EDRIVE - MEC

EPSRC Supergen Marine
Grand Challenge

1st April 2016 – 31st March 2019

Kick Off Meeting

25th May 2016

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PTO Design Challenge

PTO and power conditioning system requirements:

- convert energy from motion in **multiple directions**,
- **react large forces** or torques whilst operating at **low velocity**,
- **variable voltage and frequency**,
- exhibit **high reliability, availability and efficiency over a wide range of loads**.

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Aim

develop an integrated electrical power take off system with non-mechanical speed enhancement, integrated and reliable flexible power electronics, providing adaptive control over a range of operating regimes, taking into account nominal and extreme load conditions.

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Objectives

- Develop a low speed pole modulated generator to convert energy from devices with predominantly heave motion.
- Develop integrated speed enhancement techniques for electrical generators in wave devices, and apply to the pole modulated generator with the aim of achieving a force density of exceeding 150kN/m^2.
- Investigate generator configurations to convert energy from devices moving in surge and pitch motions.
- Investigate multi-level power converter topologies for integration into the generator.
- Include extreme loadings in the design procedures for optimisation of EDRIVE PTO systems for survivability.
- Apply the technologies developed to case studies in which wave to wire models of each will be developed for investigating system performance and control.
- Lab and FloWave demonstration of the scale prototypes to verify design tools developed.

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Academic Partners

- University of Edinburgh
  - Markus Mueller, Aristides Kiprakis, Henry Jeffrey
  - Richard Crozier, Adrian de Andres, Ben McGilton (PhD)
- University of Newcastle
  - Nick Baker, Volker Pickert, Steve McDonald
  - 2 PhDs
- TU Delft
  - Henk Polinder
- Universidad de Chile
  - Roberto Cardenas
- UNAM, Mexico City
  - Rodolfo Silva Casarin

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Industrial Partners

- Albatern – UK
  - David Findlay, Edinburgh
  - www.albatern.co.uk
- Carnegie Wave Power, Australia
  - Tim Sawyer, Cornwall, UK
  - http://carnegiewave.com/
- Columbia Power Technolgies, USA
  - Ken Rhinefrank, Corvallis, Oregon, USA
  - http://columbiapwr.com/
- Tecnalia, Spain
  - Ainhoa Pujana, Bilbao, Spain
  - http://www.tecnalia.com/en/energy-environment/index.htm
- Turbopower Systems, UK

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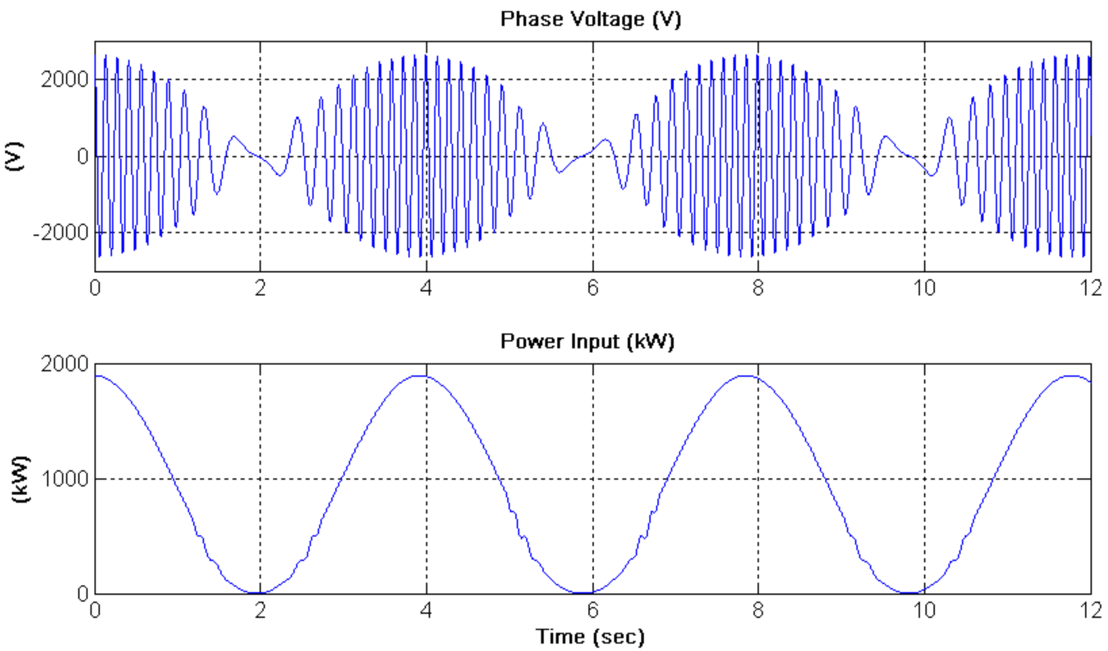
Background & Context

Engineering Challenge: Electrical Generator

- Low speed
  - Wind: 1MW – 20rpm, 7MW – 10rpm
  - Wave: reciprocating, 1-1.5 m/s peak
  - Tidal Current: 1MW – 10rpm
- High force or torque requirement
- Direct Drive
  - Physical size, weight,
- Permanent Magnet - Cost and Availability
- Environment – corrosion, impact of marine loads

Engineering Challenge: Power Conversion

- Variable prime mover
- Wave:



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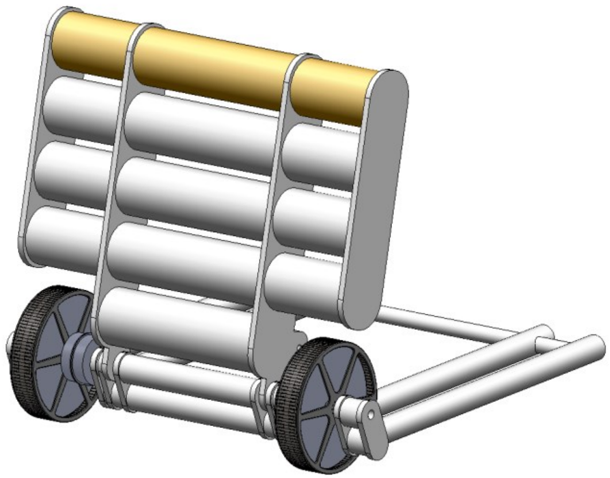
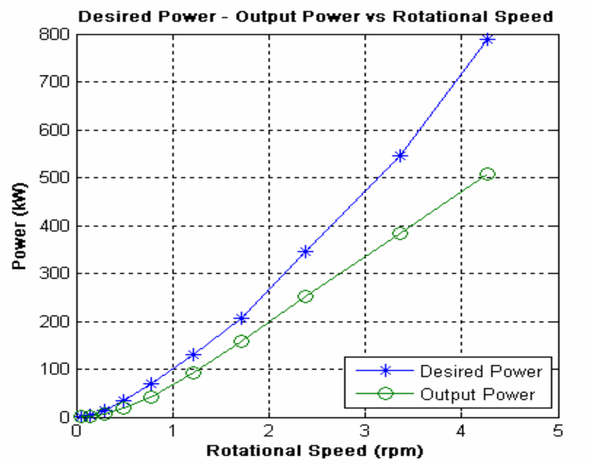
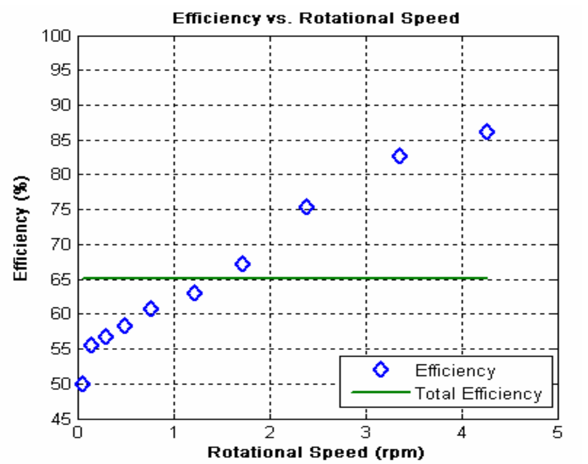
Direct Drive Challenge - Oyster





Diameter	6 m
Total Weight	118,6 t
Total Generator Cost	£ 3,066k
Power Electronics Cost	£ 116k
Total Cost	**£ 3,182k**



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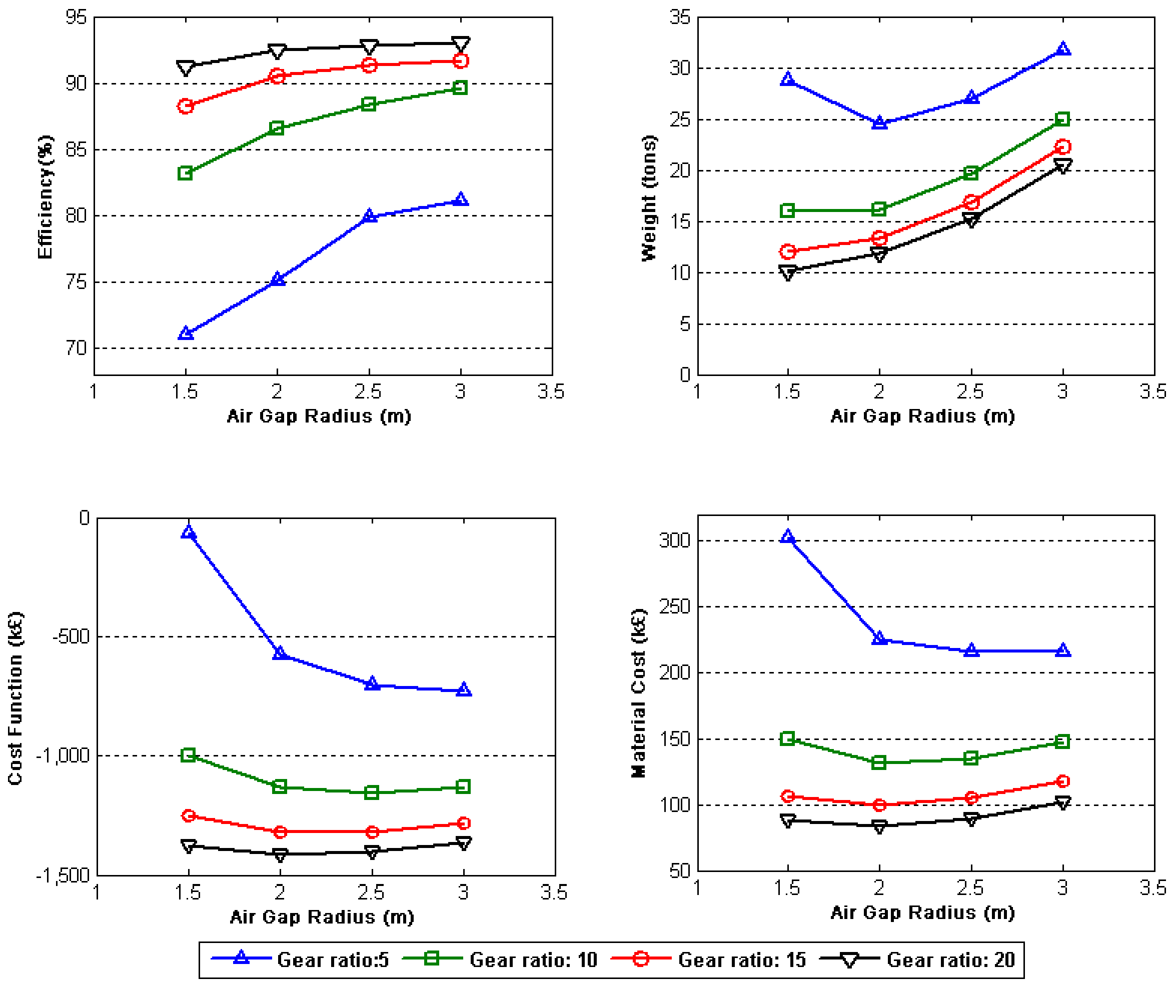
Designs with Different Gear Ratios



