SEAI RDD Project

Laser Ablation and Spectroscopy for Optimisation of Wind Turbine Performance

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Outline of the Presentation

- Overview - Wind Energy in Ireland
- Wind turbines–The (Fluid) Aerodynamics Problem.
- Orientation – What is Laser Ablation (LA) and Laser Induced Breakdown Spectroscopy (LIBS) ?
- Standoff LA and LIBS
- Project Objectives and Tasks/PhD Project Areas
- PhD Funding
- Application Information
- LA & LIBS Laboratories (DCU & UCD)

Wind Energy in Ireland – The Numbers

368 - The number of wind farms on the Island of Ireland

>250 - The number of wind farms in the Republic of Ireland

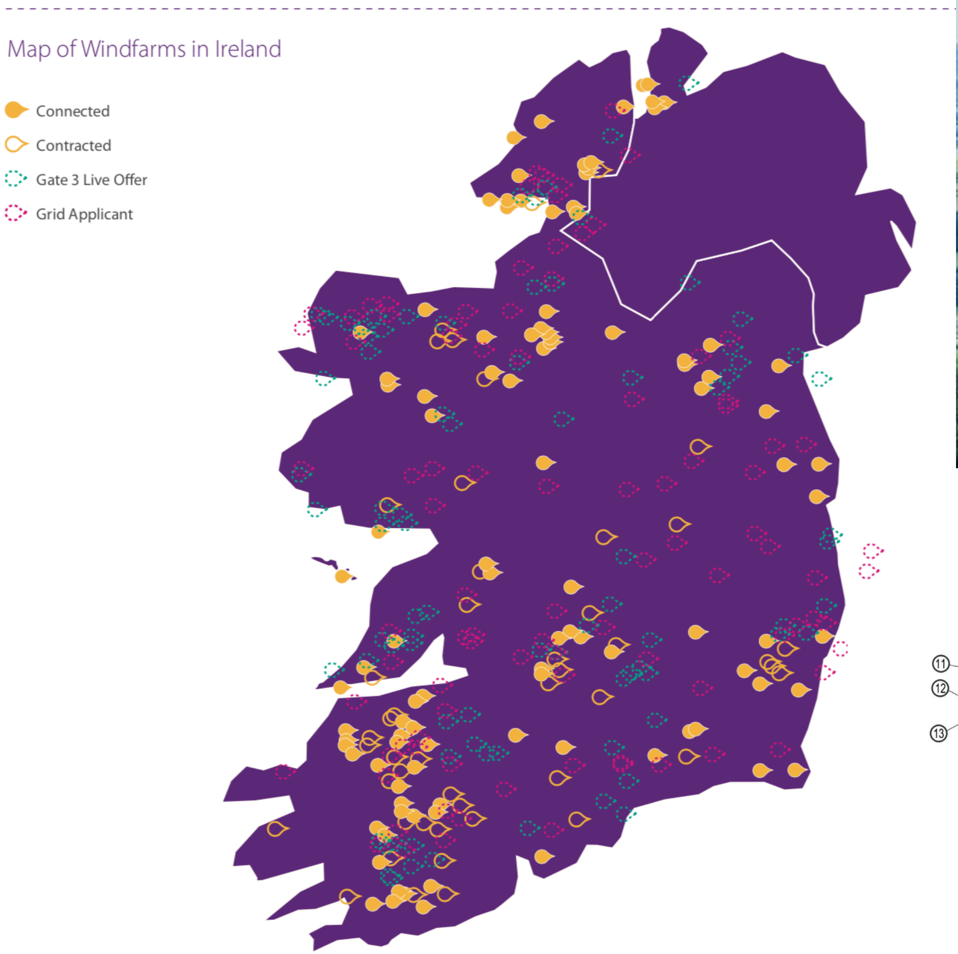
5,030 MW - Installed Wind Energy Capacity on the Island of Ireland

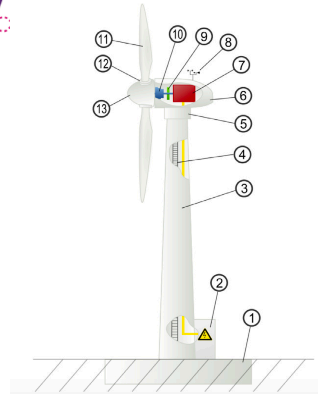
3,700 MW - Installed Capacity in the Republic of Ireland

3,347 MW - Republic of Ireland Wind Generation Record reached on Friday 21st February 2020

25% - All electrical generation accounted for by wind energy in 2017 (SEAI report, 2019)

