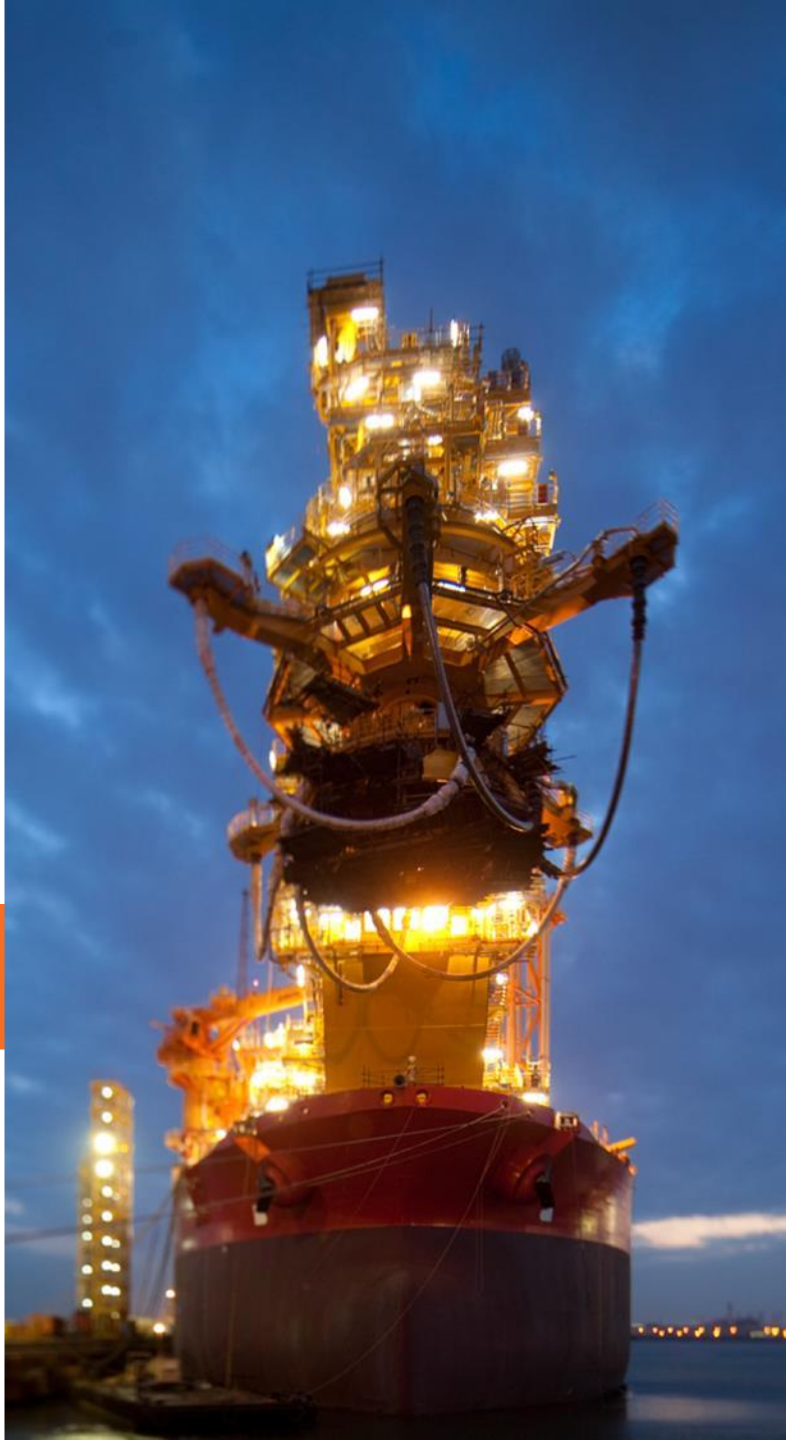
**NANTES**





# Agenda

1. General introduction to SBM Offshore
2. State-of-the-art of Wave Energy Converters (WECs)
3. SBM S3 WEC: a change in paradigm
4. Introduction to Electroactive Polymers
5. Application of EAP to S3 WEC
6. Hydro-elasto-electric model: W2W
7. Ongoing development activities

- Q&A

# Disclaimer

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Should one or more of these risks or uncertainties materialize, or should underlying assumptions prove incorrect, actual results may vary materially from those described in this presentation as anticipated, believed, or expected. SBM Offshore NV does not intend, and does not assume any obligation, to update any industry information or forward-looking statements set forth in this presentation to reflect subsequent events or circumstances.

# SBM Offshore Worldwide

## SBM offices around the World

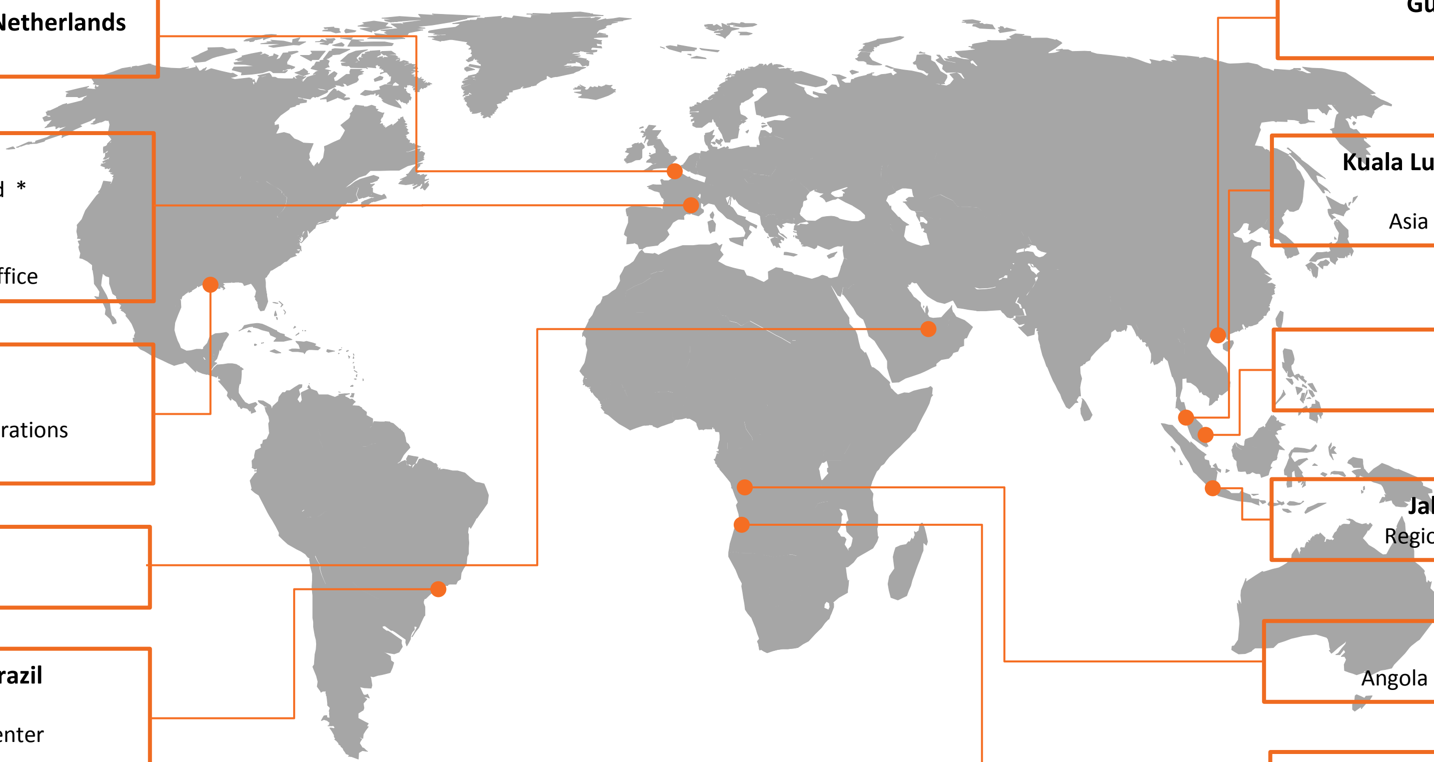
**Schiedam – the Netherlands**
Regional Center

**Monaco**
Management Board *
Group Functions *
Regional Center
Operations Head Office

**Houston - USA**
Regional Center
North-America Operations Center

**Dubai - UAE**
Yard Site Team

**Rio de Janeiro - Brazil**
Regional Center
Brazil Operations Center
Construction Yard



**Guangzhou - China**
Yard Site Team

**Kuala Lumpur - Malaysia**
Regional Center
Asia Operations Center

**Singapore**
Yard Site Team

**Jakarta - Indonesia**
Regional Support Office

**Luanda - Angola**
Angola Operations Center

**Porto Amboim - Angola**
Construction Yard

*: SBM Head Office to be based in Amsterdam (Netherlands) as of Q3-2015

Listed on the Amsterdam Stock Exchange
Over **7,500** people worldwide

Not shown: 10 shore bases

# SBM Offshore – Unparalleled expertise of floating systems

| TECHNOLOGY | PROJECT EXECUTION | OPERATIONS | FINANCE & LEASE |
|---|---|---|---|

**Focus on top-end segment**
- FPSOs
- Turret Moorings
- Turnkey Sale or Lease & Operate

**Enlarging the envelope**
- Floating LNG (FLNG)
- Semisubmersible & TLP production units
- Marine Renewables (MC, since 2006)

Leader in Floaters & Mooring systems

Over 500 offloading terminal supplied

Over 50 mooring systems supplied

> 250 years cumulated experience

19 leased units operated by SBM


$ 3.4B turnover in 2014

**SBM Vision**

To be the trusted partner of choice in the development of complete offshore floating solutions for the world's energy companies

# SBM Offshore – A History of Innovation


| 1862 | 1905 | 1959 | 1960 | 1969 | 1972 | 1973 | 1974 | 1977 | 1978 |
|---|---|---|---|---|---|---|---|---|---|
| A.F. Smulders Machine Factory | Start of Gusto Shipyard | CALM Buoy* | Drilling Jack-up* | SBM Inc. established in Switzerland | DP Drillship* | SBS Mooring System* | Semi-submersible pipelay vessel* | SALS Mooring System* | Start of Gusto Engineering |


| 1981 | 1985 | 1985 | 1986 | 1988 | 1990 | 1993 | 1996 | 1999 | 2001 |
|---|---|---|---|---|---|---|---|---|---|
| Leased FPSO* | Jacket Soft Yoke* | External Turret* | Disconnectable Turret* | MSC re-joined the Group | Acquisition of Imodco | North Sea Internal Turret* | Turnkey North Sea FPSO* | Deepwater CALM Buoy* | Acquistion of Atlantia |

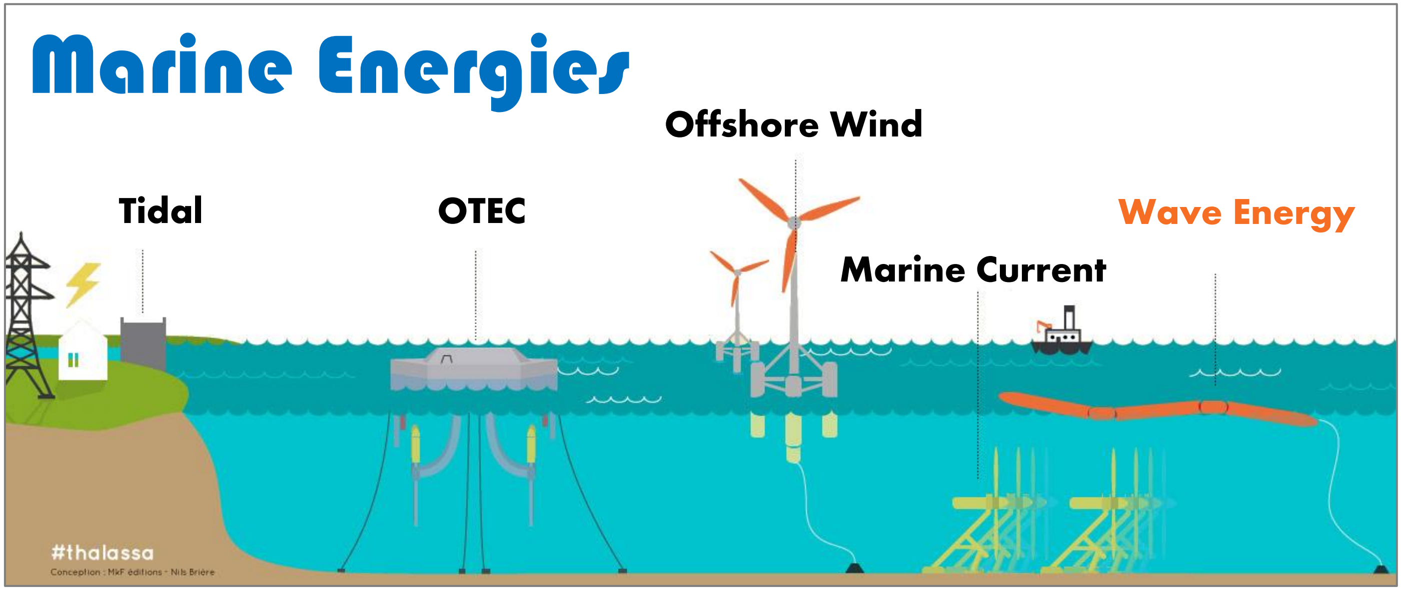

| 2002 | 2002 | 2003 | 2005 | 2005 | 2006 | 2006 | 2006 | 2007 | 2007 |
|---|---|---|---|---|---|---|---|---|---|
| Delivery of the first generic FPSO | Acquisition of Ocean Design Associates Inc. | Delivery of the largest Seastar® TLP | Company name change to SBM Offshore N.V. | New Build LPG FPSO* | Leased MOPU* | Deepest Semi-Submerisible in the GoM ■ | Offshore Offloading Line : Trelline™ Installed* | GAP™ mid water Fluid Transfer System* | Largest Internal Turret with 75 risers ■ |


| 2008 | 2009 | 2010 | 2011 | 2012 | 2012 | 2013 | 2013 | 2014 |
|---|---|---|---|---|---|---|---|---|
| First DeepDraft Semi® with PHA contract | First turret-moored FPSO using steel catenary risers | First FPSO with over 65% Brazilian content* | COOL™ LNG Transfer System* | Company rebranding | HV-AC Electric Swivel rated at 65KV and 150 MW* | VHP Swivel rated at over 800 bar* | Deepest FPSO ■ | |