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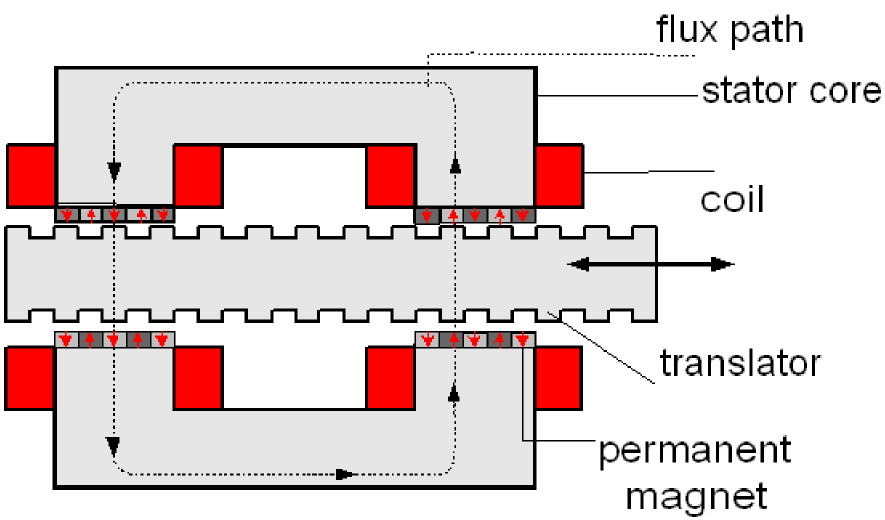
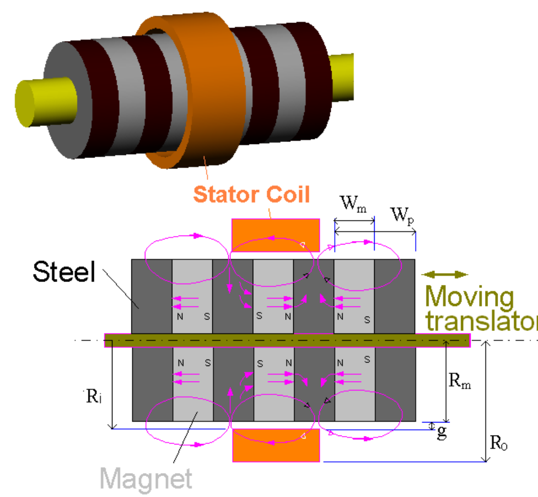
Background and Context

- Nick Baker PhD, University of Durham
  - Linear Generator for Direct Drive Marine Renewable Energy Converters





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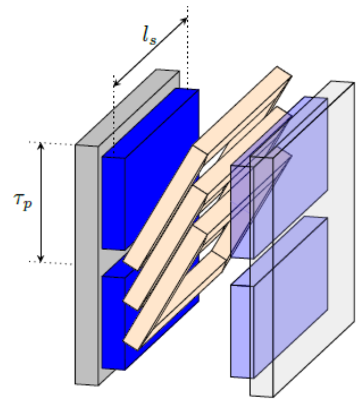
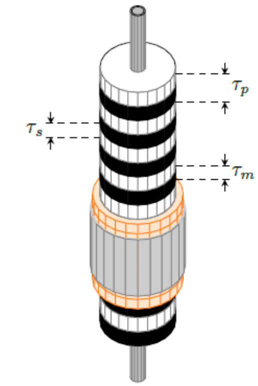
Background and Context

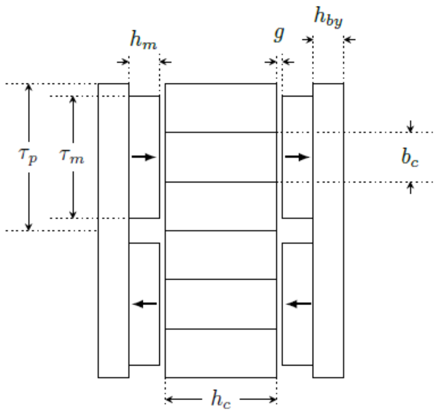
- Richard Crozier PhD, University of Edinburgh
  - Optimisation and Comparison of Integrated Models of Direct-Drive Linear Machines for Wave Energy Conversion

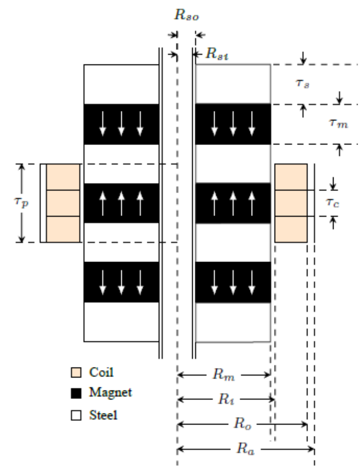


(a) 3D representation.



(a) 3D representation.





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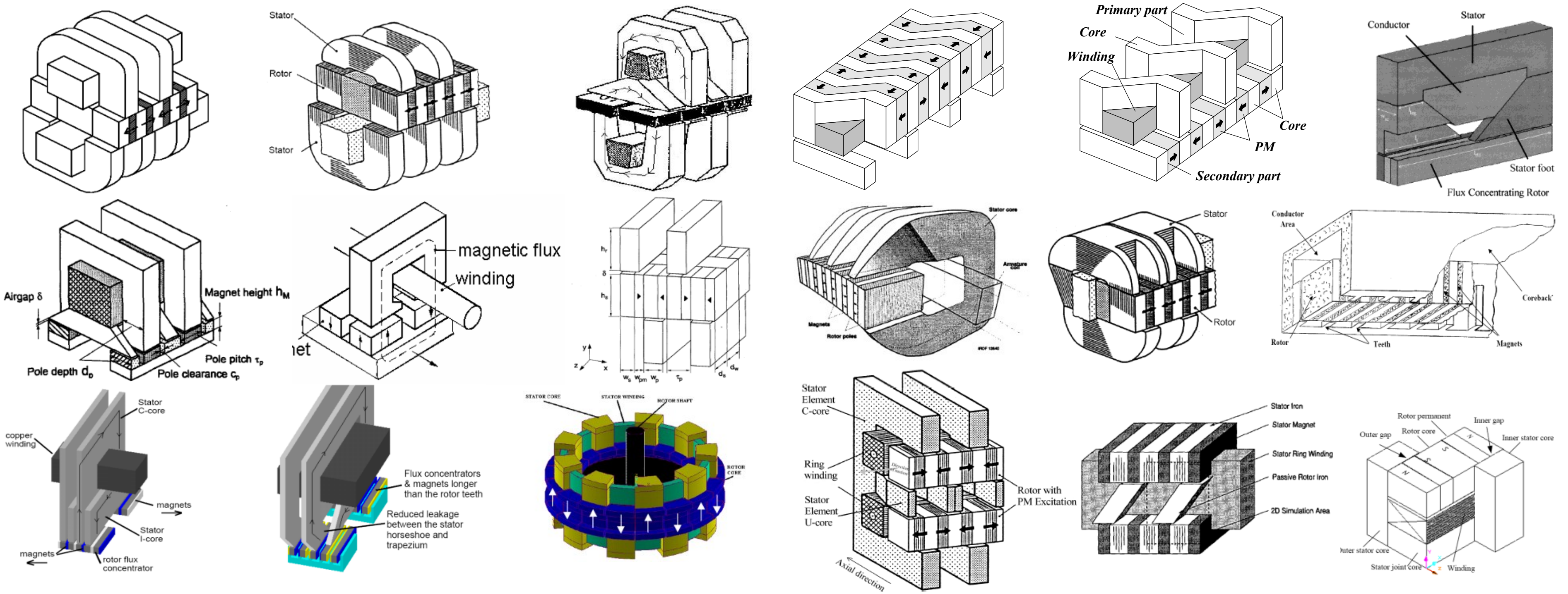
Pole Modulated Machines

- Transverse Flux Machine
- High Shear Stress at the airgap
  - 200kN/m^2 reported by Weh
  - 4-5 times conventional PM synchronous machine
- Construction is challenging
- Power Factor is an issue

What type of TFPM machine ?

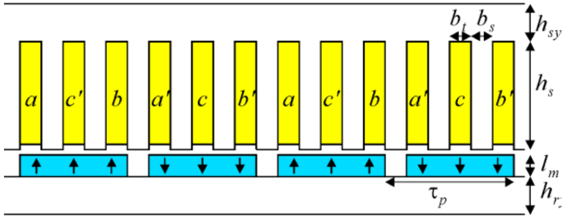
A number of TFPM machine types have been proposed.