Wind Energy in Ireland – The Numbers

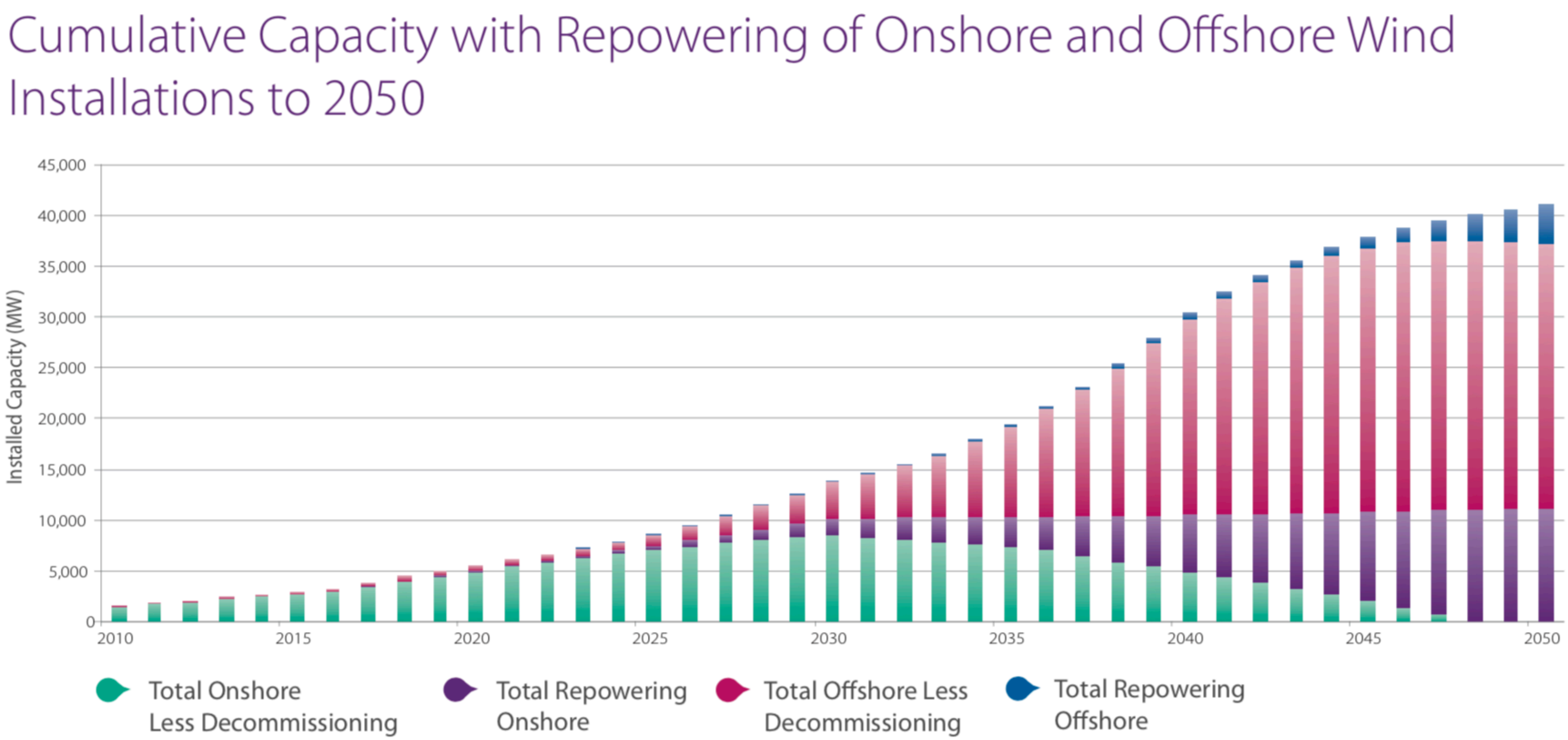




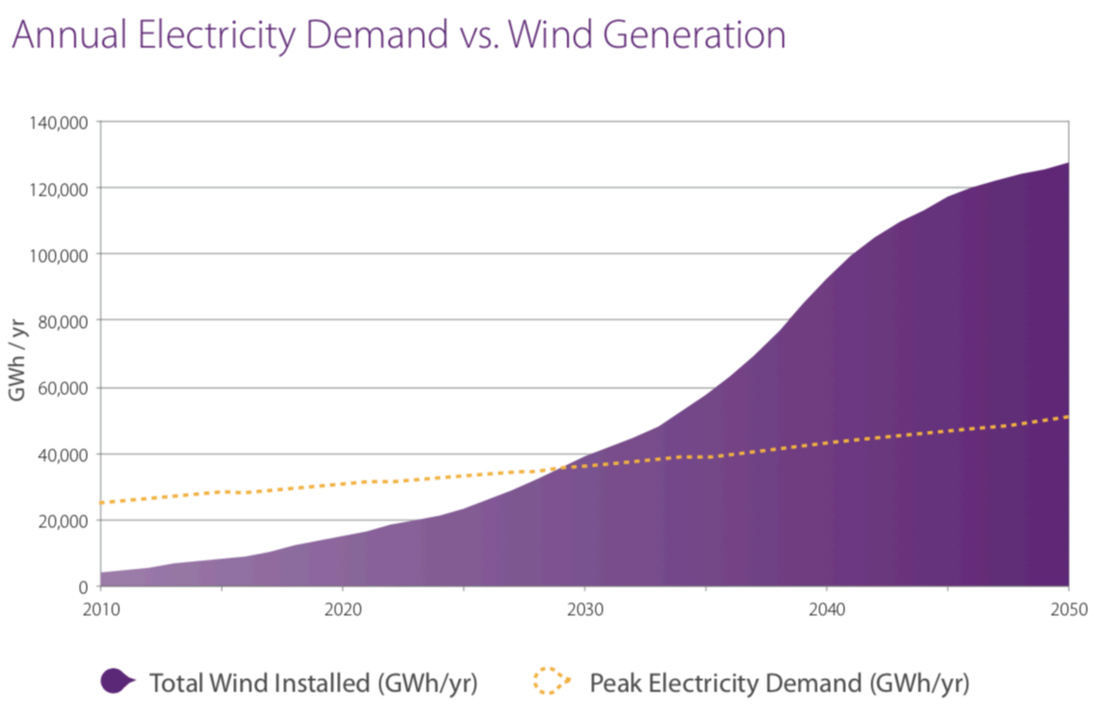
1. Foundation
2. Connection to electricity grid
3. Tower
4. Access ladder
5. Wind-orientation (yaw) control
6. Nacelle
7. Generator
8. Anemometer
9. Electric or mechanical brake
10. Gearbox
11. Rotor blade
12. Blade pitch control
13. Rotor hub

Renewable and Sustainable Energy Reviews 53 (2016) 1212–1221

Wind Energy in Ireland – The Numbers



Wind Energy in Ireland – The Numbers



Key Point: Ireland has the potential to generate enough electricity to exceed domestic demand by 2030.