■ World Record   * Industry First

# Renewable Energy Market

- Renewable energy is currently moving offshore
  - Offshore wind market in 2015 > $15Bn
  - New energy sources available:




Source: France 3 website

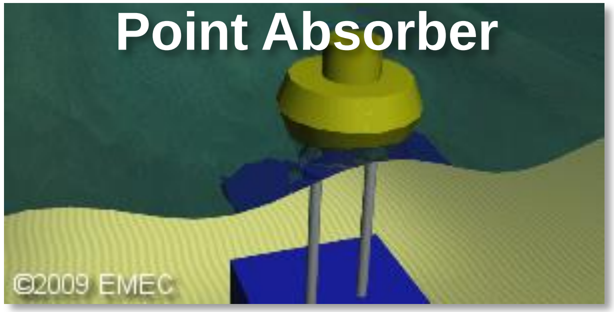
- This creates opportunities for offshore contractors as these projects require strong offshore experience

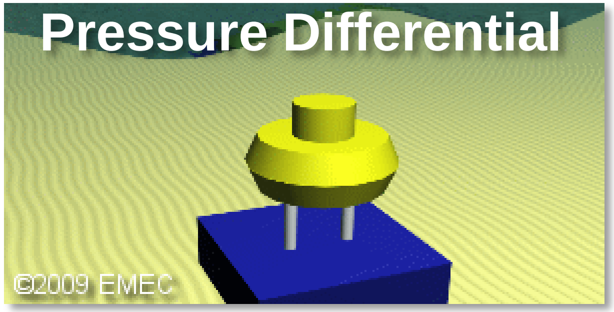
# Wave Energy

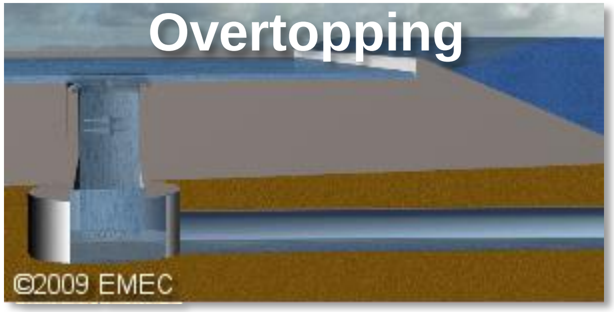
## State of the art and Generation 1 devices

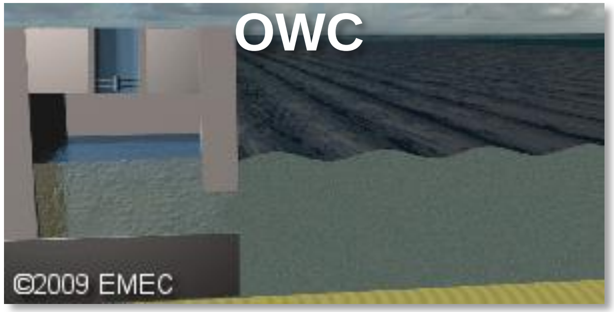
# Wave Energy – Generation 1 devices





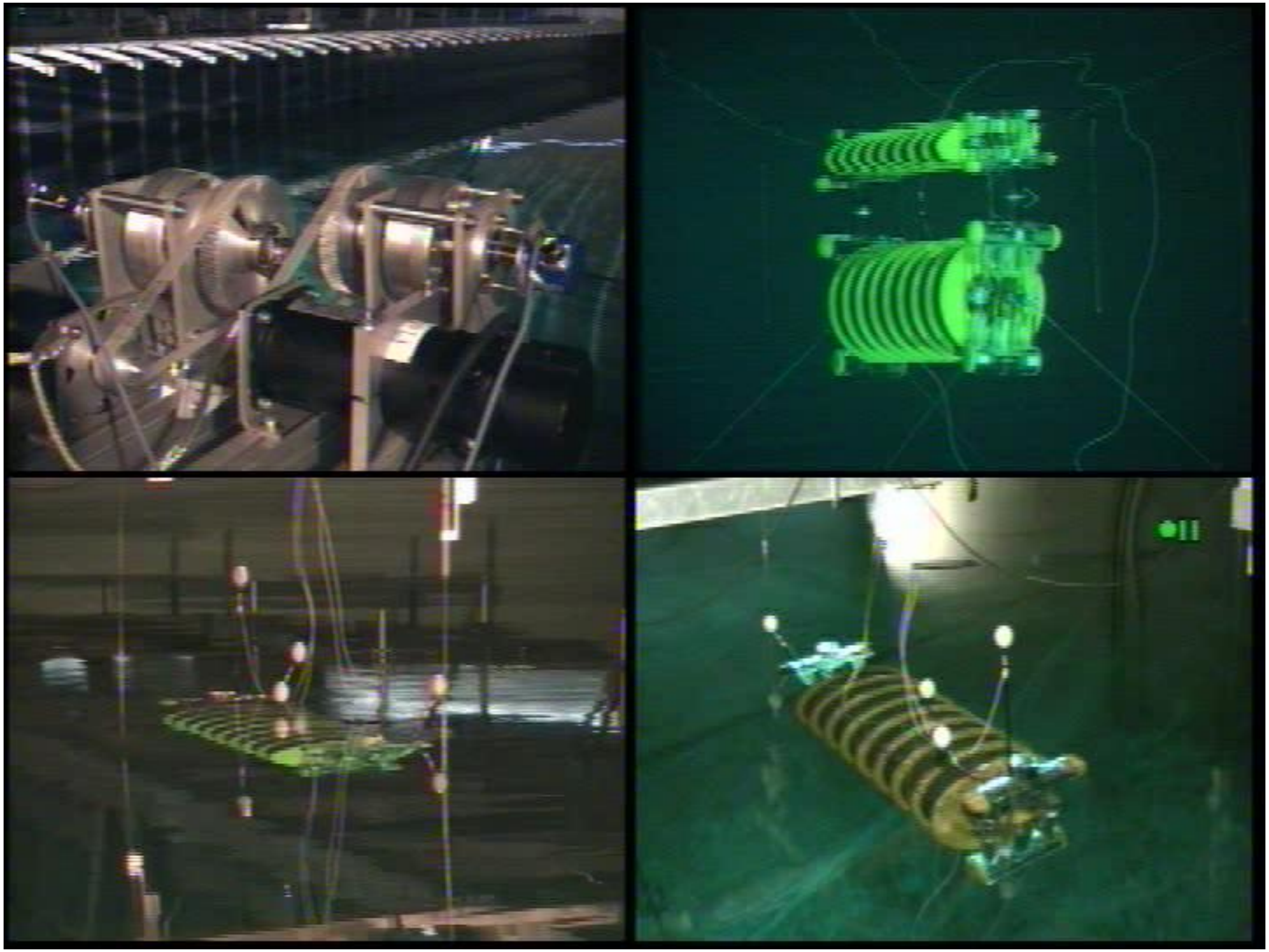




**SBM has been involved in Wave Energy since 2006**

**Capitalizing on its offshore expertise**

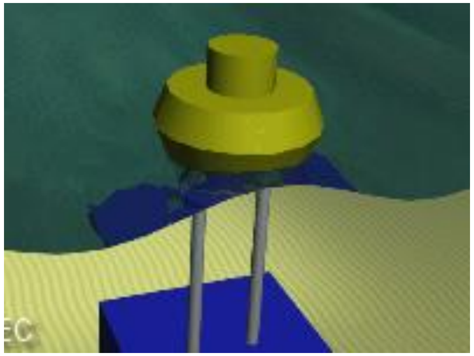
**CALM = point absorber**

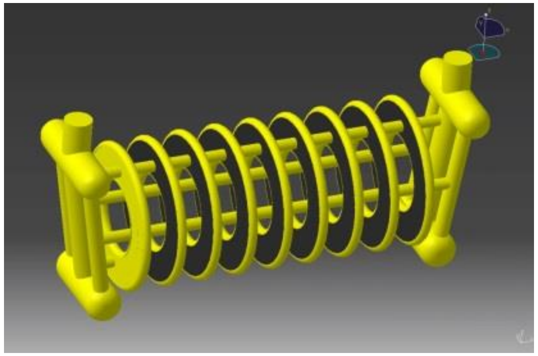
# Wave Energy – Generation 1 devices
## SBM first WEC: Diodon

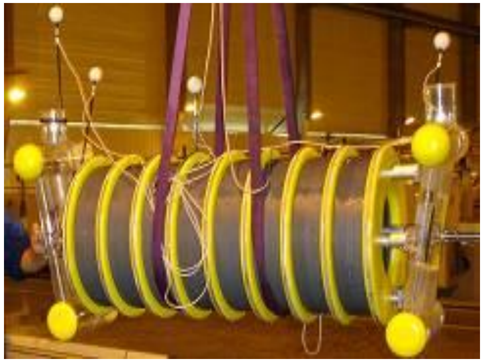


# Wave Energy – Generation 1 devices

| 2006 | 2007 | 2008 |
| --- | --- | --- |







SBM capitalizes on its know-how in floater and mooring EPCI

CALM = point absorber

DIODON developed by SBM

More efficient technology but still conventional (rigid) system

Wave tank test (operational / survival)

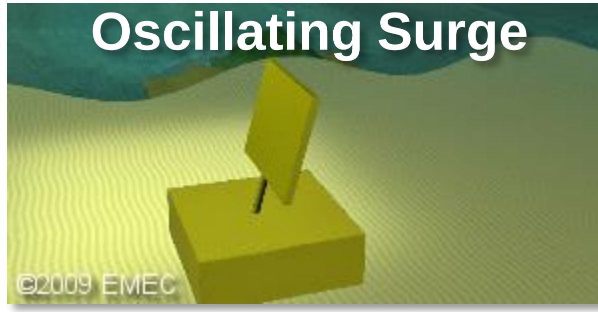
**DIODON Abandoned**

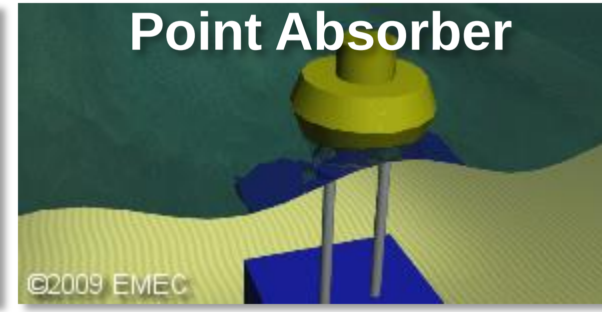
**Rigid systems are inherently limited**

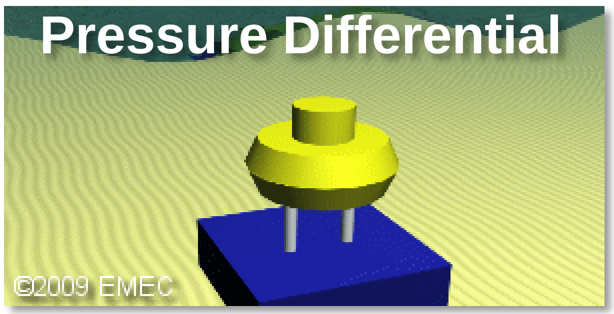
- ✖ High structural costs
- ✖ Load path concentration on Power Take-Off elements
- ✖ Mechanical Power Take-Off ➔ costly O&M
- ✖ Optimized for 1 wave period

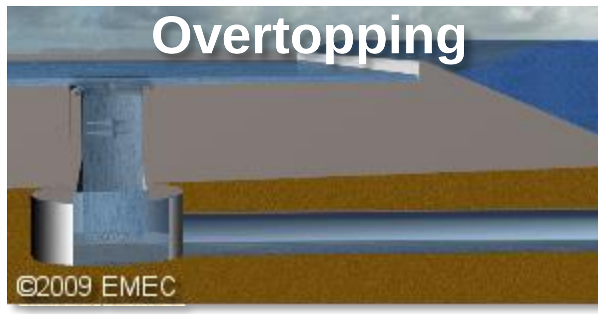
**TRUE FOR ALL CONVENTIONAL SYSTEMS**

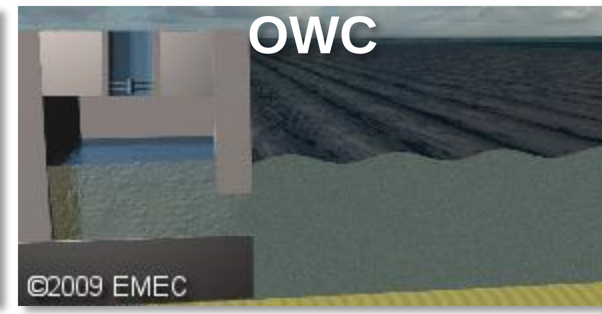
# Wave Energy – Generation 1 devices


**Rigid systems are inherently limited**

- ✖ High structural costs
- ✖ Load path concentration on Power Take-Off elements
- ✖ Mechanical Power Take-Off ➔ costly O&M
- ✖ Optimized for 1 wave period