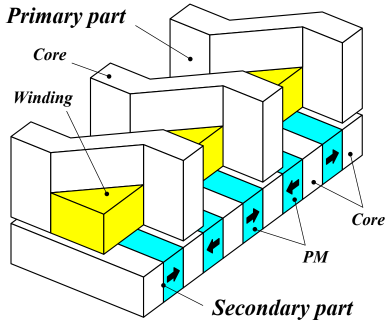
→ It is necessary to find the most suitable type. **How?**

Comparative design of PM machines

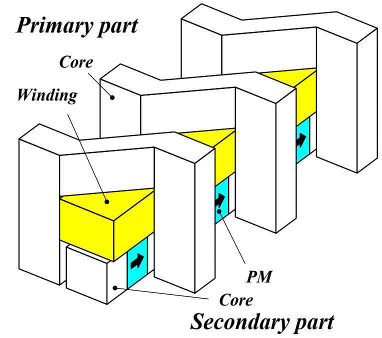
a) RFPM machine



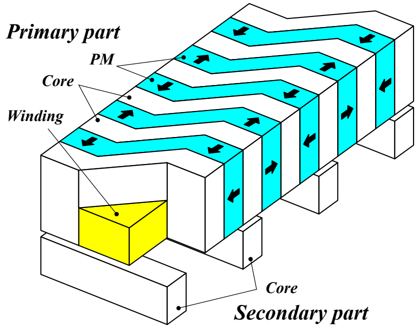
b) TFPM machine-1



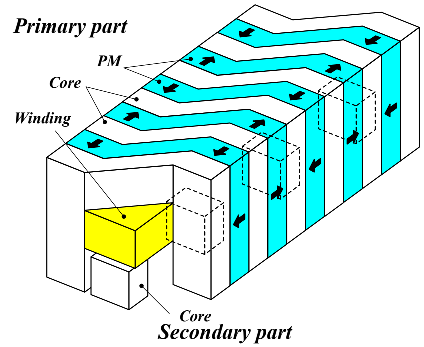
c) TFPM machine-2



d) TFPM machine-3



e) TFPM machine-4



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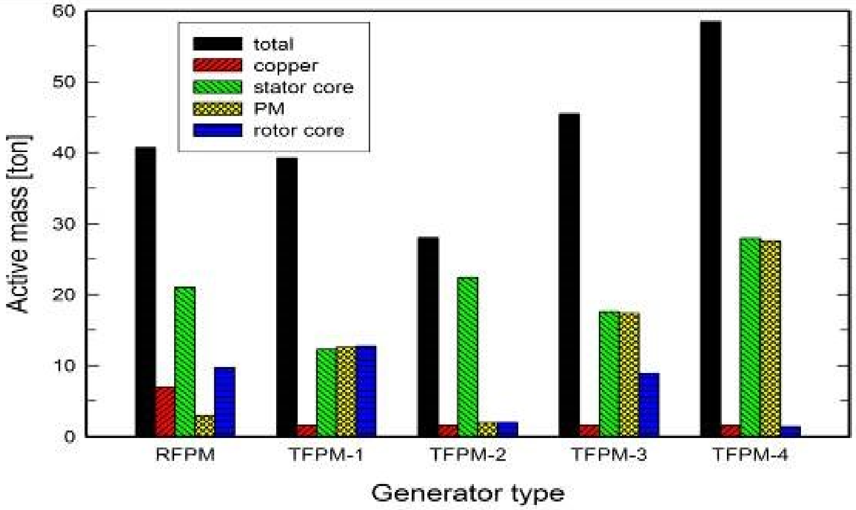
Design parameters

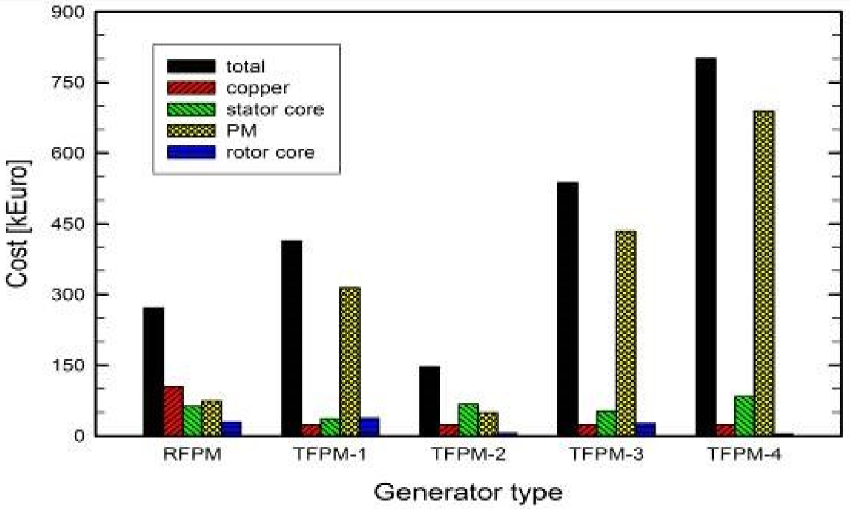
Material parameter	
Remanent flux density of the magnets (T)	1.2
Recoil permeability of the magnets	1.06
Resistivity of copper at operating temperature (μΩm)	0.025
Cost modeling	
Laminations cost (€/kg)	3
Copper cost (€/kg)	15
Magnet cost (€/kg)	25

Generator parameter	
Generator power, P	5.56 MW
Rotational speed, rpm	12
Number of phase, m	3
Nominal current, i_s	675 A
No-load voltage, e_p	2746 V
Air gap length, l_g	6.14 mm
Air gap diameter, D_g	6.14 m

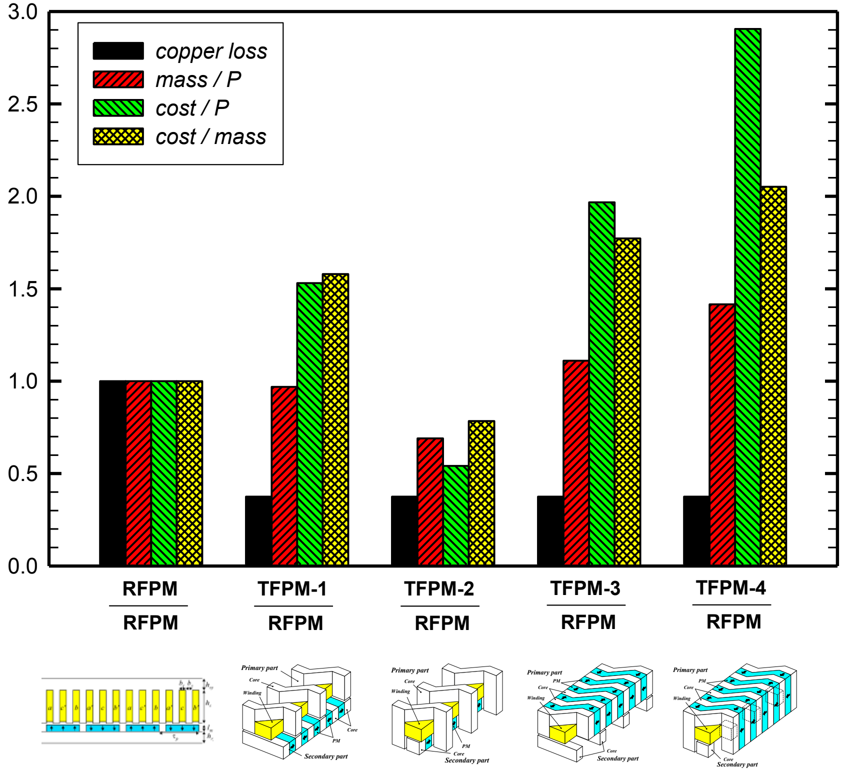
Comparison



Active mass [ton]
total
copper
stator core
PM
rotor core
RFPM
TFPM-1
TFPM-2
TFPM-3
TFPM-4
Generator type

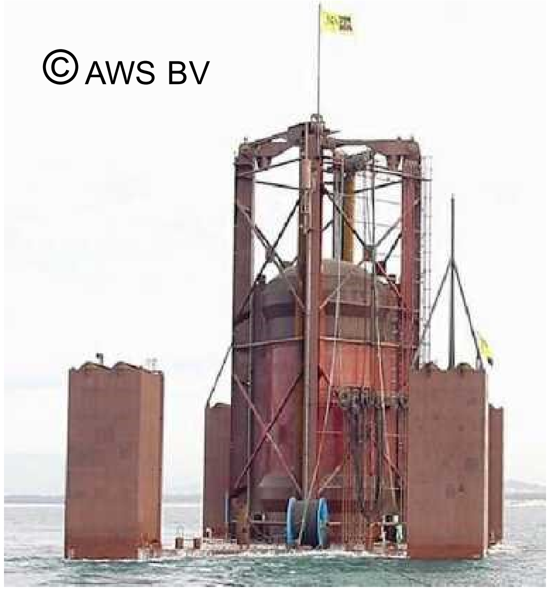


Cost [kEuro]
total
copper
stator core
PM
rotor core
RFPM
TFPM-1
TFPM-2
TFPM-3
TFPM-4
Generator type

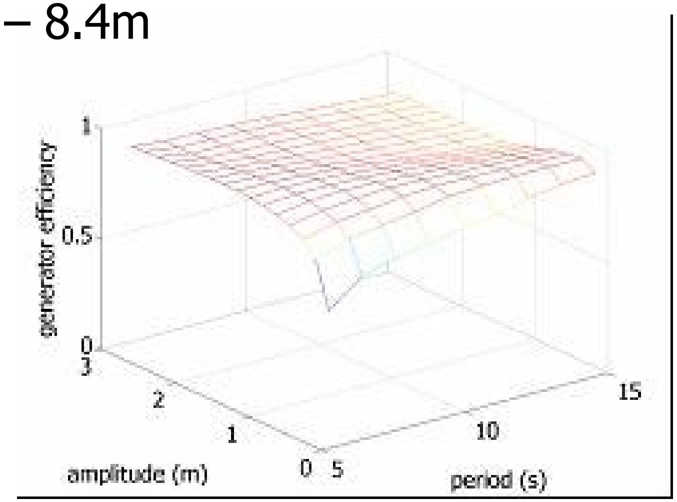


copper loss
mass / P
cost / P
cost / mass
RFPM / RFPM
TFPM-1 / RFPM
TFPM-2 / RFPM
TFPM-3 / RFPM
TFPM-4 / RFPM