Wind Energy in Ireland – Numbers & Environment

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- The SEAI 'Energy in Ireland 2018' report states that "CO_2 emissions from the combustion of fossil fuels account for approximately 60% of Ireland's total greenhouse gas (GHG) emissions."
- Onshore and Offshore wind represent a significant carbon abatement opportunity Wind could abate between 400 and 450 Megatons of CO_2 by 2050.
- At the meeting of the European Council in October 2014, political agreement was reached on the headline targets for the 2030 Climate & Energy Framework:
  (i) a reduction in greenhouse gas emissions of 40%;
  (ii) an increase in EU energy from renewable sources to 27% - cf. COP20.
- In 2018 Wind provided 85% of Ireland's renewable electricity and 30% of our total electricity demand. Ireland will be a net exporter of electricity (2025).
- Feb 2020. ESB Networks confirmed it has connected 3.3 GW of wind capacity into the Republic of Ireland's electricity system, contributing to "record levels" of renewable generation in recent weeks. - https://renews.biz/57822/esb-networks-plugs-4gw-of-wind-into-irish-grid/

The Aerodynamics Problem

- Wind turbines have blades (aerofoils) just like aircraft wings
- So basic fluid (aero) dynamics applies to wind turbines. The main parameters are the Coefficients of Drag, Lift and Moment (@Chord Length), namely C_d, C_L and C_M.
- Too much aerofoil surface roughness causes airplanes fall out of the sky due reduced C_L and/or increased C_D leading to stalling.
- Aerodynamic Stall and Loss of Control During Approach, Embraer EMB-500, N100EQ, Gaithersburg, Maryland, 2014 https://www.ntsb.gov/news/events/Pages/2016_gaithersburg_BMG.aspx

The Aerodynamics Problem

brief communications

NATURE | VOL 412, 2001, pp42-43

Insects can halve wind-turbine power

For no apparent reason, the power of wind turbines operating in high winds, may drop, causing production losses of up to 25%[1]. Here we use a new flow visualisation technique to analyse airflow separation over the blades and find that insects caught on the leading edges in earlier low-wind periods are to blame. These potentially catastrophic power glitches can be prevented simply by cleaning the blades.

Unpredictable changes in power levels have been noted on wind farms in California, with power sometimes falling to half the output predicted from the turbine design and generating two or more different power levels at the same wind speed (Fig. 1a). Although this phenomenon (termed 'double' or 'multiple' stalling) has been investigated[2-4], the cause has remained unknown.

One study[5] commissioned by a turbine manufacturer (NEG Micon) used a new invention called a stall flag[6] (patent, Energy Centre of the Netherlands) as a flow-separation detector (Fig. 1b) to try and solve the problem. This device works on the principle of a hinged flap that opens up in a separated airflow to uncover an individual reflector (Fig.1c) which allows the flow to be visualised. Operation of a stall flag on a turbine with a rotor diameter of 44 metres is illustrated in Fog. 1d, in which the light tracks are from exposed reflectors and indicate where the blades stall.

We found that the stalling behaviour of the blades depends on the degree of contamination of the leading edges. However, the reduction in power should be continuous (as debris on the blades would be expected to accumulate gradually) rather than stepped in distinct levels as shown in Fig. 1a.

We considered the possibility that flying insects caught on the turbine blades could explain this effect. Insects prefer to fly in conditions of high air humidity, low wind and temperatures