**TRUE FOR ALL CONVENTIONAL SYSTEMS**

# SBM S3 WEC

## A Paradigm shift

# SBM S3 WEC – A Paradigm shift

**Conventional (rigid) systems are inherently limited**

- ✖ High structural costs
- ✖ Energy / stress concentration on Power Take-Off elements
- ✖ Mechanical Power Take-Off ➔ costly O&M
- ✖ Narrow & fixed absorption bandwidth

**Breakthrough technology required**

- ❑ Merged power conversion function and hull structure
- ❑ No complex mechanical parts
- ❑ No routine maintenance
- ❑ Flexible and silent
- ❑ Large absorption bandwidth

# SBM S3 WEC – A Paradigm shift

**SBM S3 CONCEPT:**

**Fully flexible tube filled with water, closed at both ends**

**➔ Multimodal response (standing waves)**

**Energy conversion system = Electro-Active Polymers (EAP)**

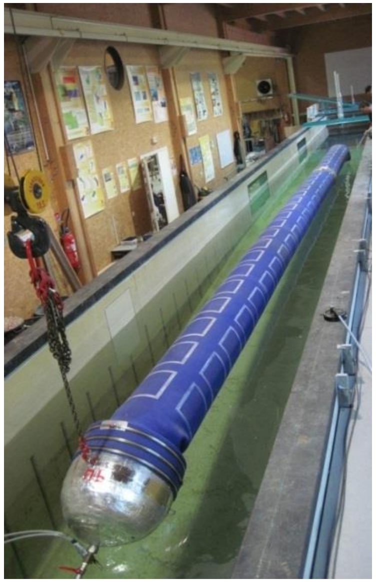
**EAP-based PTO embedded in the structure**

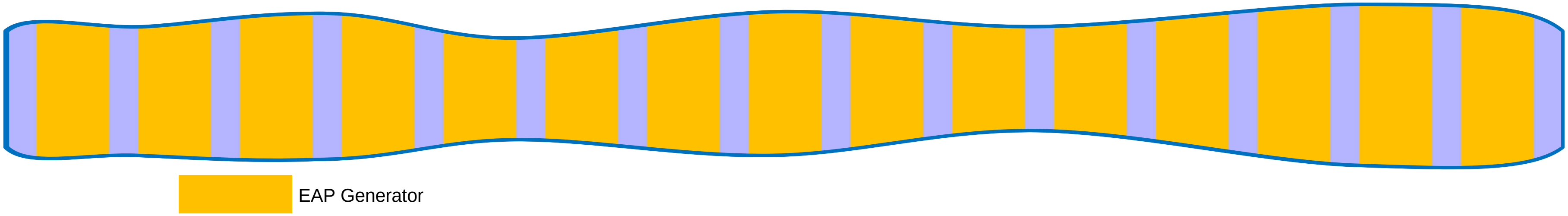
**Energy converted DIRECTLY from waves to electricity**

**Distributed power generation**

**EAP = roll-to-roll process**

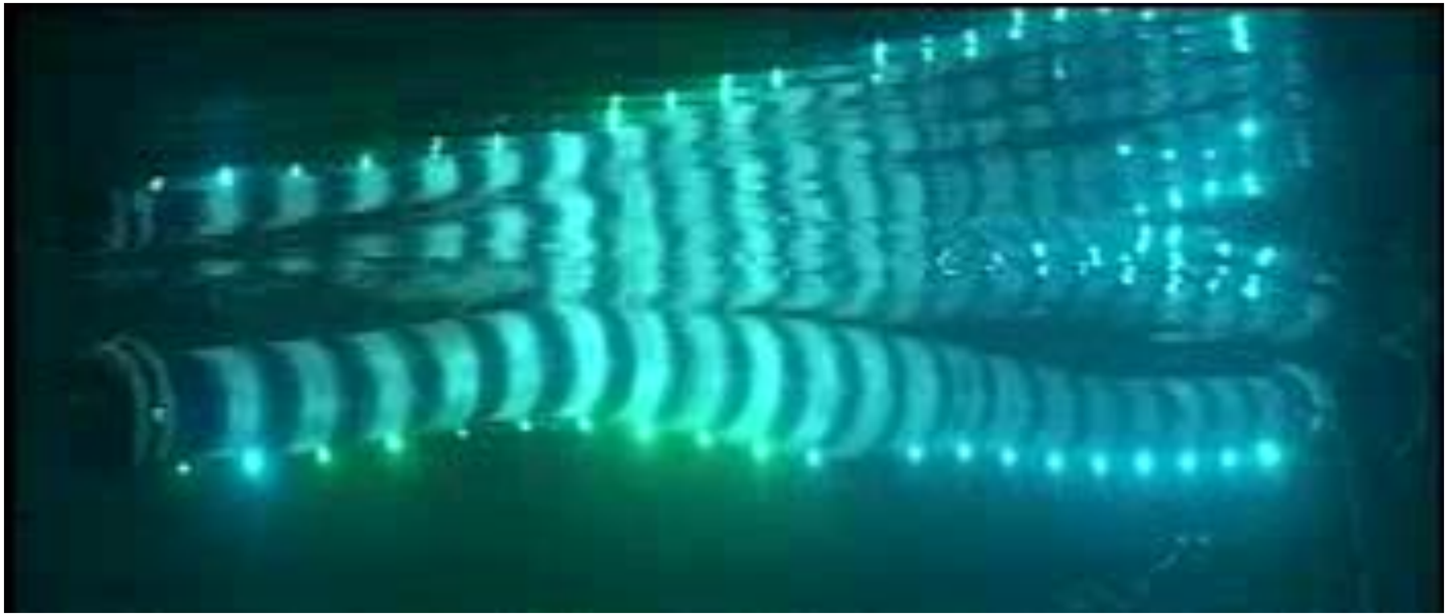
S3 test campaign, ACRI IN, 2010





# SBM S3 WEC – A Paradigm shift

- ✓ Merged power conversion function and hull structure
- ✓ No complex mechanical parts
- ✓ No routine maintenance
- ✓ Flexible and silent
- ✓ Large absorption bandwidth



S3 test campaign, ECN, 2011

# EAP

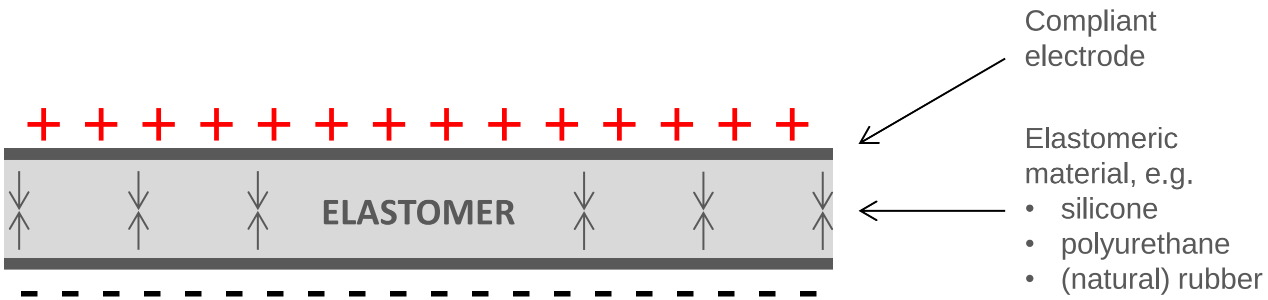
## Introduction

# What is an electroactive polymer?

- Classified as smart material
  “a designed material that significantly changes some of its properties in response to external stimuli”

- Physical basis:

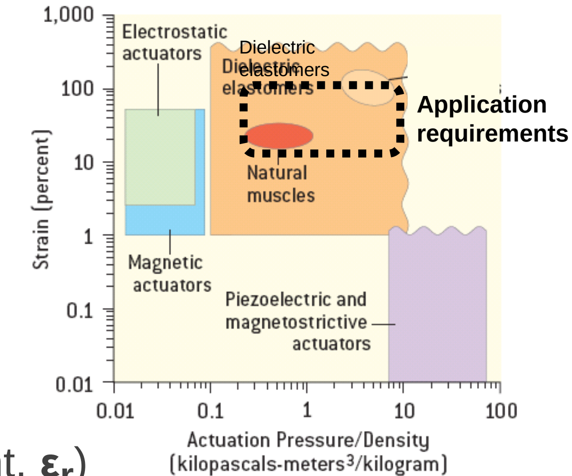
**Actuation: add charge**



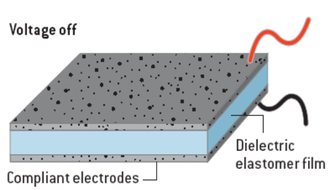

**Maxwell Pressure: electromechanical energy conversion**

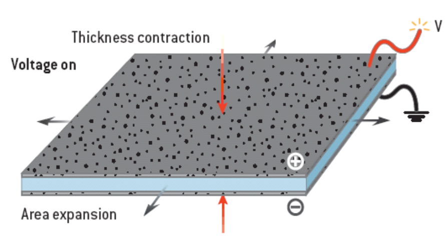
# What is an electroactive polymer?

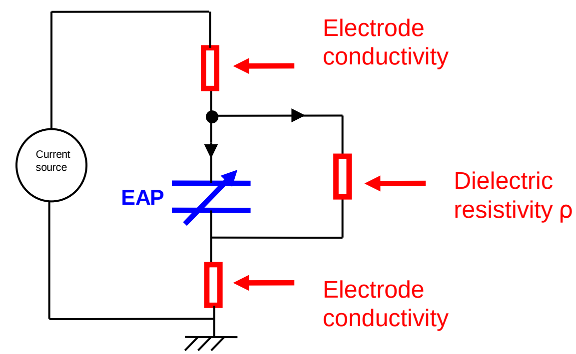
- EAP films are **electrostatic energy transducers**
  - Able to convert mechanical energy into electric energy
  - Passive materials
  - Soft and stretchable
  - High energy density




- Good EAP = good capacitor
  - Ability to handle high electric field stress (high Dielectric Breakdown Strength, **DBS**)
  - Ability to accumulate charges (high dielectric constant, $\boldsymbol{\varepsilon_r}$)
  - Ability to keep charges (high resistivity, **ρ**)
  - Ability to be deformed (**compliant** electrodes, low elastic modulus **Y**)



# ELECTROACTIVE POLYMERS
## Advantages and applications

- Main advantages:
  - Monolithic structures
  - Soft and flexible
  - Biocompatible
  - Actuation, generation, sensing: seamlessly and simultaneously