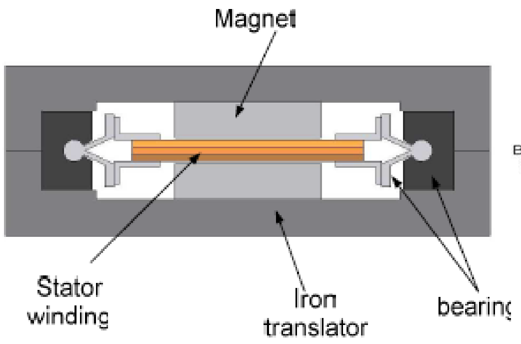
Archimedes Wave Swing

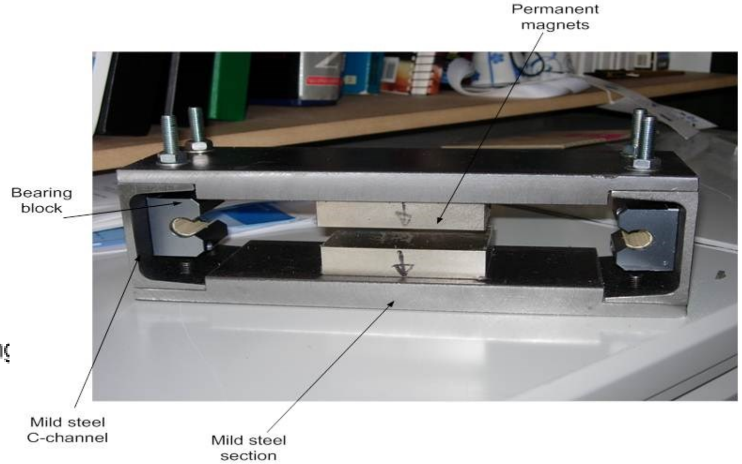


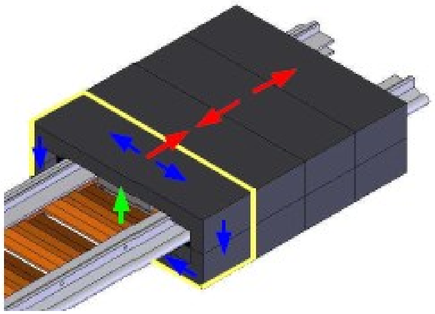
- Linear PM synchronous machine
- Rating – 2MW
- Average – 400kW
- Stroke – 4 to 7m
- Velocity <= 2.2m/s
- Double sided
- Stator – 5.6m
- Translator – 8.4m
- Mass ?



C-GEN – an air cored machine







- 50kW (pk)
- Vpk = 2m/s
- Machine Length = 3m
- Stroke = 2m

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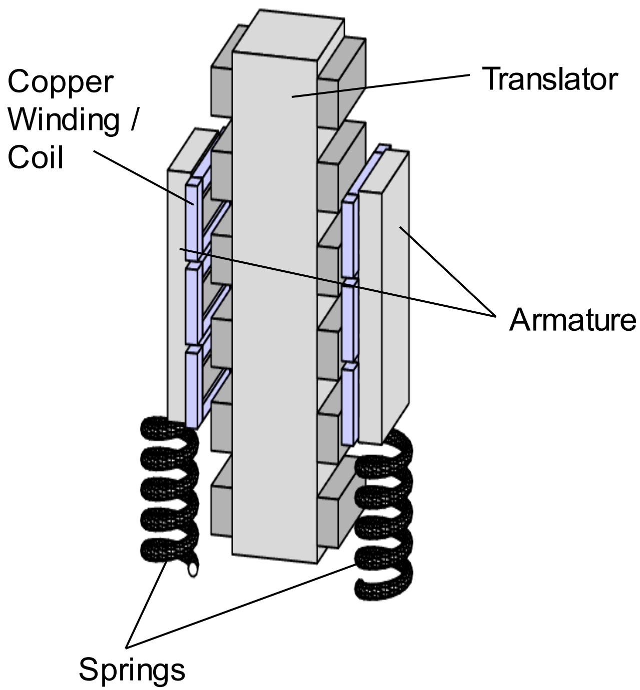
SNAPPER – EU FP7, Narec



Phase 1

Spring force is less than magnetic attraction force:

Translator and armature move in same direction.

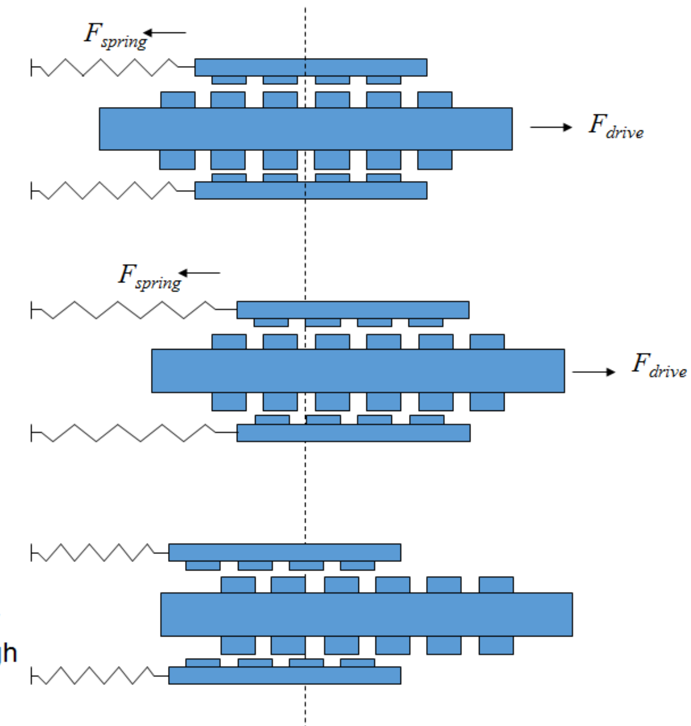
Phase 2

Spring force matches magnetic attraction force:

Armature movement ceases

Phase 3

Armature becomes decoupled from translator and begins to move at high velocity relative to the translator.



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SNAPPER – the movie

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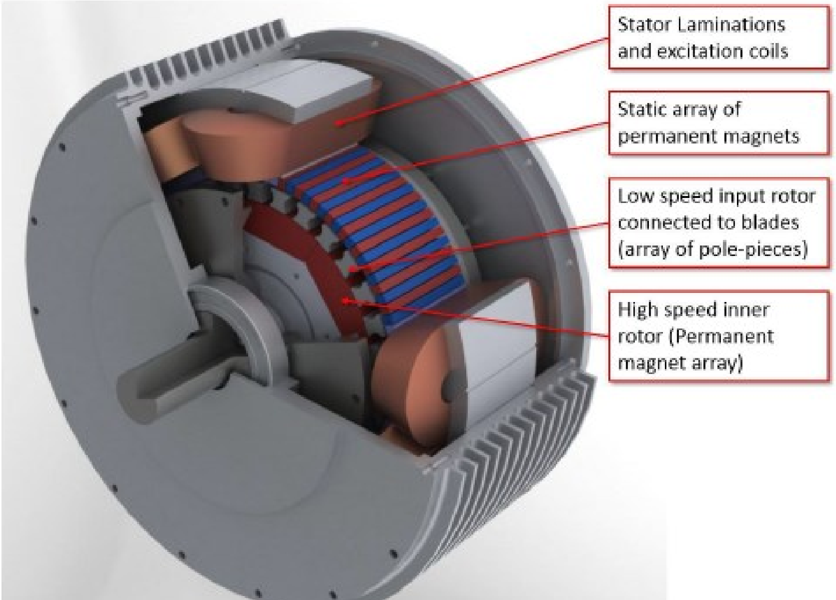
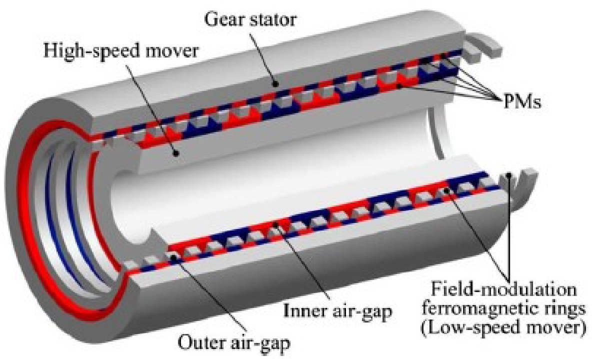
Speed Enhancement

- Electromagnetic Gearing
- Torque Density: 100kN/m^3
- Machine: 10-30kN/m^3



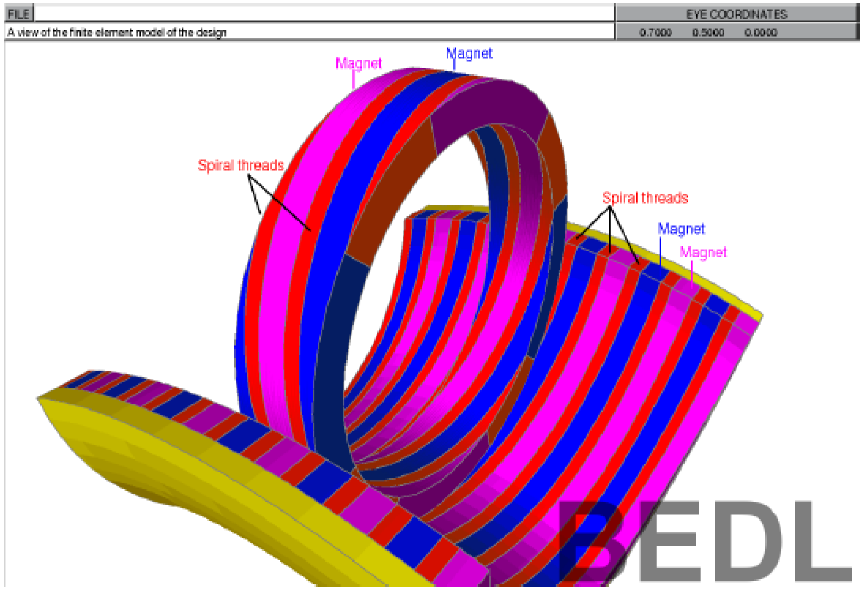
Magnomatics and Uinversity of Sheffield



Application of Linear Magnetic Gears for Pseudo-Direct-Drive Oceanic Wave Energy Harvesting, Li et al, IEEE TRANSACTIONS ON MAGNETICS, VOL. 47, NO. 10, OCTOBER 2011

Speed Enhancement

- Electromagnetic Worm Gear
- Prof Dave Rodger
- Bathwick Electrical Design Ltd.