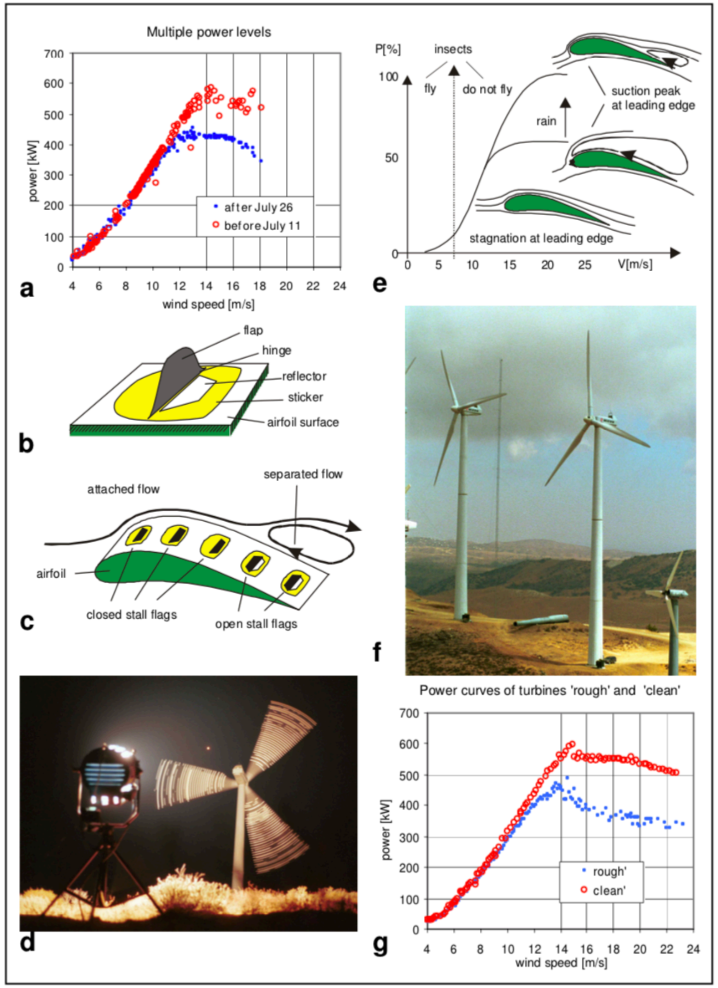


Figure 1 Insects cause multiple power levels from wind turbines. a, Example of two power levels at the

The Aerodynamics Problem

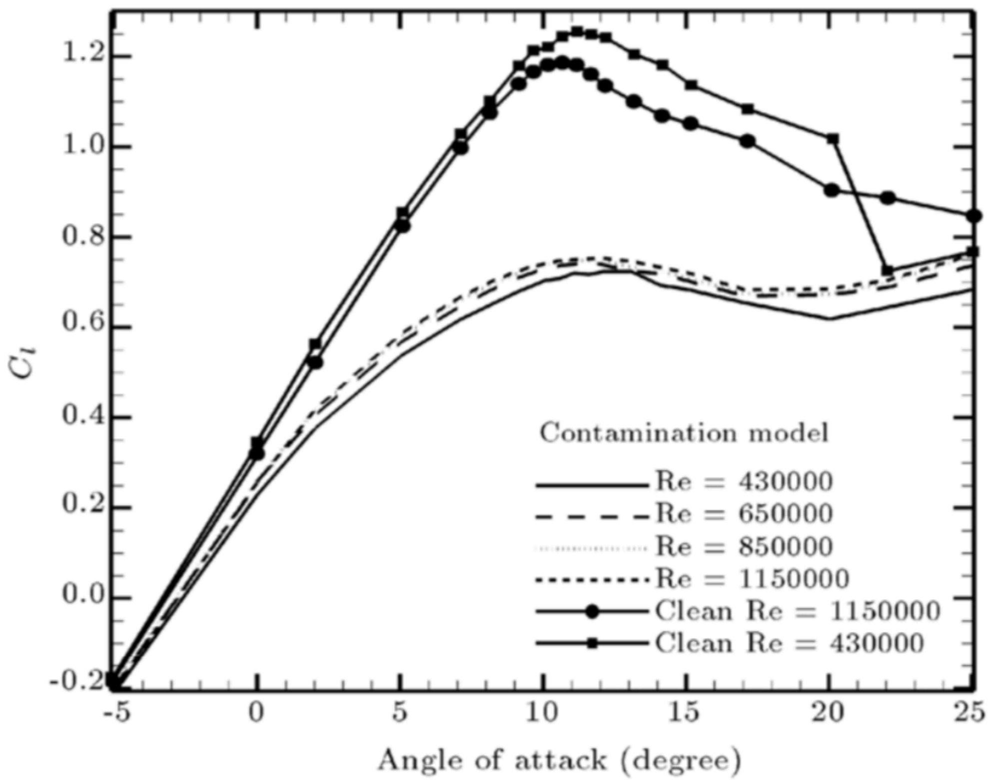
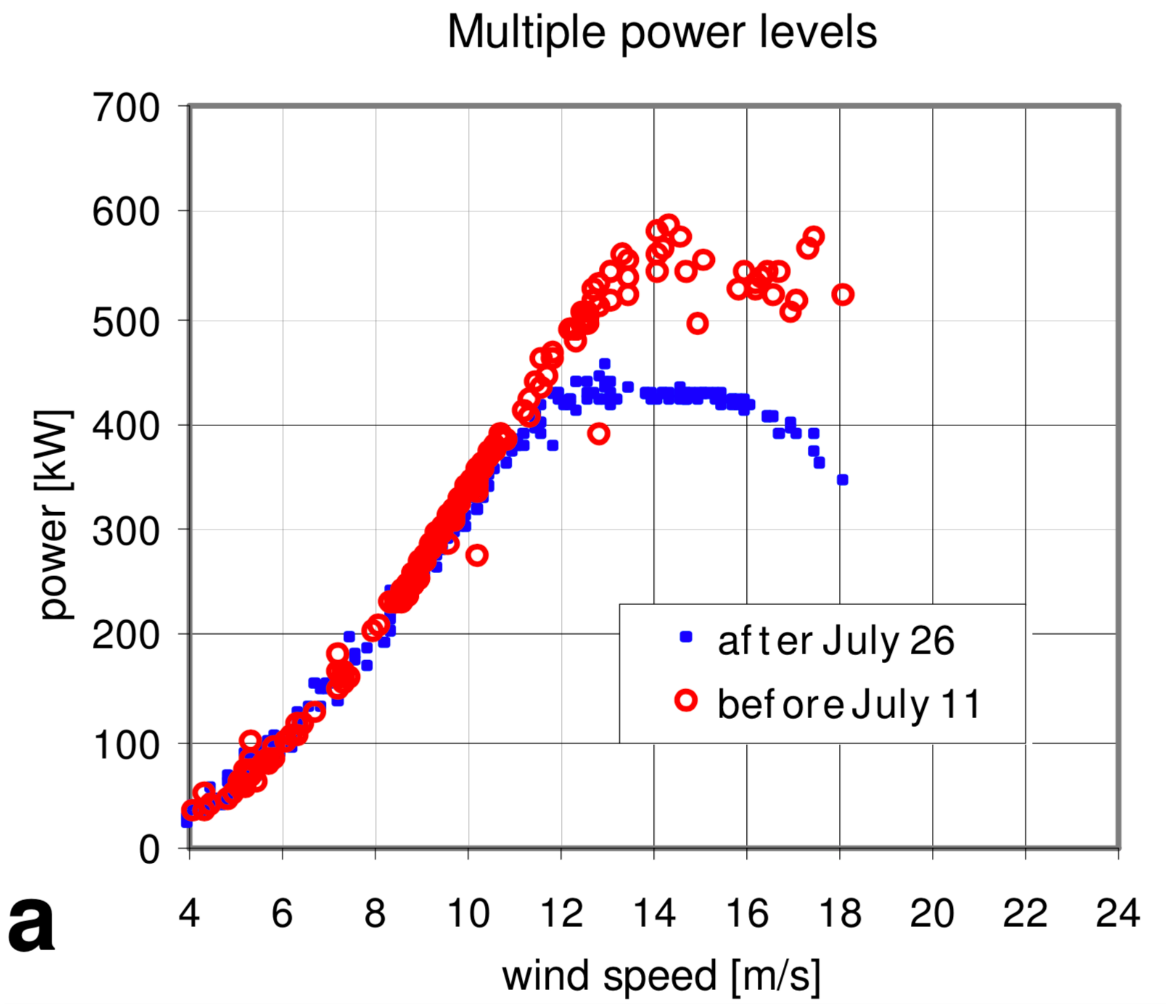