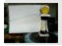
Robotics | Biomedical | Automotive

Entertainment | Drives & Controls

Artificial muscles & (bio-mimetic) robotics

StretchSense flexible sensors

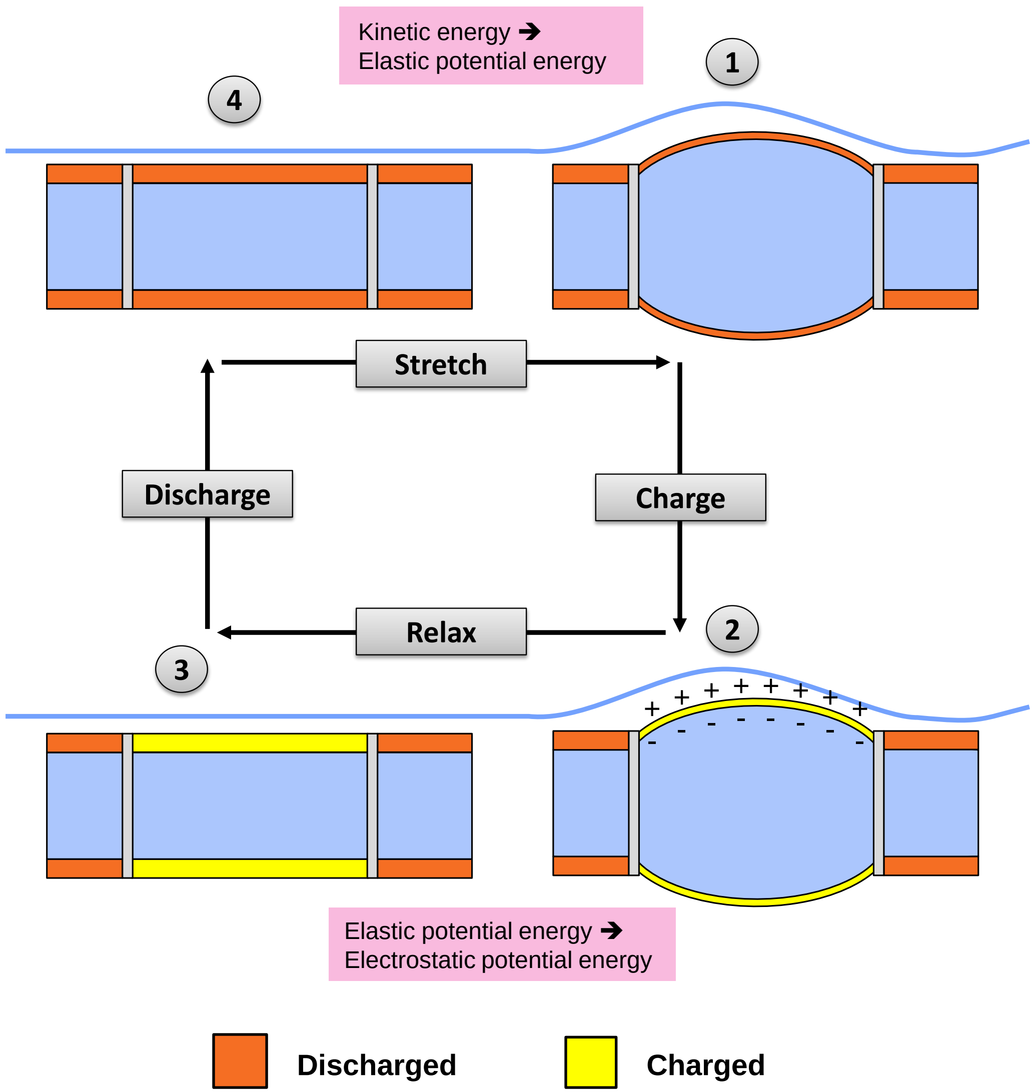
Active Vibration Damping

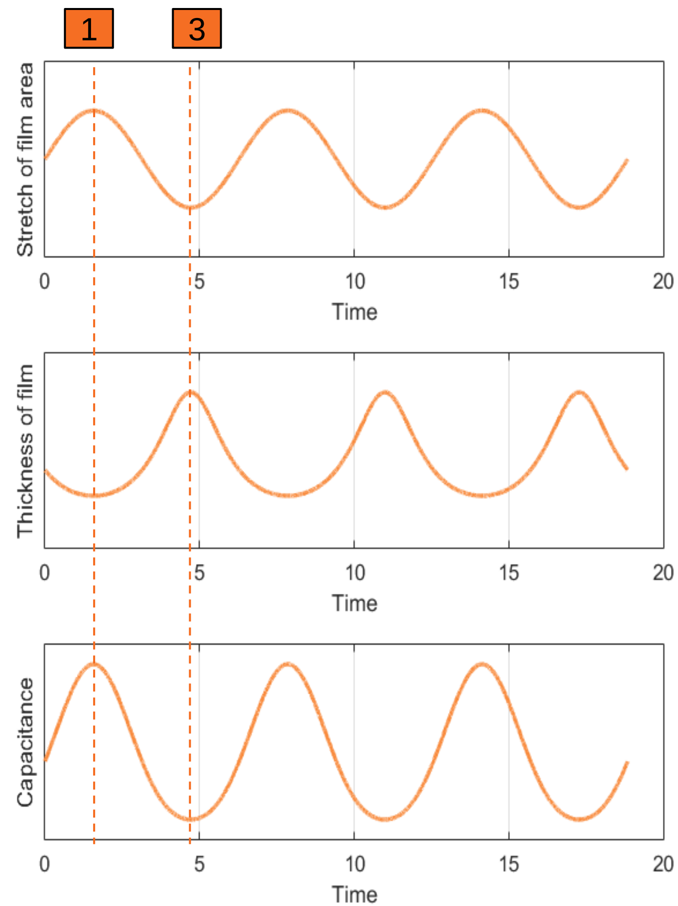


# EAP

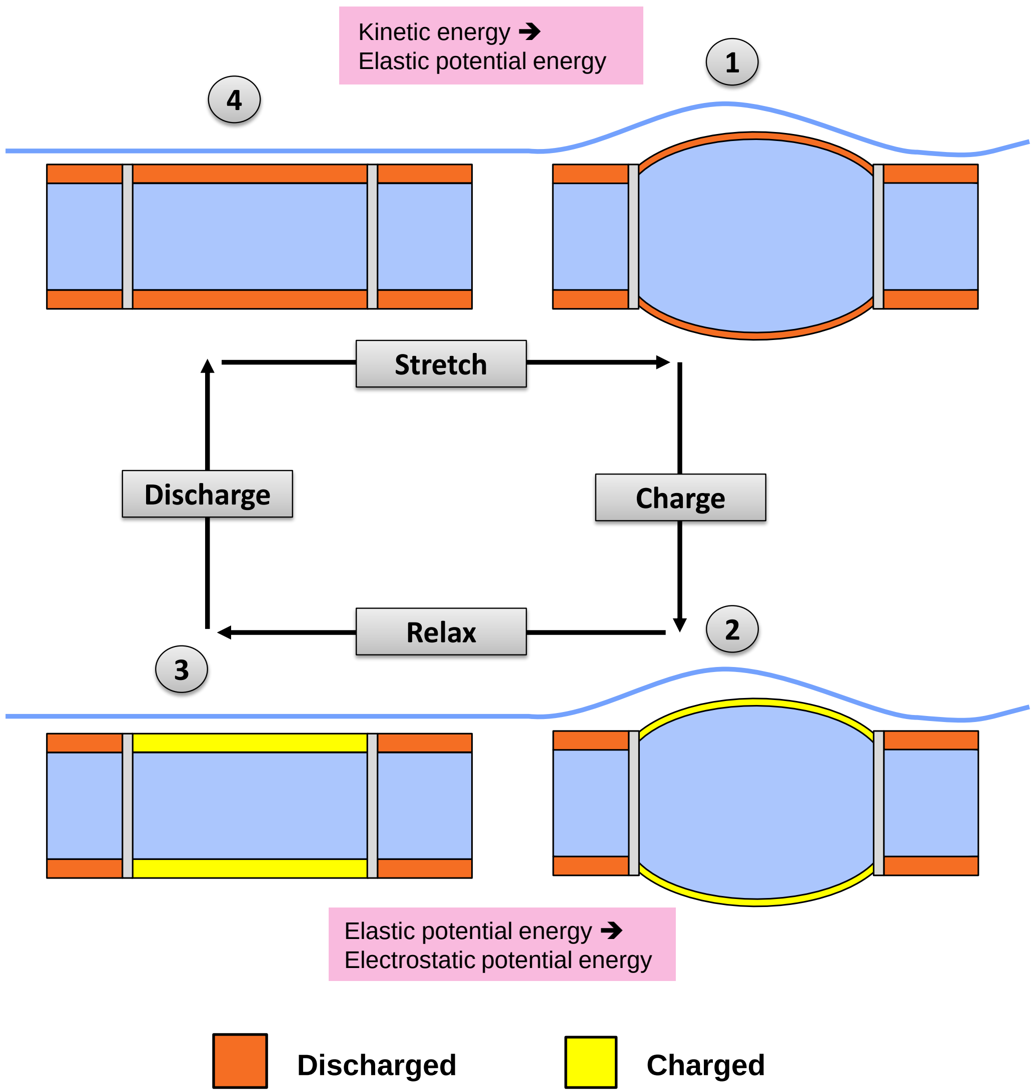
## Application to S3

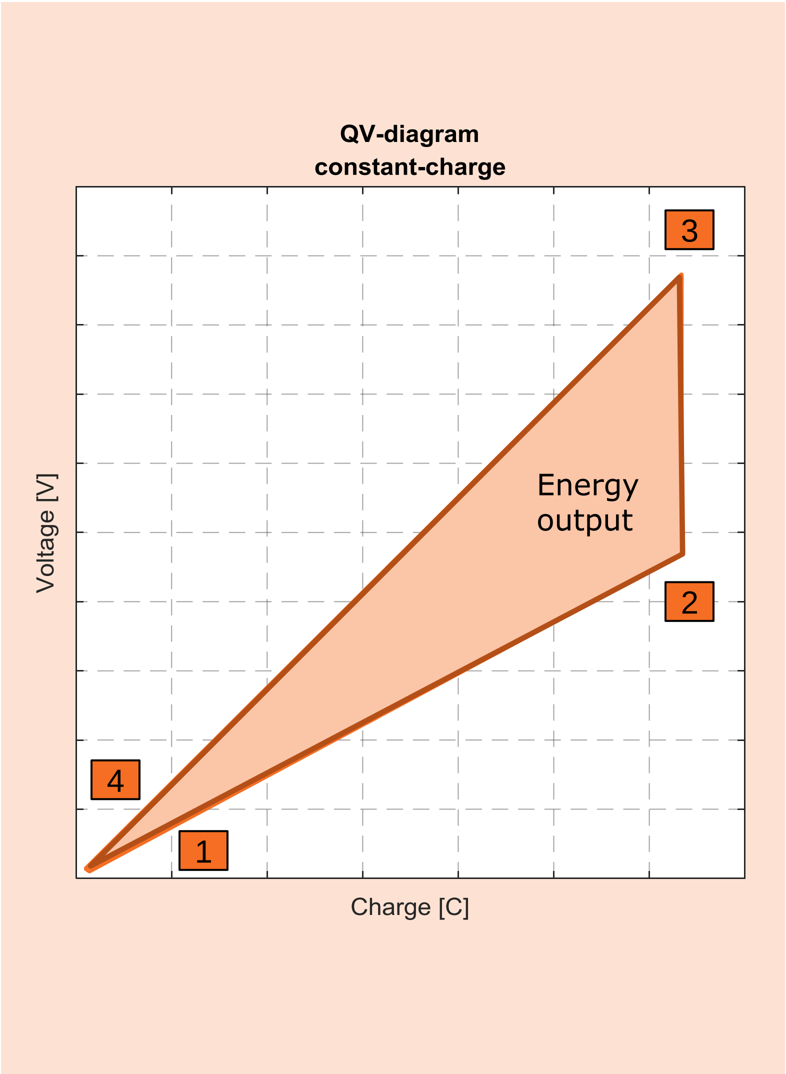
# ELECTROACTIVE POLYMERS
## Application to S3 WEC