Comparison with other machines

	AMSC [10] HTS 10MW	NREL [10] PM 10MW	GE [9] LTS 10MW	BEDL OMEGA 10MW
o/d m	5 ?	4.3	4.83	4.8
Active Length m	1.72	6.78	1.88	1.0
σ kN/m^2	??	42.0	179.0	400.0
Total mass t	142.0	311-336	145.0	64.0

Novel Lightweight Wind Turbine Generatior, Rodger et al,
UK Mag Soc Seminar on Novel Machines, Newcastle Feb 2015

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PTO Design Challenges

- Reliability
- Affordability
- Availability
- Efficiency – at all loads
- Survivability
- All impact on LCoE

Aerospace

- All Electric Aircraft.
- Replace hydraulics with electric systems.
- Reliability
- Fault Tolerance
- Efficiency
- High Power Density

WP Description

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WP1:Integrated Electrical Generator Speed Enhancement Design

1.1. Low Speed Pole Modulated Generator for Heave Based Devices, NCL lead, TU Delft, M1-36

- Learn from automotive
- Soft Magnetic Composites & Modular
- Design study of different topologies – TUD
- Optimise for high force density, low inductance, efficiency
- Electromagnetic, thermal and structural

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WP1:Integrated Electrical Generator Speed Enhancement Design

1.2 Speed Enhancement , UoE lead, NCL & TU Delft,M1-36

- Non-mechanical technology
  - Magnetic gearing options, internal and external
  - Magnetic ball screw
  - Magnetic worm gear
- Internal/external spring
- System force density target – 150 kN/m^2
- High efficiency and low cost

WP1: Integrated Electrical Generator Speed Enhancement Design

1.3 Integrated Generator Speed Enhancement Design Review, joint UoE/NCL lead, TU Delft M12

- Integrate tasks 1.1 & 1.2.
- Optimum electrical generator system with speed enhancement
- Recommendations for different wave devices
  - direct drive only;
  - magnetic gearing with low speed;
  - internal generator spring with low speed generator;
  - external electromagnetic spring with low speed

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WP2: Integrated Power Converter Generator Systems

- **NCL lead, Pickert & McDonald, University of Chile, M1-36**
- Thermal cycling is an issue for power converters.
- Low frequency pulsating power flow in wave.
- Multiple Bi-directional inverters connected in series for multi-phase machines.
- Approach used in wind and automotive, but not for bi-directional power flow.
- Smaller, cheaper devices.
- Improved reliability, modularity, flexibility
- Interactions will be evaluated and optimised:
  - converter architecture,
  - machine power factor,
  - power flow, cost,
  - complexity, overall drive train efficiency,
  - thermal fatigue, switching device utilisation and
  - wave energy converter control

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WP3 System Modelling and Control (UoE Lead, University of Chile)

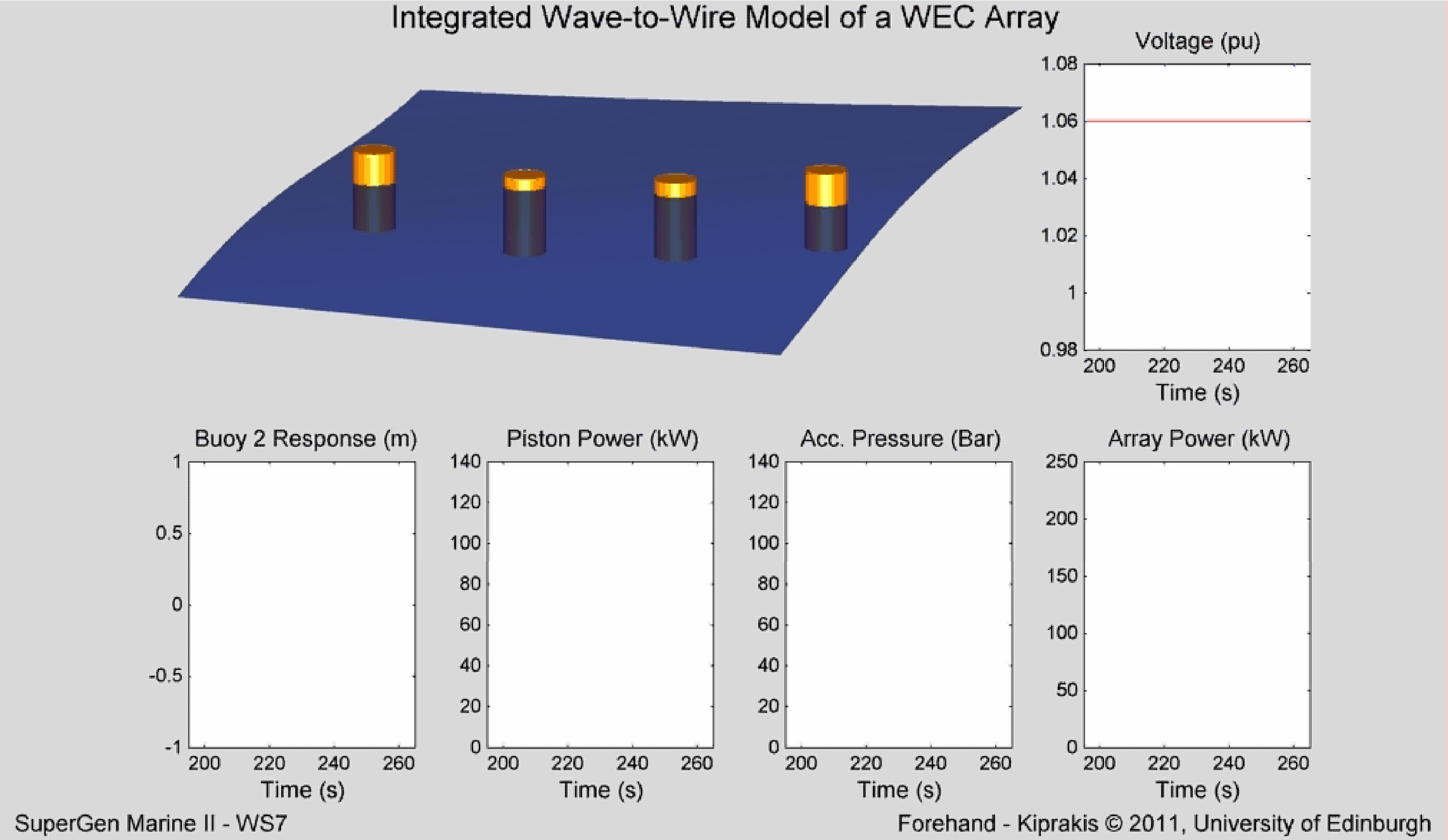
3.1 Wave to Wire Models (Kiprakis & Crozier)

- UKCMER Wave to Wire models.
- Model industrial partners' device – block in SIMULINK.
- Integrated Speed Enhancer Generator block.
- Power converter block from WP2.
- Reactive force control investigation for device tuning.
- Tool used in WPs 4 & 5.

3.2 Multi-Directional Energy Conversion. (Mueller and Crozier)

- Determine forces for multi directional Energy generation.
- Evaluate concepts for generator configurations to produce these forces.

Wave-to-Wire Model of Heaving Buoy Array



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WP4 Design for Survivability (Mueller & Crozier)

- **UoE lead, support from industrial partners,**
- Included on recommendation of Carnegie Wave Power.
- Extreme events – no generation, so mechanical and structural survivability.
- Estimate stresses, fatigue, displacement in generator structural design.
- Matrix of extreme load severity versus percentage reduction in structural life.
- Design guidelines and recommendations.

WP5 Experimental Demonstration

- **NCL lead, M19-36**.
- Prototype electrical generation system based on previous WPs. Fully instrumented.
- Test dry at NCL; wet at UoE.
- Demonstrate reactive force control.
- Integrate into Carnegie device and test in FloWave.
- Emulate extreme events in FloWave.
- Experimental verification of design tools.
- NCL will build prototype. UoE will test.

WP6 Design Case Studies

- **UoE lead, support from industrial partners M25-36**
- Design studies for each industrial partner device.
- A full design report including a fully integrated electro-mechanical generator and power converter design with CAD drawings (WPs 1, 2 & 4);
- Dynamic simulation results of each device under different sea states (WP5).

WP7 Industrial Engagement & Impact Management (M1-36)

- Henry Jeffrey, Adrian de Andres & David Bould
- HJ will Chair IAB.
- Adrian and David will lead industrial engagement: device developers and supply chain.
- Attendance at trade conferences.
- Partner database and project web-site.
- EDRIVE Commercial Roadmap.
- Impact Management and Collation of Impact Data.

Project Management.

- Mueller and Baker are responsible.
- Weekly Webex meetings between UoE and NCL.
- Quarterly Management Meetings:
  - monitor and review the technical progression
  - Risk Register, project plan,
  - Resources and other non-technical issues
  - Alternate between UoE and NCL
  - TUD, UdC & UNAM join if available by Skype
- Stage Gate Approach and Change Management Procedure.

Economic Impact: Industrial WP7

- IAB
  - meetings M12, M24 and M36
  - Funding for travel to kick off meeting and one IAB.
  - Alternate IAB at different partners
- Annual Flyer on Project Progress
- Meetings with other wave, tidal developers and supply chain.
- Commercial Roadmap

Economic Impact: Investment

- Attend Investor conferences
  - Low Carbon Energy Investor Forum, 2017
  - Scottish Low Carbon Investor Conference, annual.
- Work with Scottish Development International and UK Trade and Industry to attend trade missions.
- IP generation, patents and spin outs

Economic Impact: Technology & Practice

- Contribute to supply chain workshops
  - Scottish Enterprise and The Neptune Centre
- Link up with Wave Energy Scotland.
- Organise and EDRIVE Supply Chain Workshop
  - Strengthen links with other partners who could benefit from project.
  - Siemens, Control Techniques & Parsons Peebles in the machines & power electronics supply chain;
  - Arnold Magnetics, Tata Steel and Höganäs in the material supply chain;
  - Linear machines companies Libertine and Force Engineering.