Figure 16: Lift coefficient variation for airfoil with surface contamination.

Scientia Iranica B (2011) 18 (3), 349–357

The Aerodynamics Problem



NATURE | VOL 412, 2001, pp42-43

Aerodynamics – Contaminants and Cleaning

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WIND POWER BLADE CLEANING OF EXISTING

(a) Manual Cleaning

(b) BladeCleaning[4]

(c) EXTREME Wind Services[8]

Fig. 4. Wind Power Blade Cleaning of existing

2012 Proceedings of the 29th International Symposium of Automation and Robotics in Construction, ISARC 2012

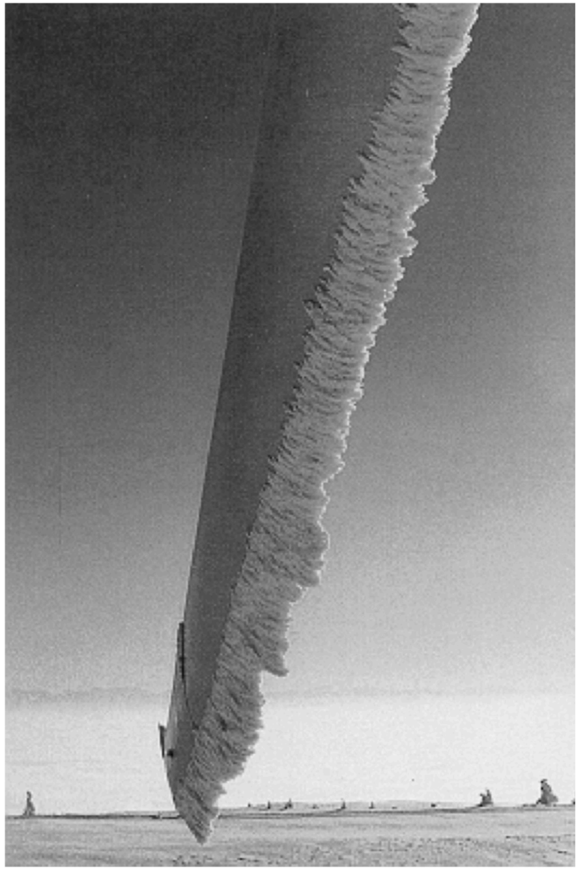

Fig. 1. Iced turbine blade in Switzerland; Tammelin et al. [6] (Photo by ADEV).

Renewable and Sustainable Energy Reviews
Vol. 13 (2009) 428–438

Aerodynamics – Our Solution – Project Pitch

- It has been well established by both computational fluid dynamic (CFD) modelling and wind tunnel tests that the fouling of turbine blades has a dramatic negative effect on their aerodynamic performance and hence on the wind to electrical energy conversion efficiency (CE), reductions of ca. 40% can occur.
- Currently the only solution is wet cleaning which is labour intensive, hazardous and dirty.
- We propose laser ablation, i.e., the removal of thin layers of material by irradiation of a surface with a pulsed laser, as an alternative green solution. It has been applied already to the delicate task of cleaning everything from cultural artefacts such as paintings and sculptures to large buildings of historic interest.
- As a side effect, the material ablated by the laser forms a light emitting plasma plume which contains spectral signatures (emission lines and bands) that are fingerprints of the elements constituting the material ablated allowing them to be classified and quantified. This technique is known as LIBS (laser induced breakdown spectroscopy).
- In addition, the signatures can be used to identify when all contaminants have been removed and the blade surface is clean.
- The ***overarching objective*** of this proposal is to develop and apply standoff Laser Ablation-Laser Induced Breakdown Spectroscopy to both ***classify and quantify*** blade fouling and to ***provide a safe, clean and efficient solution*** to it for wind energy providers.