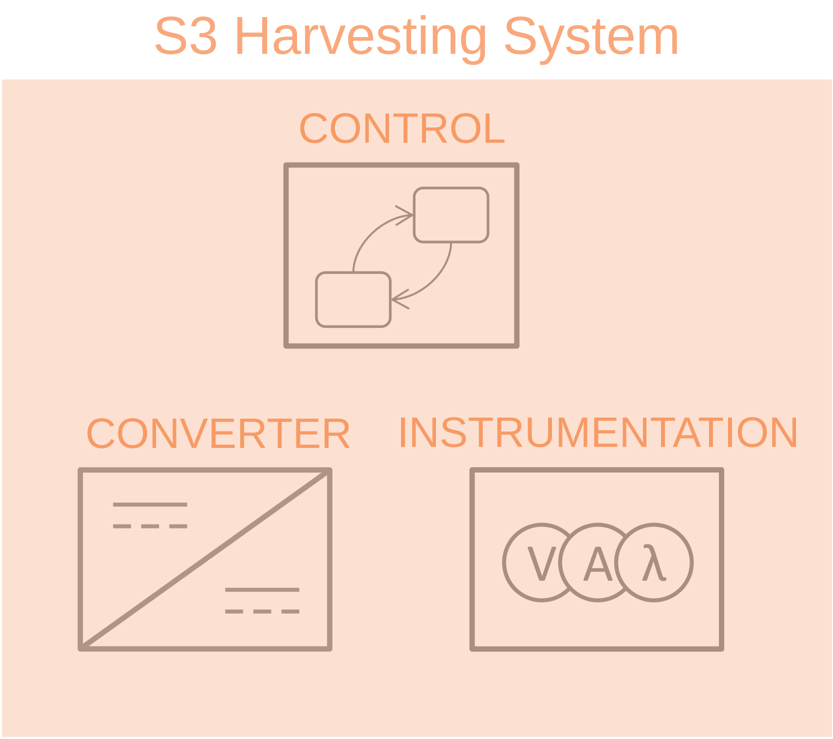



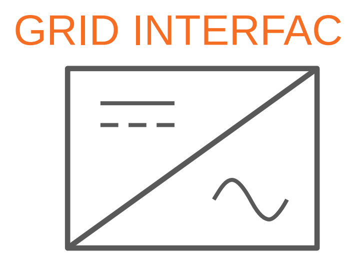
# Application to S3 WEC

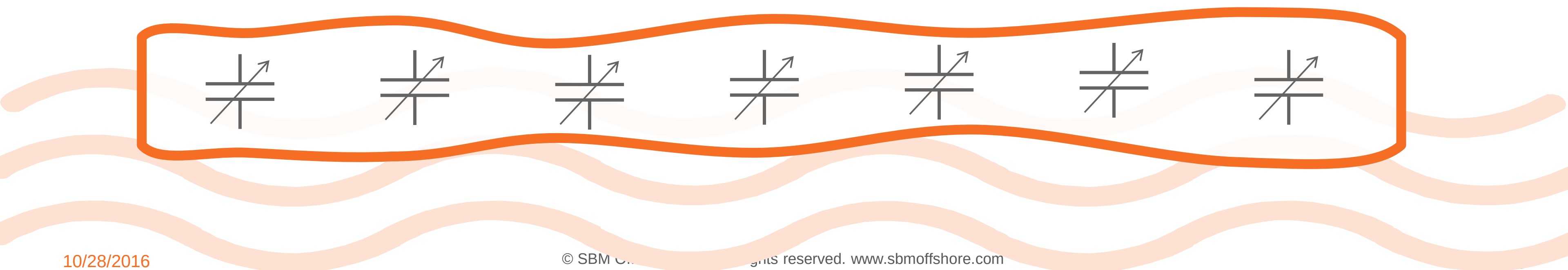


# Harvesting system for the S3 WEC

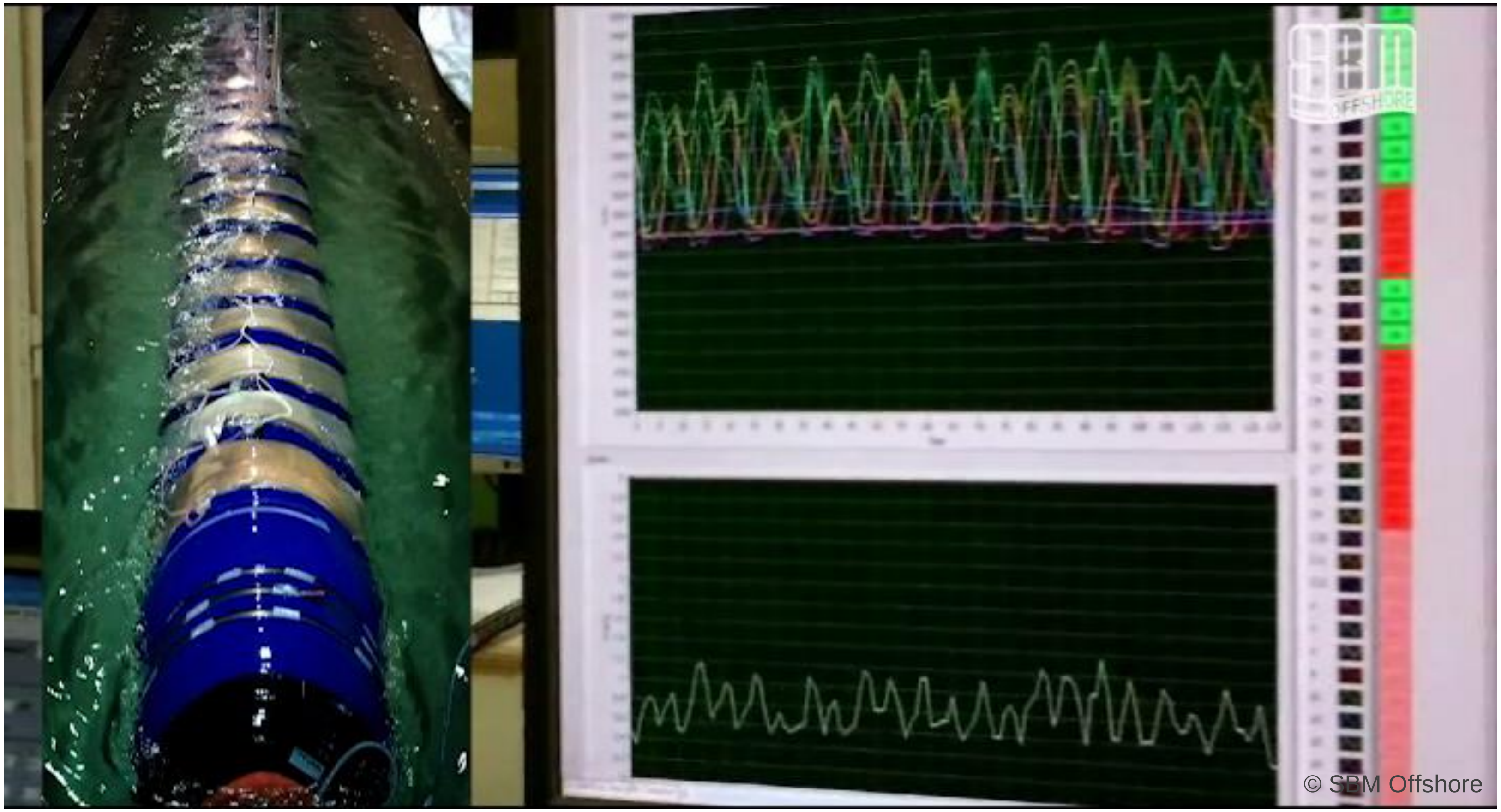


- World first energy production with a realistically moored flexible EAP WEC

S3 test campaign, ACRI, 2010



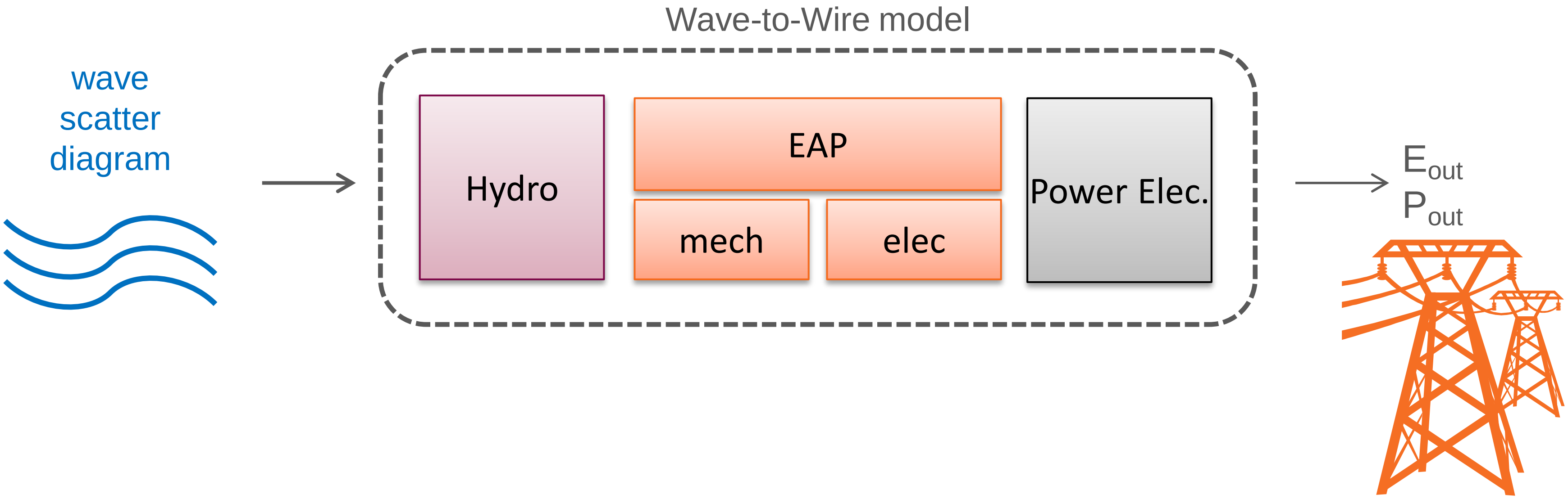
# W2W

## Hydro-elasto-electric model

SBM OFFSHORE

# Overview

- SBM and ECN developed a fully coupled numerical model of its S3 WEC that integrates realistic excitations and interactions from the wave excitation to the power generation



# Equations

## External flow:

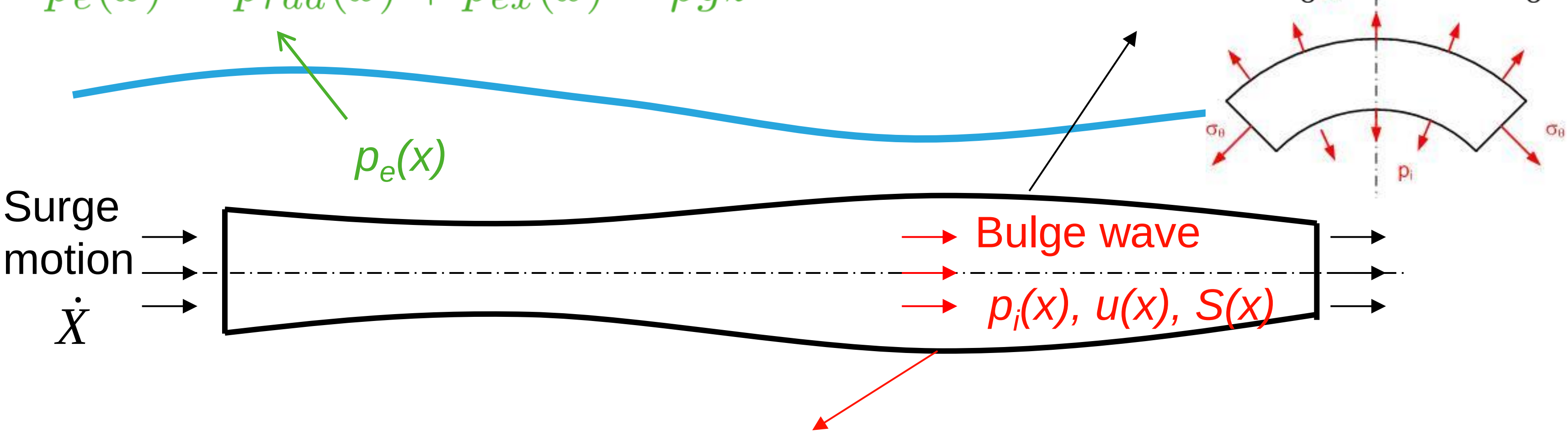
- Linear potential flow theory
- Unknown is pressure on the tube.
- Equation:

$$p_e(x) = p_{rad}(x) + p_{ex}(x) - \rho g z$$

## Wall equation:

- Unknown is the deformation of section S(x,t).
- Equation:

$$p_i^* - p_e^* = \frac{1}{D}\frac{S - S_0}{S_0} - \frac{1}{DS_0}\frac{\partial^2 S}{\partial x^2}$$




+ Boundary conditions & PTO model

## Internal flow:

- Unknown are pressure and velocity in the tube.
- Euler equations:

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial p_i}{\partial x} \quad \frac{\partial S}{\partial t} = -\frac{\partial}{\partial x}(Su)$$

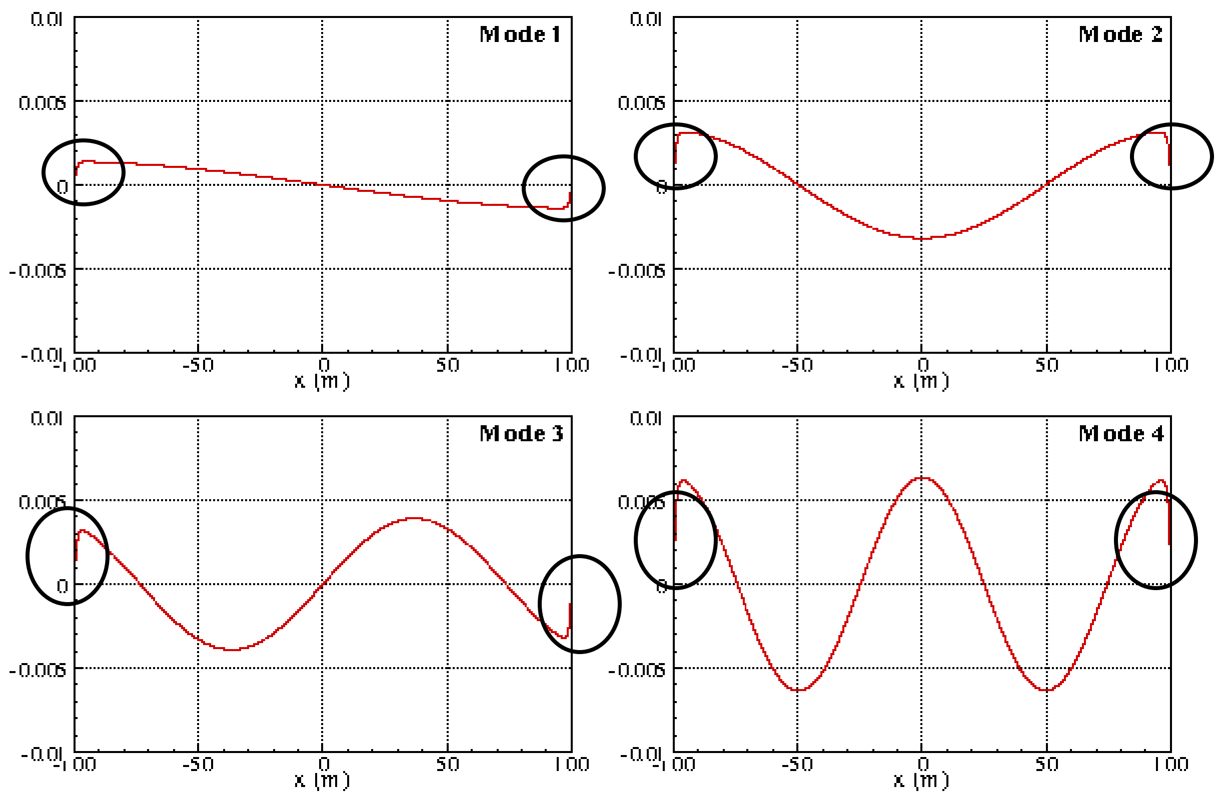
# Modal basis

Inertia — Elastic stiffness — Geometrical stiffness

Seek for solutions of the propagation equation:

$$\frac{\partial^2 \chi}{\partial t^2} - \frac{1}{\rho D}\frac{\partial^2 \chi}{\partial x^2} + \frac{1}{\rho D}\frac{1}{K_0^2}\frac{\partial^4 \chi}{\partial x^4} = 0$$

No deformation at tube extremities



Decomposition on modal basis: $\chi(x,t) = \sum_m c_m(t)\,\hat{\chi}_m(x)$

After linearization, motion equation reduces to:

$$\left(\mathbf{I} + {}^{\chi}\mathbf{A}\right)\ddot{\mathbf{C}} + \left({}^{\chi}\mathbf{B} + \eta\boldsymbol{\varepsilon}\right)\dot{\mathbf{C}} + {\omega_m}^2\mathbf{C} = {}^{\chi}\,\mathbf{p}_{\mathbf{ex}}$$

Identity

Radiation

Stiffness

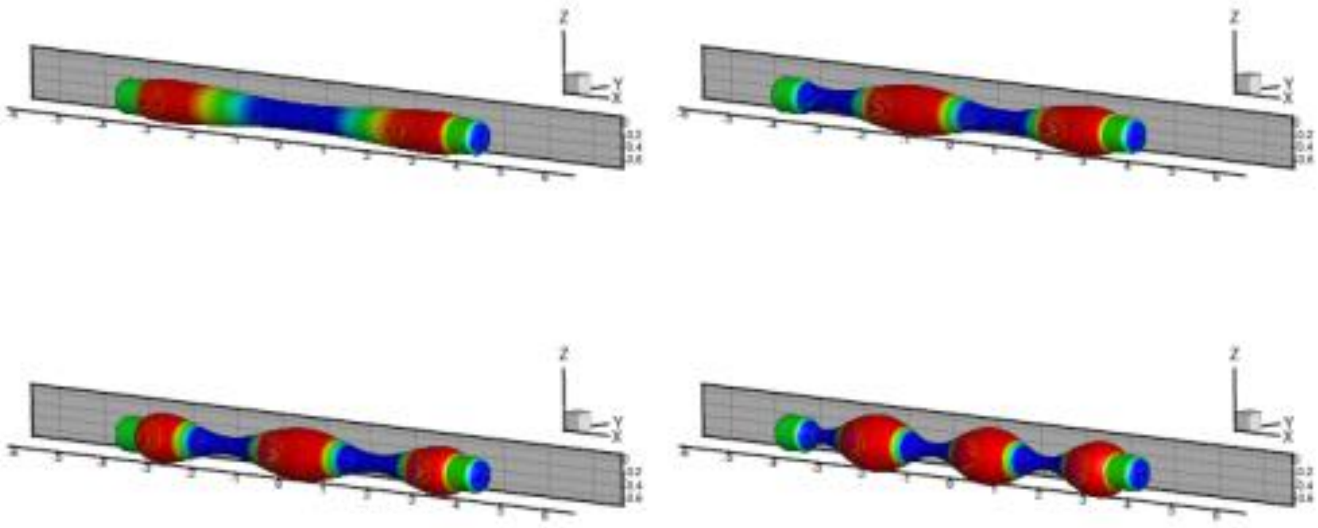
Excitation

Damping (material and PTO)