Pathways to Knowledge Impact: Scientific Advances & Techniques

- UKCMER and Centre for Power Electronics
  - Attendance at ¼ ly meetings and assembly
- Marine Renewable Innovation Centre (MERIC) in Chile Prof Cardenas
- CEMIE Ocean and Prof Casarin, in Mexico
- International Conferences and Journal Publications.

Pathways to People Impact – Skills and People Pipeline

- Develop a summer school activity for school pupils such as Headstart – years 2 & 3.
- Undergraduate MEng and BEng projects.
- PhD summer schools – UKCMER, Power Electronics Summer School (UK and EU).
- Contribute to IDCORE and CDT courses.
- Tutorial Sessions at Conferences.
- PhD recruitment onto project.

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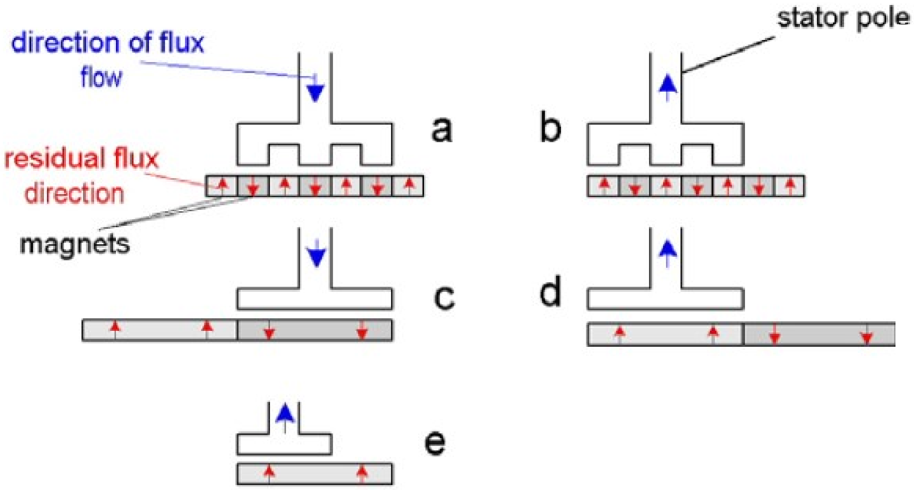
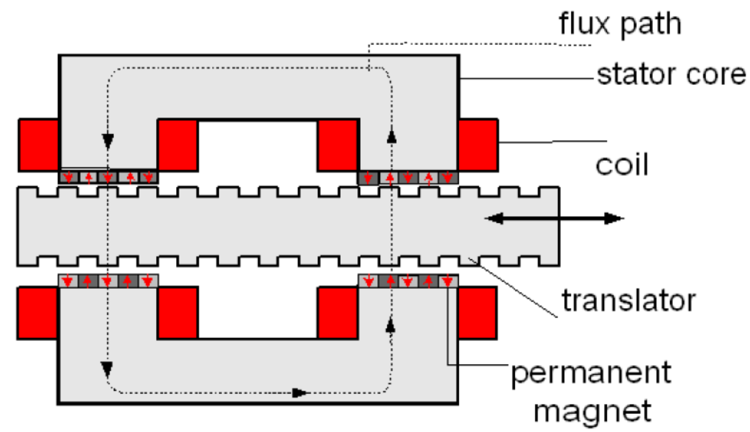
Pathways to Society Impact (Policy and International Development)

- Inform policy through Technology Roadmapping.
- Partnership with MERIC and CEMIE at International Level.
- Feed into EERA Ocean Energy – chaired by HJ, UoE.
- Disseminate through EU Ocean Energy Association – HJ sits on the board.
- Project website and media interaction.

Current Status

EDRIVE machines work





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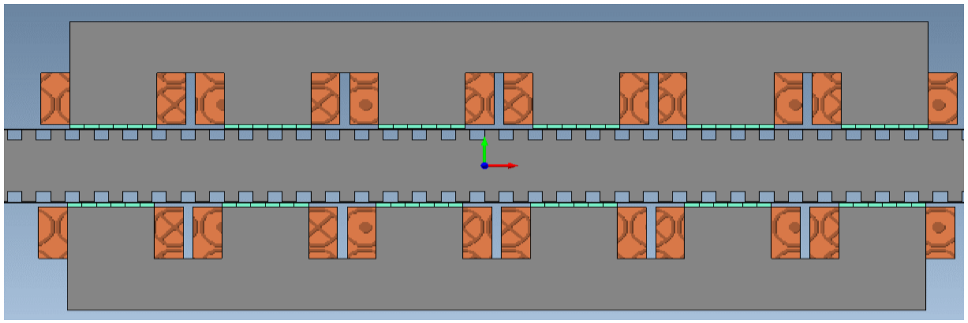
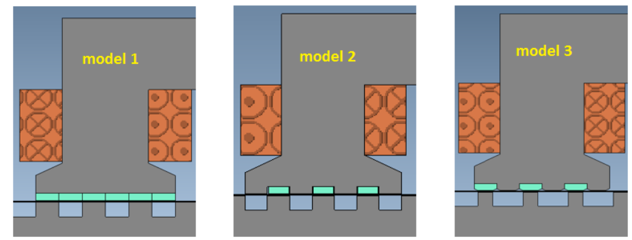
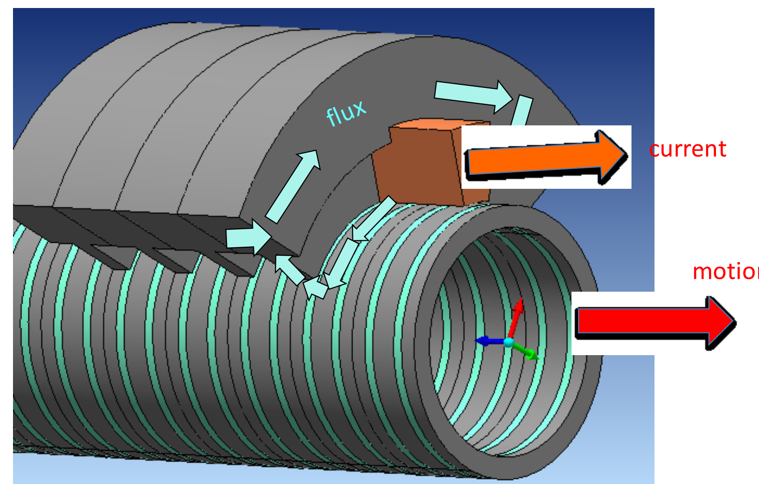
EDRIVE machines work – 2PhDs







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EDRIVE machines work

WP1 Integrated Electrical Generator Speed Enhancement

Low speed machines with integrated magnetic gearing

Speed enhancement through control

High shear stress topologies
- Linear
- oscillating rotary

Integrated machine design (eg effect of cogging and inductance on device / converter)

Power electronic

EDRIVE Converter Work (Steve McDonald)

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EPSRC Engineering and Physical Sciences Research Council

SUPERGEN GRAND CHALLENGES

EDRIVE Converter Work - Aims

WP2 Integrated Power Converter Generator Systems

Prioritise reliability of converters *within* wave devices.

Thermal management / pulsating power

Variable device loading

Multi level, reliable, flexible, modular and scalable

Drive implications of “electronic” spring / control on the VA rating of the converter

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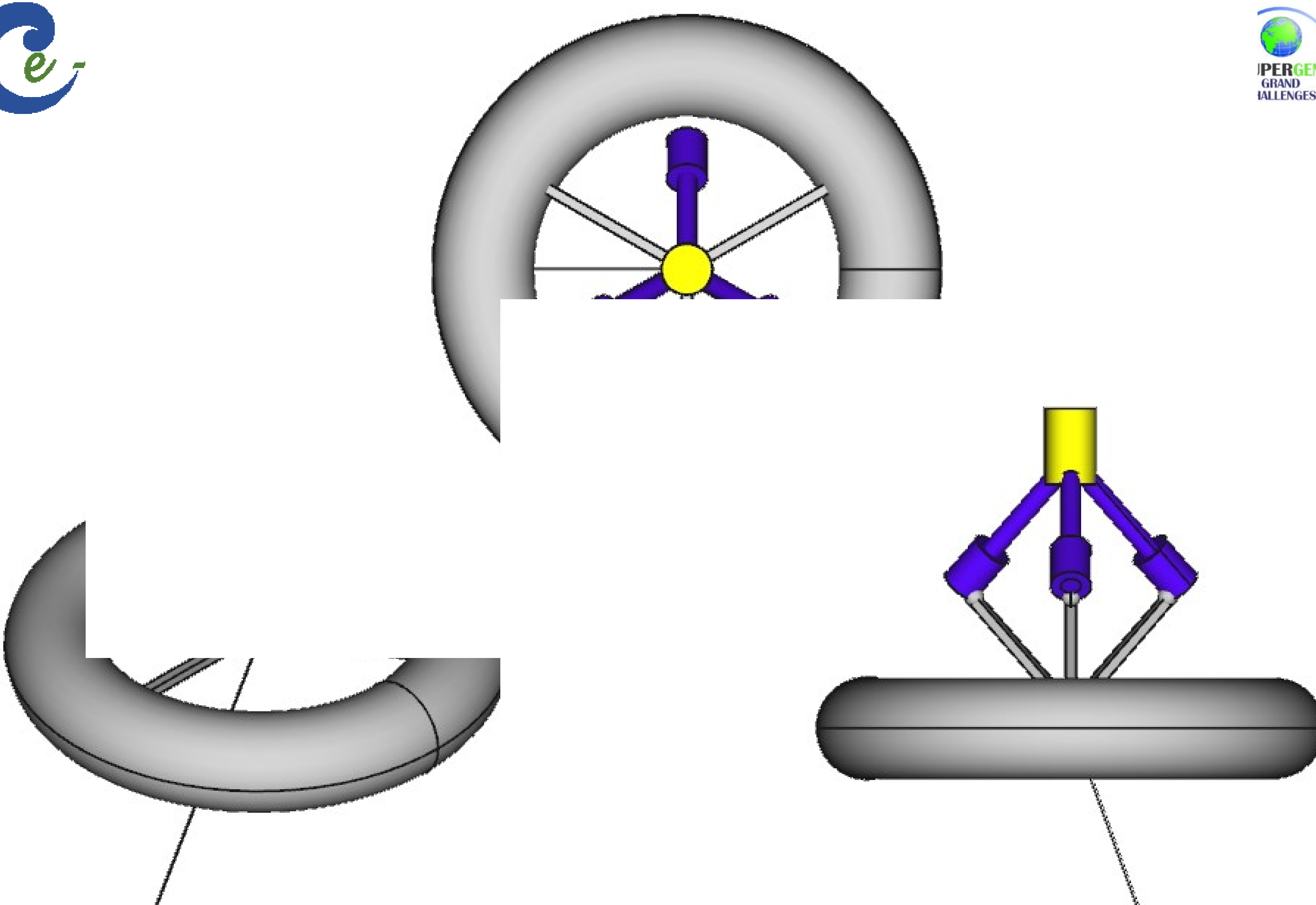
What Newcastle needs….