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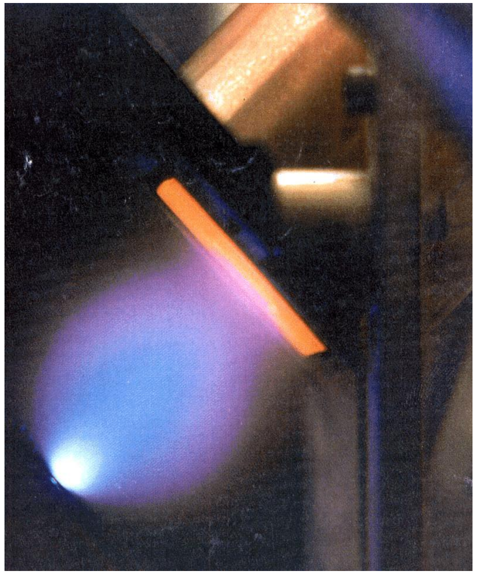
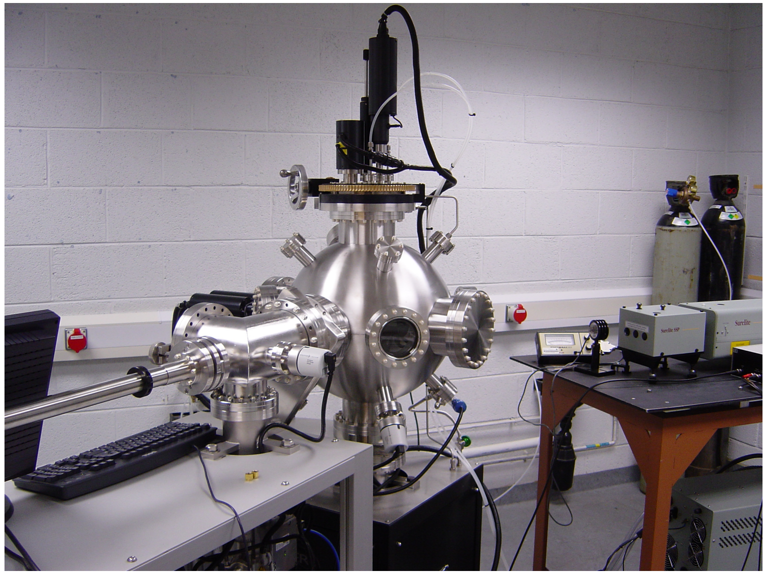
Orientation - Laser Ablation

The selective removal of materials from surfaces irradiated by pulsed lasers. Depends on laser, material bulk and surface parameters.



PLD - Laser ablated material deposited on a solid substrate



Commerical Pulsed Lased Ablation (Deposition) System – (DCU)

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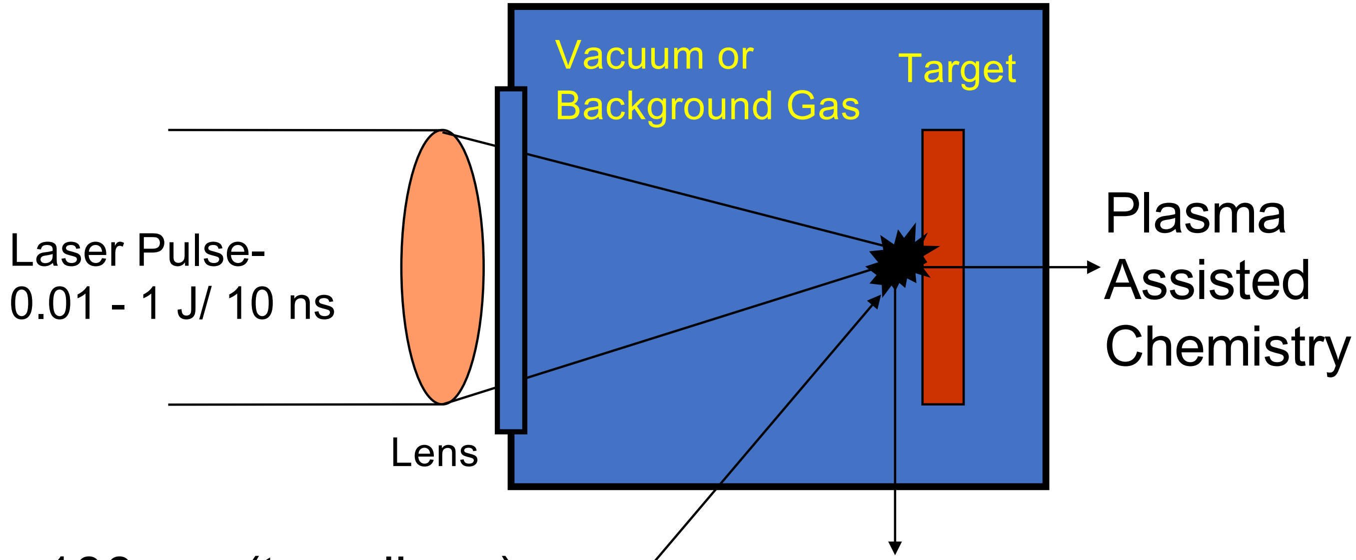
Orientation - Laser Ablation & Plasma Formation



Spot Size = 100 μm (typ. diam.)