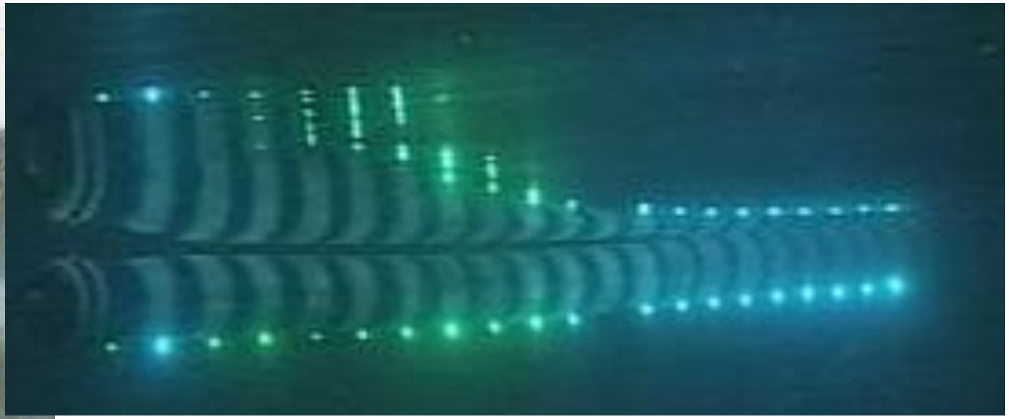
Acces to velocities, motions, deformations and absorbed power

# W2W: Wave To Wire model
## equations resolution

- Fundamental response modes used to project forces and motions
- ➔ CPU-friendly calculations thanks to the modal decomposition
- ➔ Time domain model also uses the modal decomposition while being fully coupled (non-linear material properties, harvesting strategy…)



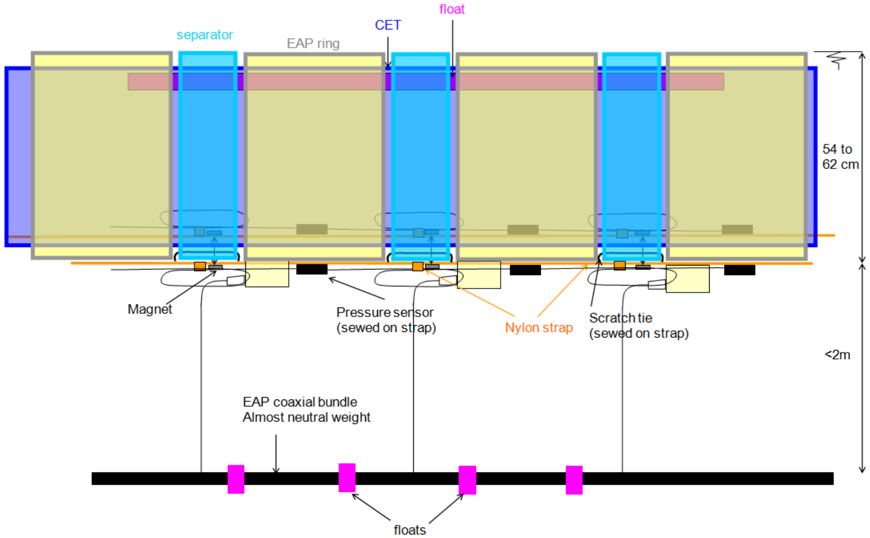
# W2W: Wave To Wire model
## Basin validation



Horizontal mooring to avoid additional complexity in the calibration of the W2Wmodel

Instrumentation:

- 20+20 pressure sensors
- 20 EAP rings
- 4 mooring loads
- 9 wave elevations
- 21 targets for trajectometry



20 inner sensors

20 outer sensors

Range: -100 to 400 mbar

Resolution: 0.1 mbar

Precision: 1 mbar

Rise time: 400 mbar/s

Protocol: RS485 half duplex

Technology: capacitive

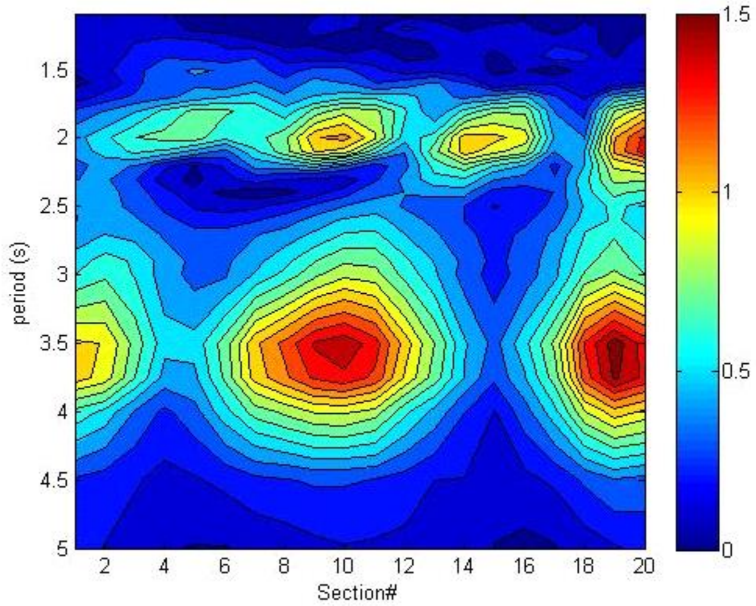
# SBM S3 WEC – A Paradigm shift
## Basin validation

Capacitance and ESR meters
Channels: 20 capacitance and 20 ESR
Capacitance Range: 10-300nF
Precision and resolution: 1nF
Resistance Range: 0-500 ohms
Precision and resolution: 1 ohm
Protocol: RS485 half duplex

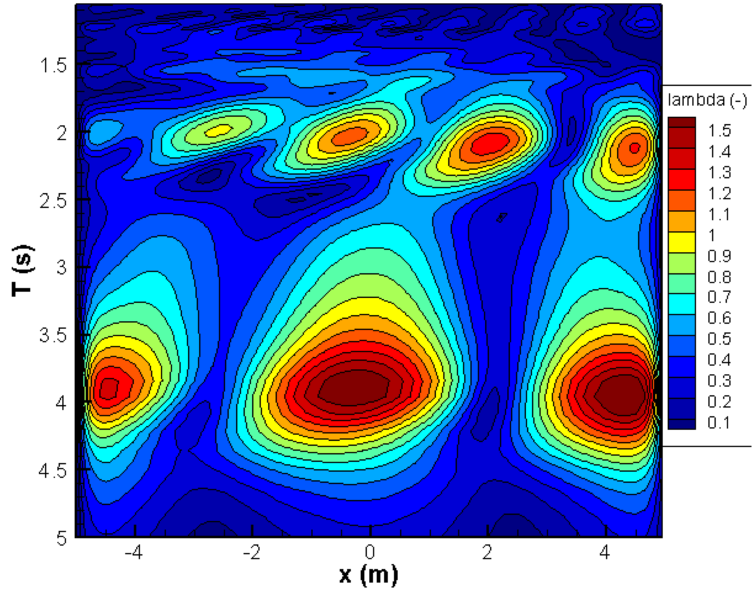
# Basin validation

- SBM calibrated its numerical model thanks to a series of wave tank tests achieved on a moored S3 prototype equipped with:
  - Internal + external pressure sensors
  - Deformation sensors composed of EAP rings
  - 3D positioning