Specifications of…
power rating, force, amplitude, frequency, target mass, available space

WP1 Progress: Concepts

- PTO Arrangements
- Novel Vernier Hybrid Machine Topology
- Spherical Vernier Hybrid Machine Concept
- "Chain Drive" Magnetic Gear



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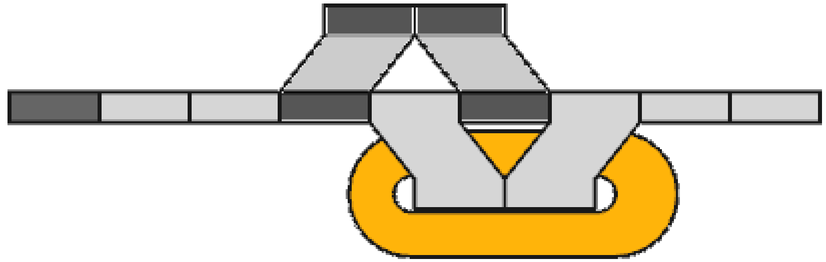

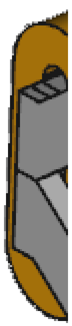

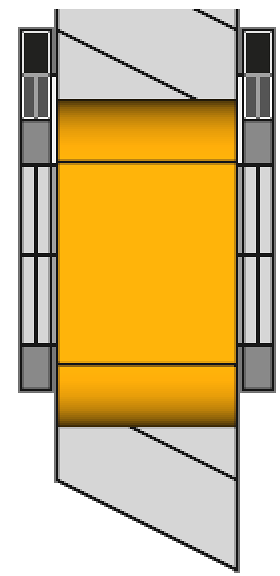

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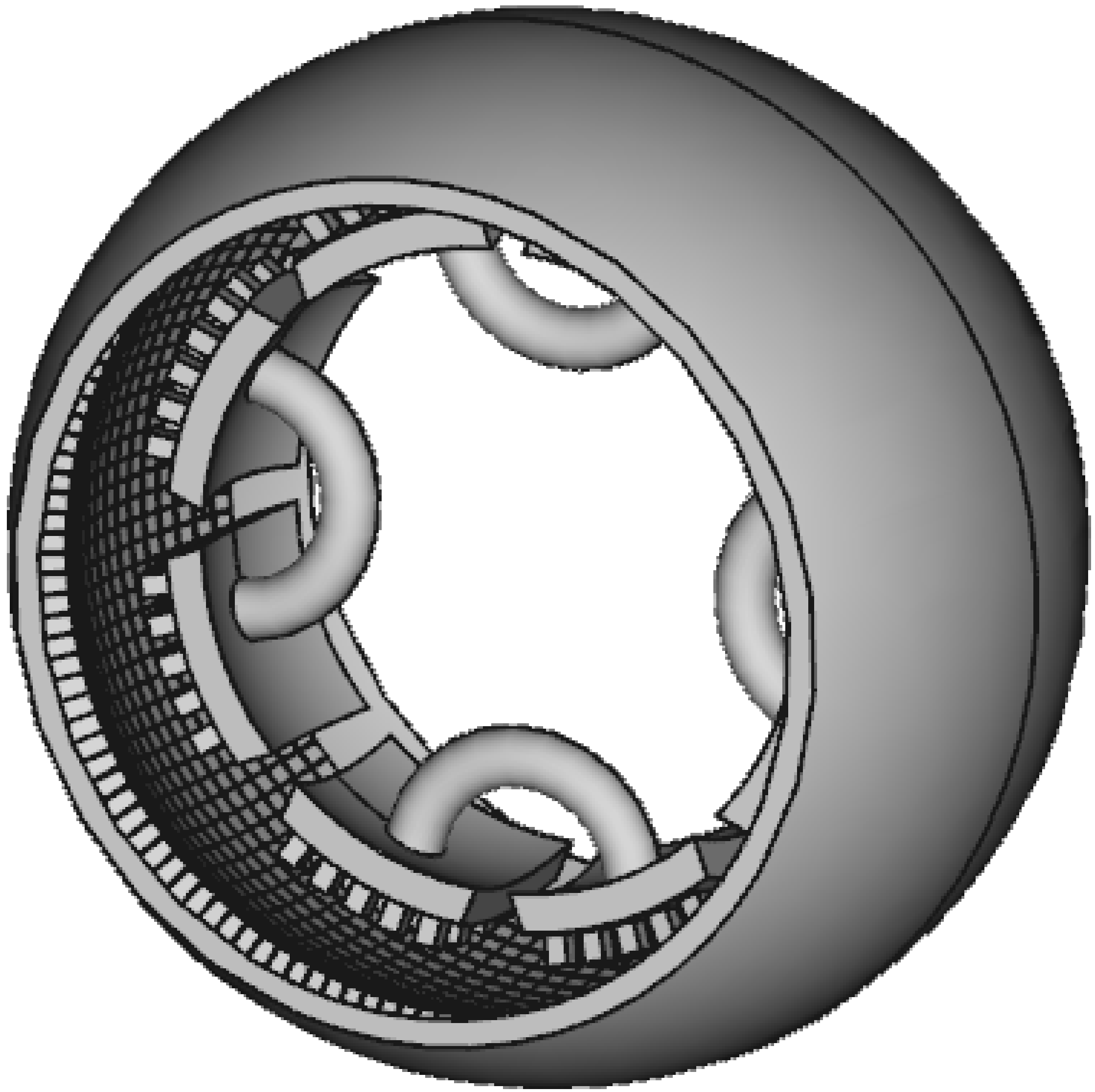

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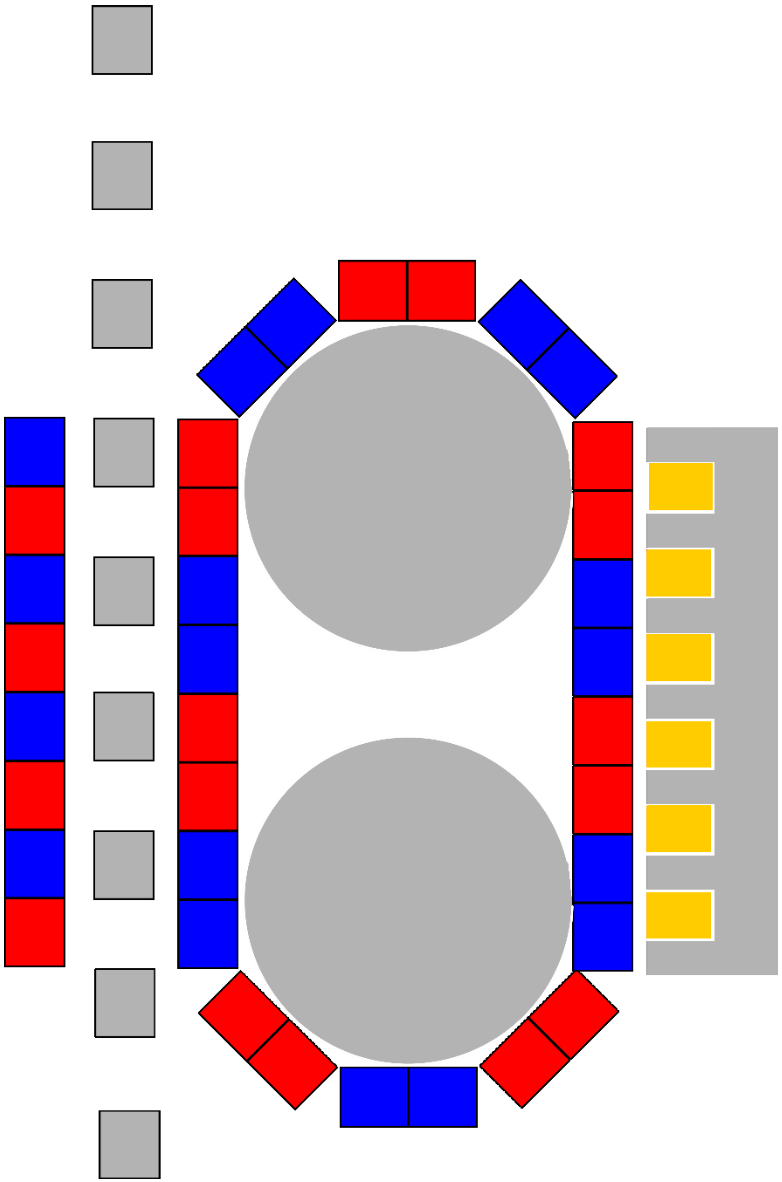