$\Phi > 10^{8-12}$ W.cm^{-2}

T_e = 1 - 100 eV (~10^{4-6} K)

N_e = 10^{19-21} cm^{-3}

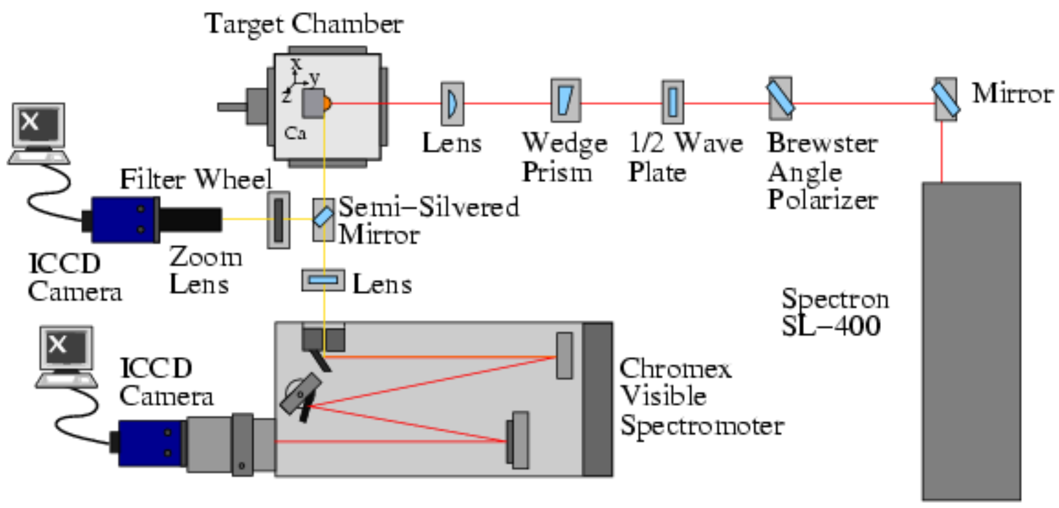
$V_{expansion} \geq 10^6$ cm.s^{-1}

Emitted =>
Atoms, Molecules, Ions,
Electrons, Clusters, Globules.
IR, Vis, UV, X-ray Radiation

LIBS – Laser Induced Breakdown Spectroscopy

- An analytical technique used to identify and quantify low concentrations of trace elements within a host matrix.
- A laser pulse is focussed onto the surface of a material to produce a localised plasma at the focal spot.

1. The laser pulse melts → vapourises → ionises the target material
2. The plume emits characteristic spectra that depend on the atoms, molecules and ions present.
3. These 'lines' are the fingerprints that allow us to classify and even quantify the atomic/molecular constituents in the ablated plume.

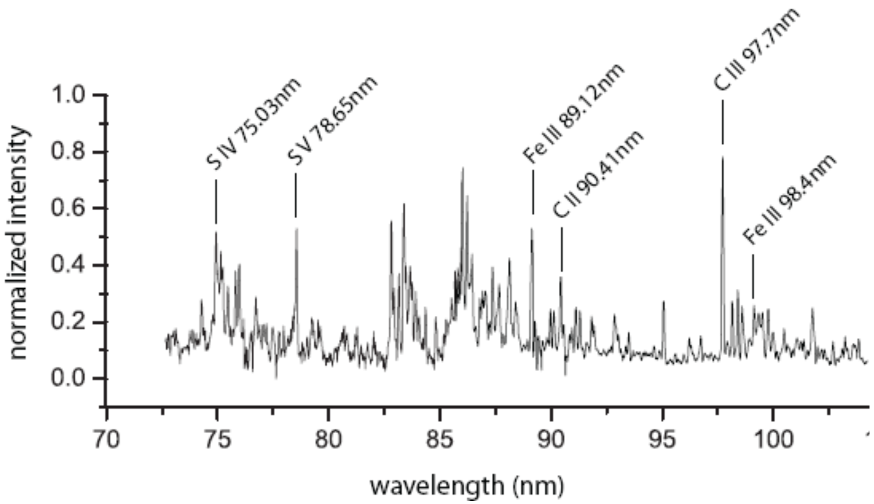


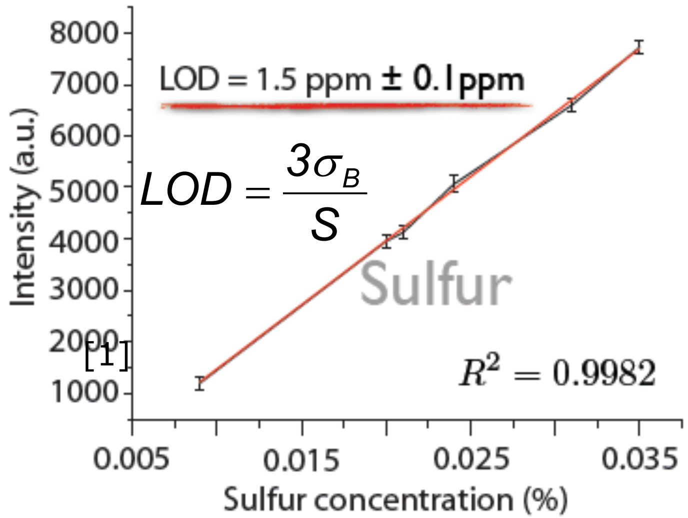
Typical LIBS layout (DCU)

LIBS – Laser Induced Breakdown Spectroscopy

Qualitative analysis:

- Each element in a sample produces a unique spectral signature, by collecting and analysing the light emitted from the plasma, elements (contaminants) present in the target material can be identified.