Test campaign, ECN, 2011




Model tests




W2W simulation

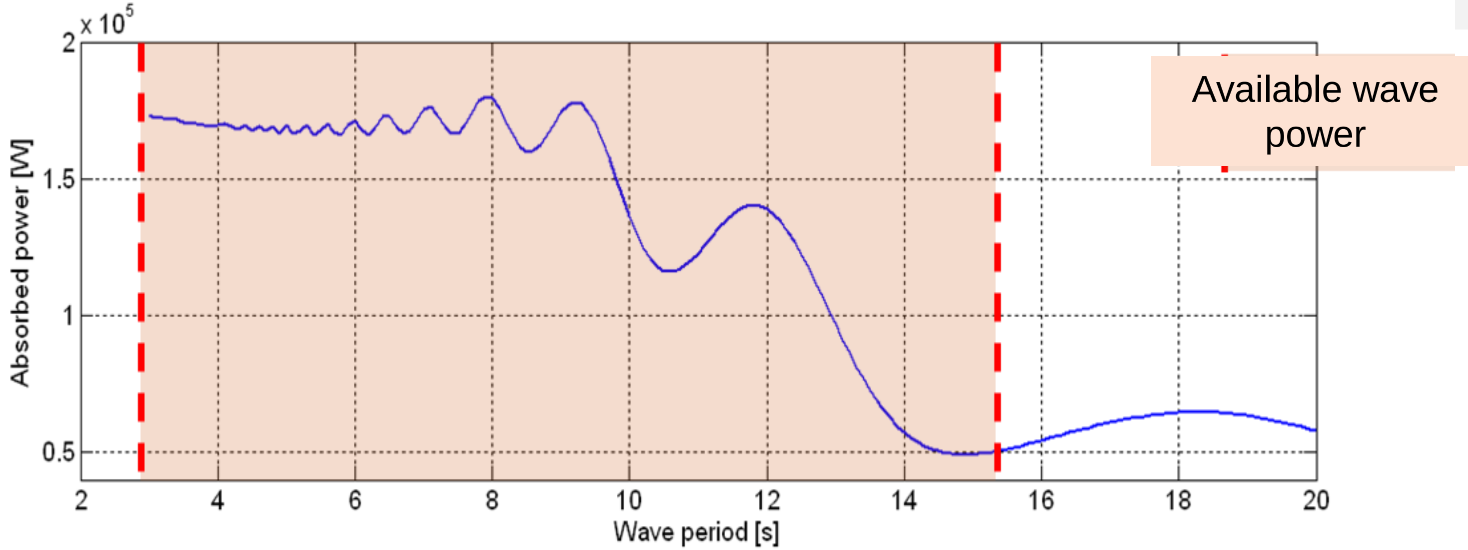
# SBM S3 WEC – A Paradigm shift

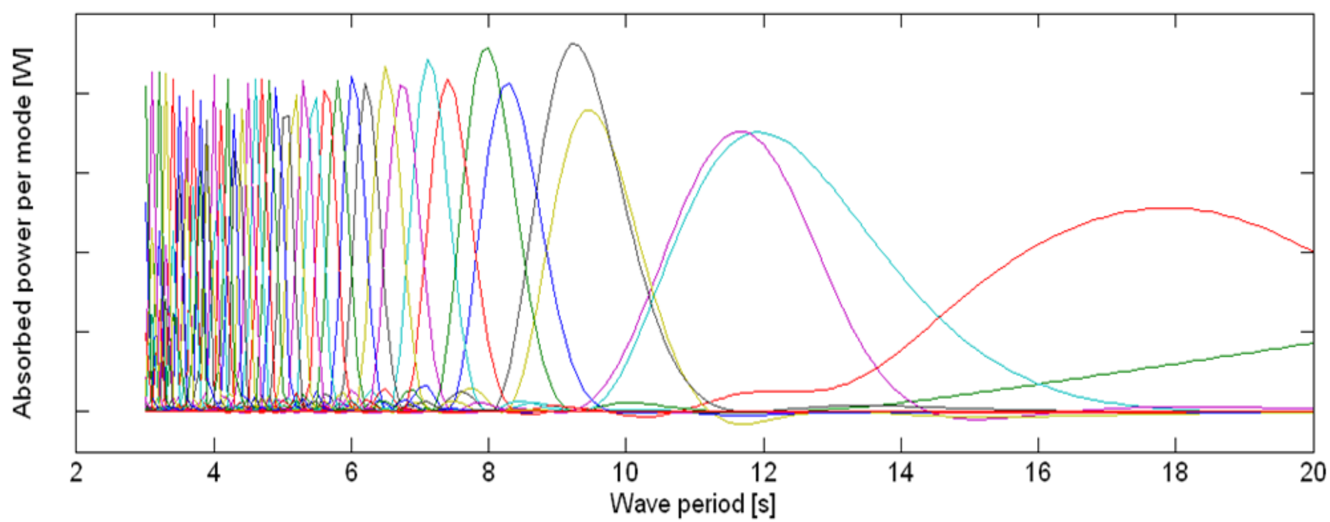
Continuously deformable

Infinite number of degrees of freedom

Infinite number of response modes

Higher capture efficiency

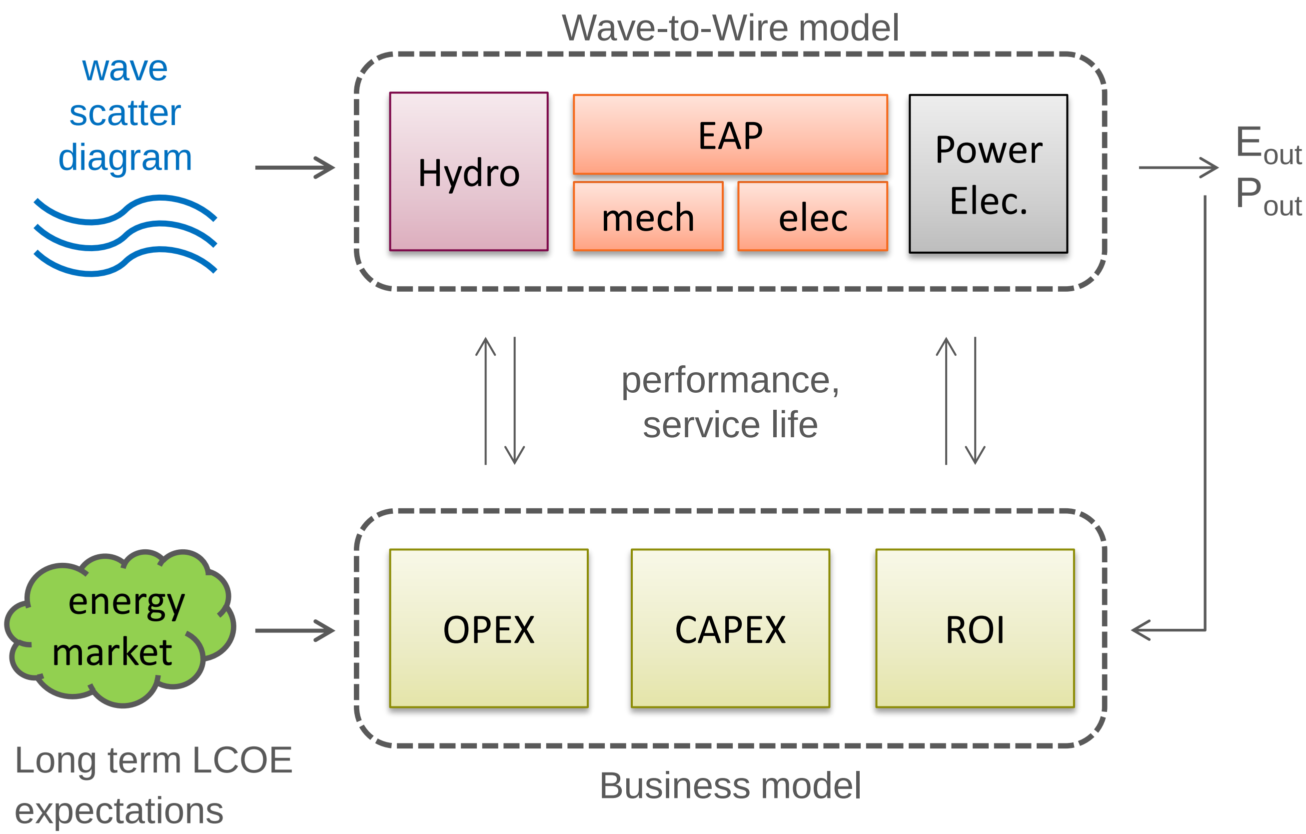


# R&D

## Ongoing developments

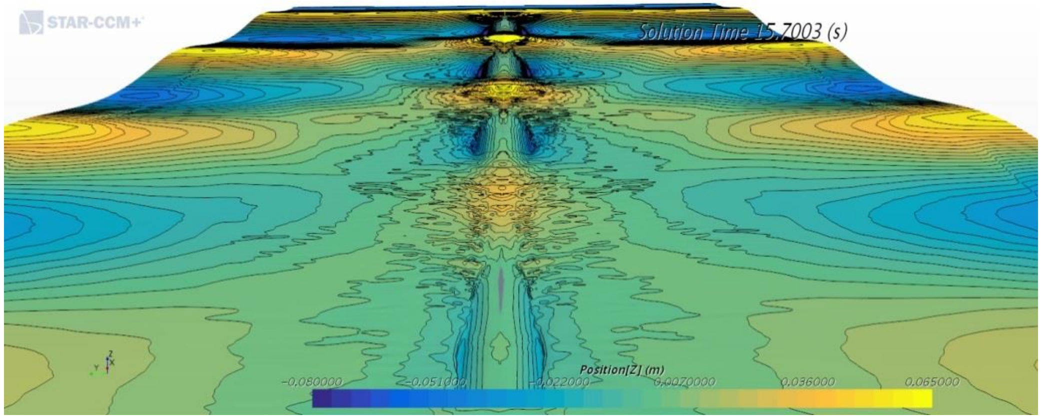
# ONGOING RESEARCH & DEVELOPMENT
## Main areas of development




- Business case drives main areas of development:
  - Hydrodynamics
  - EAP material
  - PTO technology
- Validation with several test campaigns and test benches

Working towards small scale prototype

- Confirm and improve W2W model at basin scale
  - Model tests planed in Q1 2017 at ECN
  - Hydro only, no PTO
- Investigate the system overall behavior
  - Real scale effects
  - Find optimal design
  - Understand the physics behind the system
- CFD?

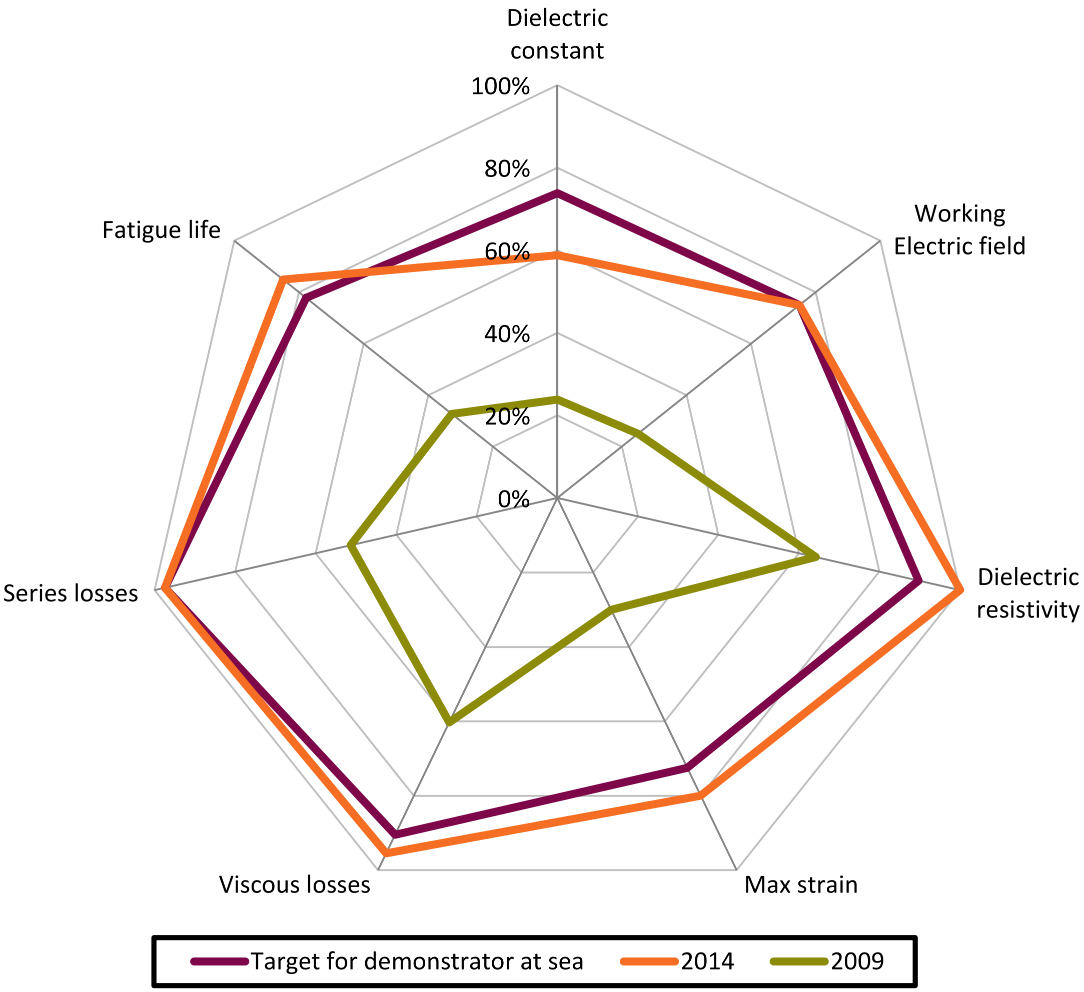


# ONGOING RESEARCH & DEVELOPMENT
## EAP material

- Development of EAP material specific to WEC by 2 PhD's
  - Energy density
  - Strain
  - Stiffness
  - Losses

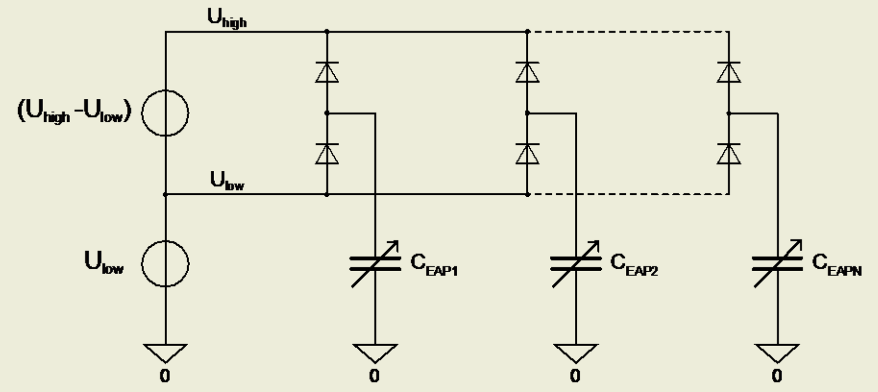
- SBM has built a network of expert companies to develop and manufacture high performance EAP film

Courtesy of Danfoss PolyPower



# Harvesting topologies

## Passive VCMPS

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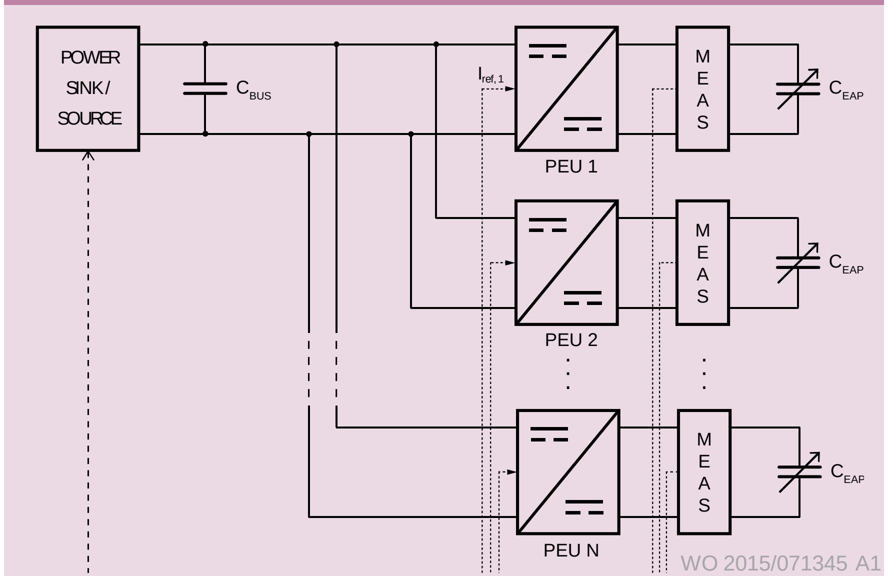
## Active DPEU

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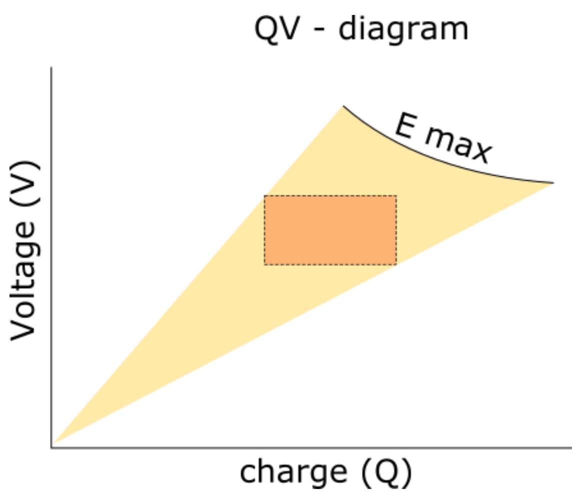
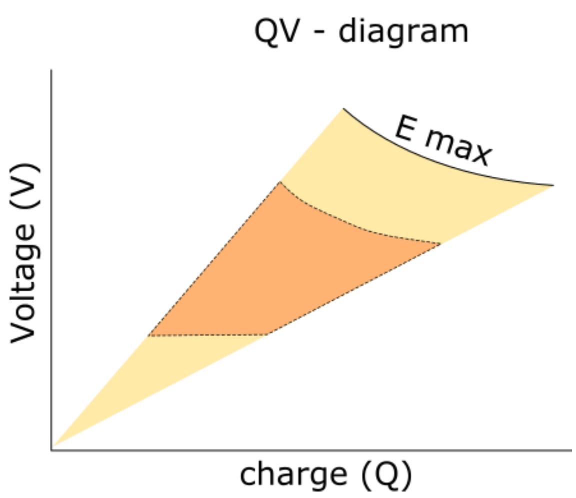
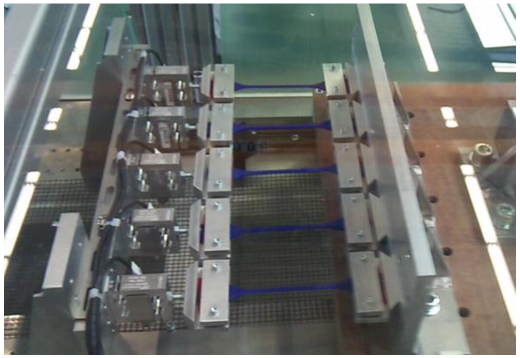