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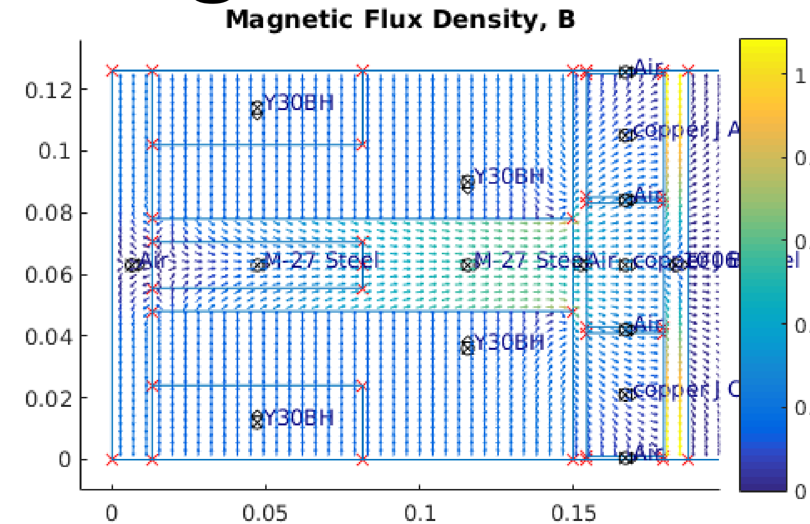
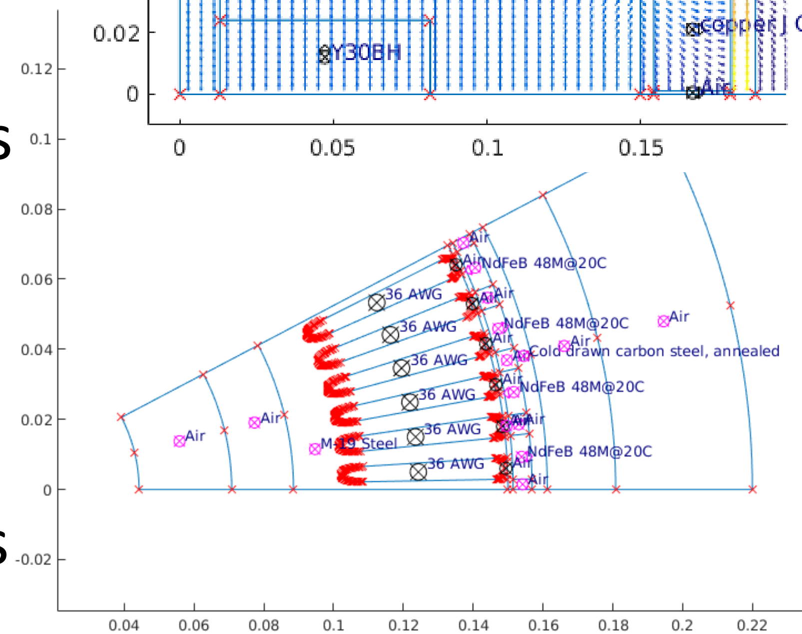
Electrical Machine Design Software

- Produces many metrics for a design
- Modular so you can replace part as desired while retaining what you need
- Can runs optimisations on high throughput computing systems (tested on google cloud compute engine)
- Doesn’t use Simulink (by default)
- Automatic reporting functions produce pdf reports on designs





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E-Drive: WP7 Industrial Engagement & Impact Management

Dr Adrian de Andres
Policy and Innovation group
The University of Edinburgh

EDRIVE Kick Off Meeting 25th May 2016

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Policy and Innovation group

- Examine the dynamics of innovation in energy systems, focusing specifically on the relationship between policy, investment and innovation.
  - Innovative technologies
  - Technology and policy development/deployment strategies and roadmaps
  - Investment strategies through roadmaps
- We examine gaps and barriers within the industry
- We make a lot of recommendations of how to overcome said gaps and barriers
- Influence a wide variety of stakeholders

Projects

- *DTOcean*
- *LEANWIND*
- *EERA*
- *Roadmaps*
- *OPERA*
- *ClearWater*
- *Joules*
- *Mocean*
- *Hi Drive*
- *TC114*

Roadmaps

- What are they and why do we use them?
  - Identify priority actions for governments, industry, financial partners and civil society that will advance technology development in order to achieve international climate change goals.
  - Roadmaps are an effective tool to underpin the identification of policies and measures.
  - Focus R&D and business investments to accelerate technology development
  - Coherent approach and significant engagement with the global market

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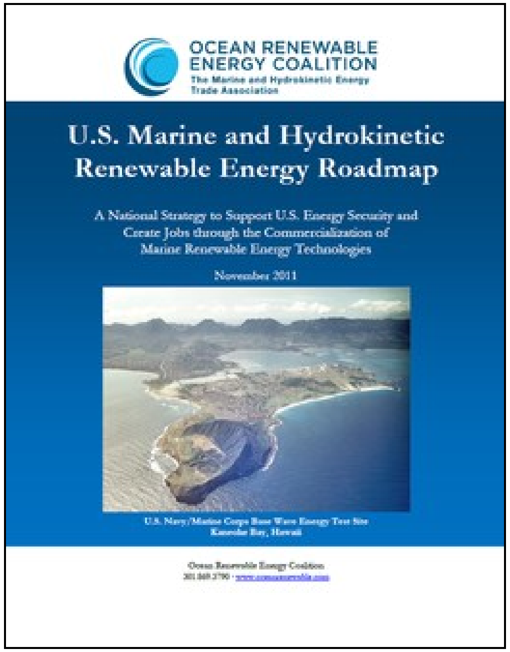
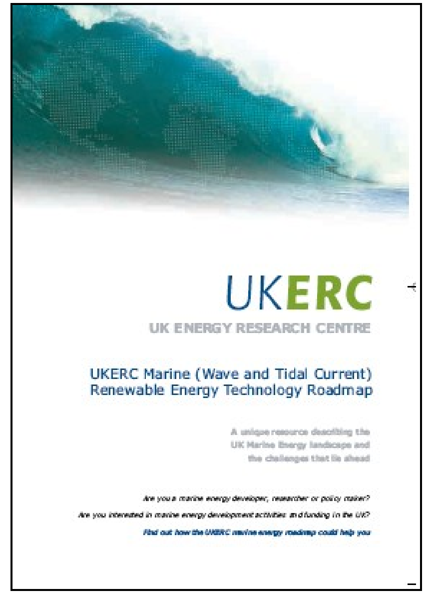
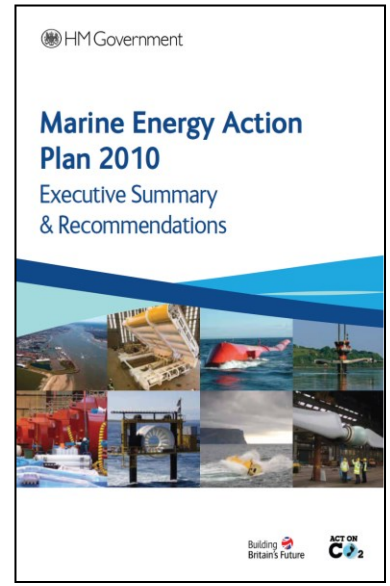
Strategy documents authored by UEDIN

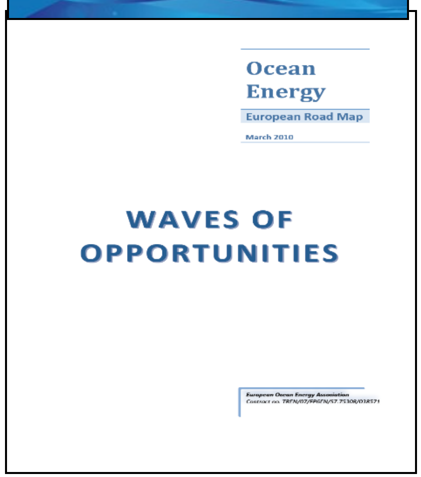


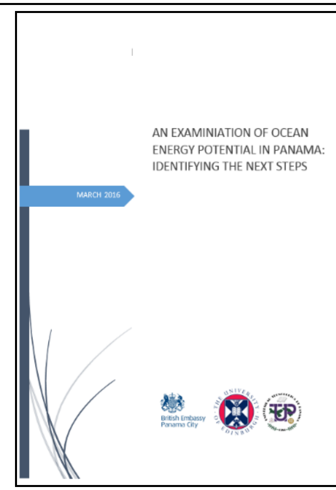


The Scottish Government



NREL
National Renewable Energy Laboratory
Innovation for Our Future





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Roadmaps

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- **Two main types of roadmaps**
  - **Deployment**
  - **Development**

SI OCEAN
strategic initiative for ocean energy

Chilean Roadmap and Targets

- Resource:
  - 165GW estimated gross potential (wave)
  - 500 MW estimated gross potential (tidal)
- Finance:
  - Quota or minimum percentage of energy from NCRE
    - Corfo funding
- Regulation and Legislation:
  - Early-stage consenting process.
  - Studies ongoing to decise if and how marine energy is to be developed.
- Development strategy
- Deployment strategy

IEA- OES VISION

- **An International Vision for Ocean Energy**

- **The objectives of the Vision document will be to provide a firm vision for ocean energy to 2020 with a perspective on developments to 2050**

- **Ocean Energy Resources, Technologies Market development**

- **By 2050**
  - **337 GW installed wave and tidal energy capacity**
  - **1.2 million direct jobs created**
  - **1.0 billion tonnes of CO_2 emission saved**

ORECCA Roadmap

- ORECCA Roadmap
  - Resource
  - Finance
  - Technology
  - Infrastructure
  - Environment, Regulation & Legislation

Roadmap Structure and Methodology

- INTRODUCTION
  - RESOURCE
  - FINANCE
  - TECHNOLOGY
  - INFRASTRUCTURE
  - ENVIRONMENT, REGULATION & LEGISLATION

→ 5 Principal streams, each with identified

- -Synergies
- -Commonalities
- -Gaps
- -Opportunities
- -Recommendations

WP7 Plan/ activities

Industrial Advisory board

Select members

Organize fist IAB

Stakeholder engagement

Decide events for communication activities

Commercial roadmap

Cost study

Gaps/opportunities

Project website

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Thank you for your attention

Any questions?

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Industrial Contribution

Industrial Contribution in WPs

- WP 1 & 2
  - Provide Data/Specification for Design
- WP3
  - Support Wave to Wire Modelling
  - Provide hydrodynamic data for device model
- WP4
  - Environmental Load Data for Design for Survivability

Industrial Contribution in WPs

- WP5
  - Use of model for FloWave testing - Carnegie
- WP6
  - Provide data/specification for Case Studies
- WP7
  - Participation on Advisory Board
  - Advise on commercialisation strategy

Case Study Examples

- Npower juice project
  - Aquamarine Oyster Case Study
  - AWS Case Study
- Input from Company
  - Device Specification/Performance Data from developer
  - General dimensions of device
- Output from Case Study
  - Optimised PTO design
  - Performance curves under different scenarios
  - CAD drawings with dimensions
  - Power Converter options
  - Use Wave to Wire model to look at system operation and control
  - Detailed confidential report on each case study.