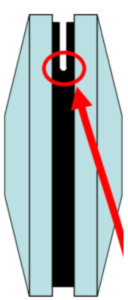



# ONGOING RESEARCH & DEVELOPMENT
## Test and qualification facilities

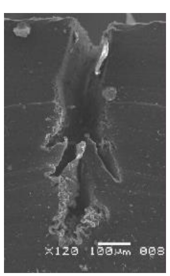


### Standard mechanical and electrical testing

- Stress-Strain
- Mechanical fatigue
- Electrical ageing
- Crack growth analysis



Courtesy of Will Mars, Endurica



Courtesy of Ecole Centrale de Nantes

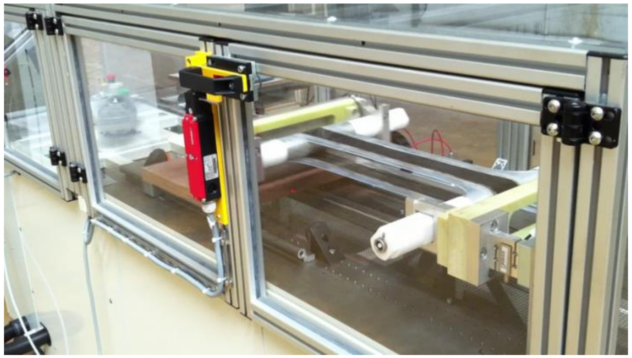
### Large Power energy harvesting rig

- Energy output up to 1 kW
- Film quantity up to 1000 m
- Voltage up to 10 kV
- Film or ring shape

- Passive & Active PTO technologies

- High precision and high frequency acquisition

➔ Energy harvesting validation
➔ Ring design validation
➔ Power electronics validation



### Coupled electro-mechanical fatigue

- Frequency up to 2.5Hz
- Voltage up to 12 kV
- Film or ring shape

- Real operating cycles (combined mechanical + electrical)

- Health monitoring

➔ Lifetime estimation
➔ Ring design validation (long term)

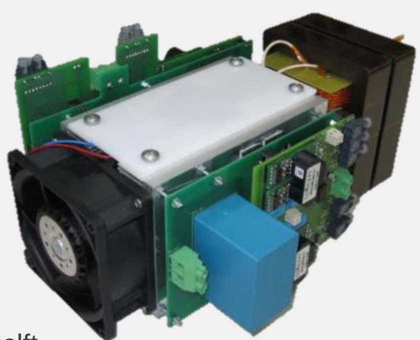
# ONGOING RESEARCH & DEVELOPMENT
## Power Electronic Converters

### Dedicated Converter per EAP generator

- High electric fields: high voltages
- Large power flows: ultra high efficiency needed

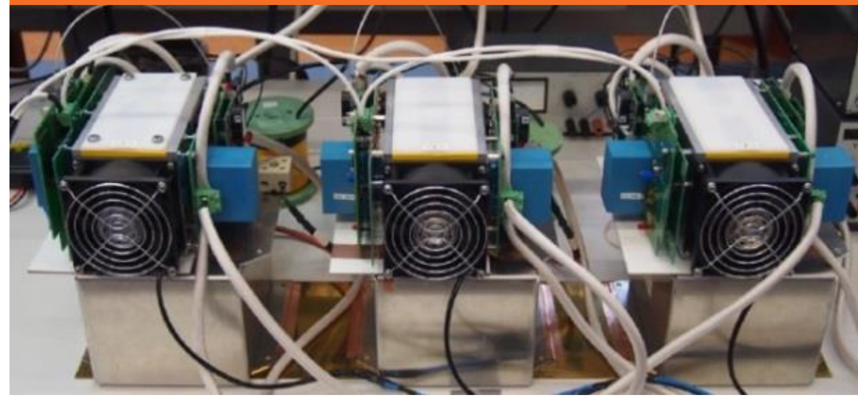
- Since 2009, SBM and TU Delft have progressively developed converters with efficiencies >98%

- Input Parallel, Output Series converter
  - Modular concept with Dual Active Bridges
  - Standard IGBT switches: 97.2%
  - Novel SiC switches: 98.5%

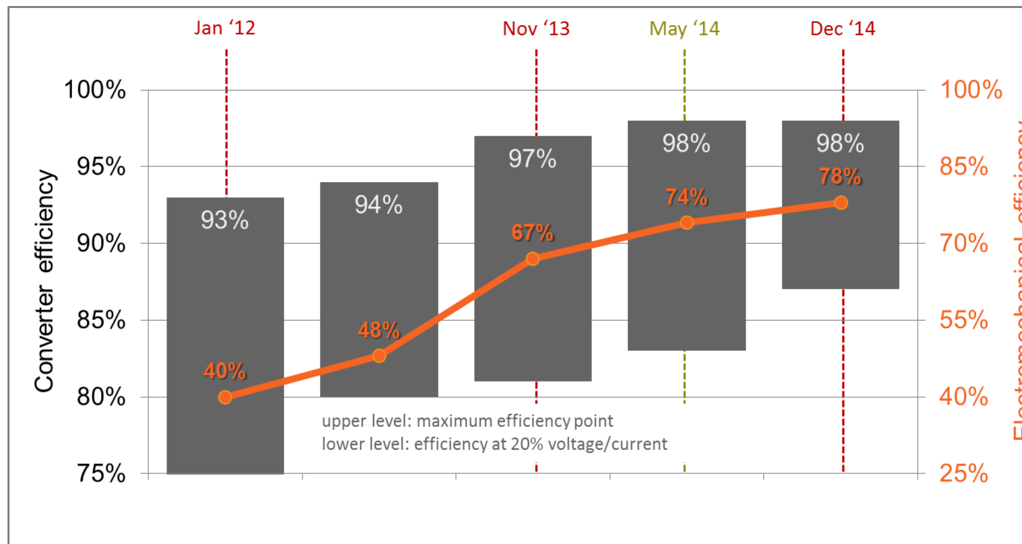


DAB module by
Todor Todorcevic,
PhD student TU Delft

### Tests in Power Electronics Lab TU Delft, 2015



- 2.4kV
- 12kW
- >97%



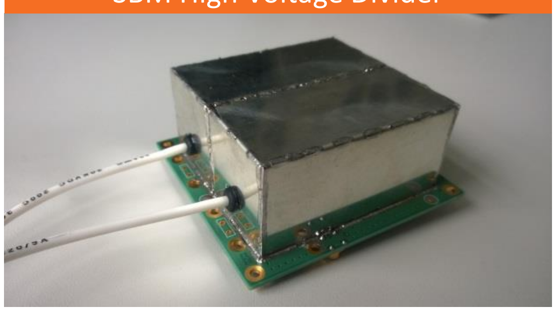

Todorcevic, T.; van Kessel, R.; Bauer, P.; Ferreira, J.A., "A Modulation Strategy for Wide Voltage Output in DAB-Based DC–DC Modular Multilevel Converter for DEAP Wave Energy Conversion," in *Emerging and Selected Topics in Power Electronics, IEEE Journal of* , vol.3, no.4, pp.1171-1181, Dec. 2015
Todorcevic, T.; Bauer, P.; Ferreira, J.A., "Efficiency improvements using SiC MOSFETs in a dc-dc modular multilevel converter for renewable energy extraction," in *Power Electronics and Motion Control Conference and Exposition (PEMC), 2014 16th International* , vol., no., pp.514-520, 21-24 Sept. 2014

# ONGOING RESEARCH & DEVELOPMENT
## Power electronics platform

### SBM Dedicated PEU for EHVT



### SBM High Voltage Divider



### SBM Harvesting Platform

Real-Time controller

Optical Link

Instrumentation & safety

High-Voltage amplifier

EAP generator interface

# SBM S3 WEC

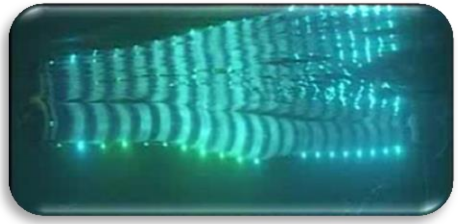
# Gen 2 devices: the way to reduce LCOE

Engineering | Procurement & Construction | Installation | Operations & Maintenance

Rigid Structure & inappropriate PTO

↓

Fatigue Friendly structure
Frequency indep. distrib. PTO
Large absorption bandwidth

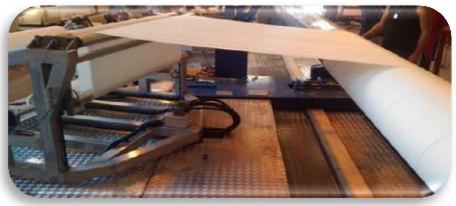


**Reduced CAPEX & Improved efficiency**

Extensive Construction

↓

Industrial Roll to Roll



**True Ramp up to commercialization**

Heavy lift & Installation

↓

Easier load out & Installation

**Reduced Cost of Installation**

Periodic maintenance

↓

Run Until Failure

**Reduced OPEX**

**Lower Cost Of Electricity**

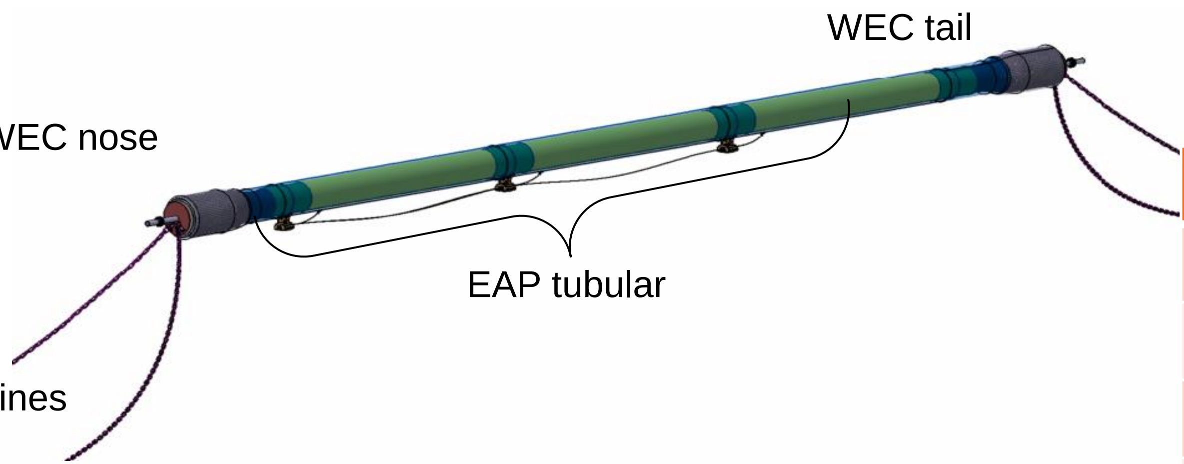
# SBM S3 WEC – A Paradigm Shift

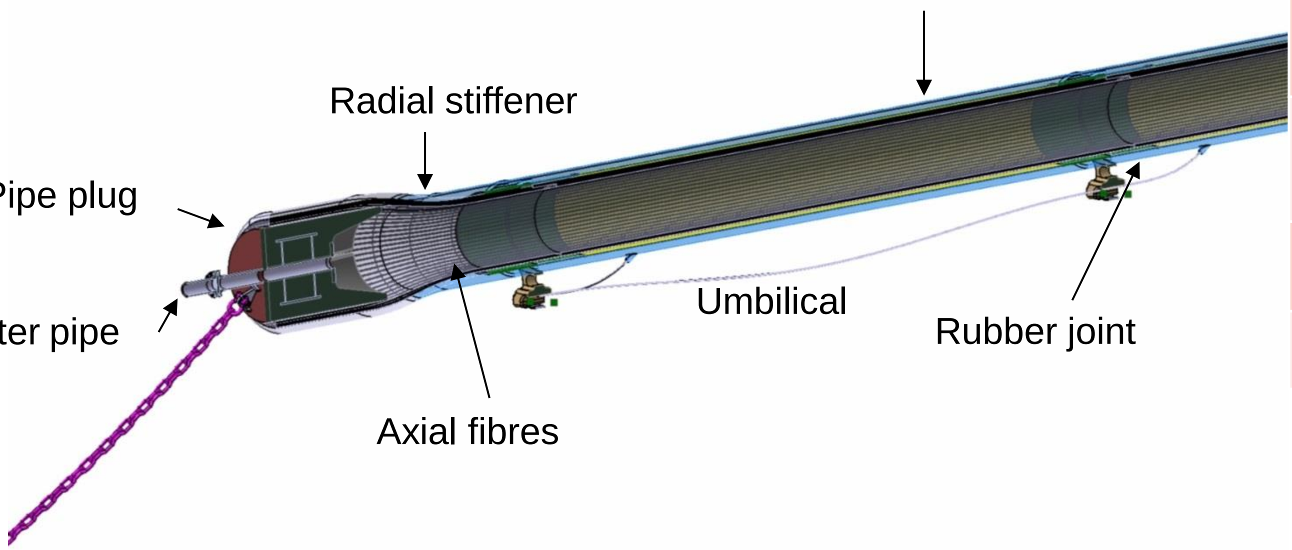
- First milestones passed:
  - Proof of concept (direct power gen with EAP in water demonstrated + Wave2Wire model developed and validated)
  - Large scale power electronics topology developed
  - EAP control algorithms developed
  - Generator ring design validated
  - EAP performance and large scale manufacturing
  - Comprehensive business model

- Next step: small-scale prototype at sea

- Developments up to full technical and commercial maturity will require significant investment.
  Partners will be sought to participate

# SBM S3 WEC – A Paradigm shift




| Characteristic | Value |
|---|---|
| Tube diameter | 2 to 4 m |
| Tube length | 200 to 400 m |
| Tube thickness | 5 to 10 cm |
| Power production | 100 ➔ 800 kW ➔ 2MW average |
| Tube materials | Natural Rubber, Neoprene, EPDM |
| Number of layers EAP | 100 to 300 layers (100 µm thick) |
| Operating voltage | 12 kV |
| Service life | 10 ➔ 20 years |

# Q&A