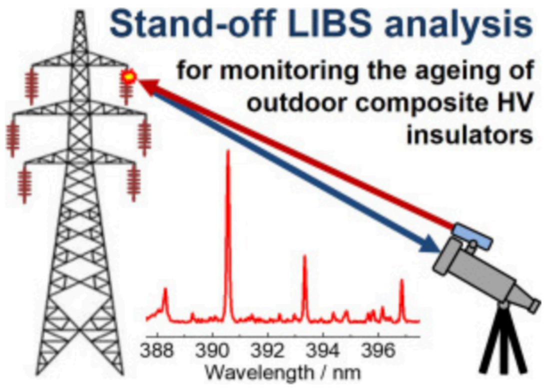




Quantitative analysis:

- By studying the intensity of the spectral lines, or their intensity relative to lines from other elements present, absolute concentrations and/or relative concentrations of the element(s) of interest can be determined.

Remote or ‘Stand-Off‘ LA-LIBS



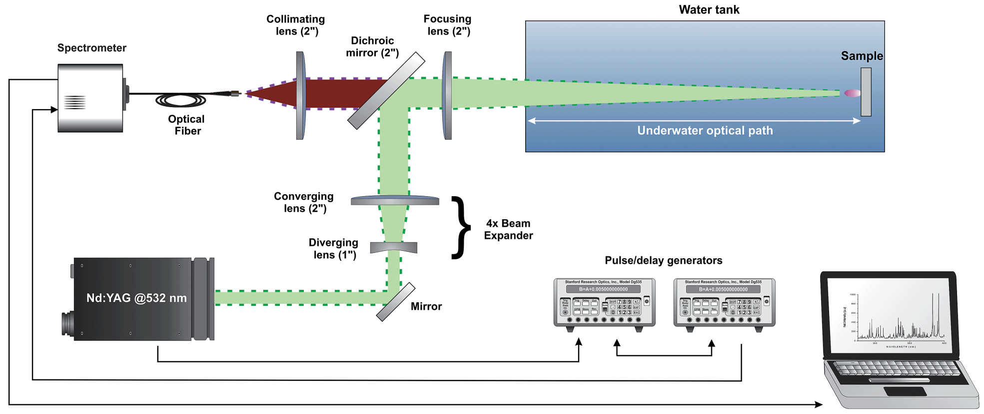
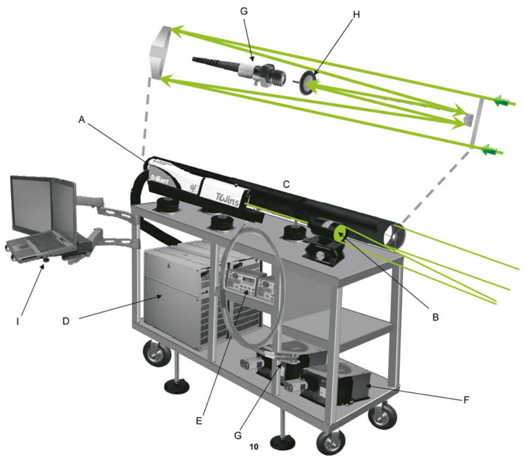
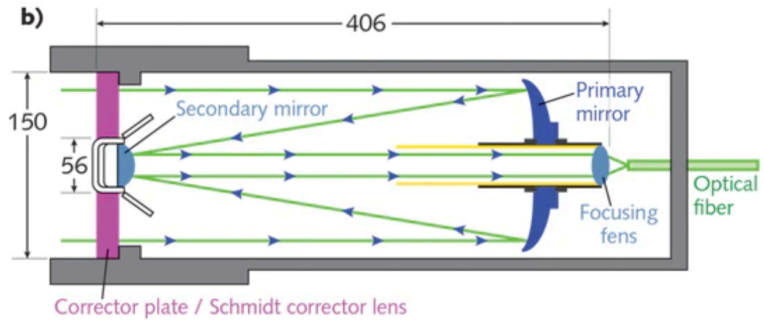


Fig. 1. (Color online) Standoff LIBS system.





Sources - SAB, Appl. Spec., JAAS, etc.

Project Aims and Objectives

The overarching objective of this proposal is to develop and apply standoff laser ablation to both classify and quantify blade fouling and to provide a safe, clean and efficient removal solution to it for wind energy providers.

WP No.	Objectives
1	Development, commissioning and characterisation of a Standoff Laser Ablation (LA) and LIBS system for field deployment.
2	Optimisation of LIBS parameters for turbine blade contaminant detection, identification and quantification.
3	Determination of optimal parameters and material thresholds for efficient laser ablation (LA) of contaminants with zero damage to blade surfaces.
4	Investigation of the feasibility of ultrafast laser ablation for contaminant classification, quantification and removal from turbine blades.
5	Feasibility of drone based remote laser ablation and LIBS
6	Dissemination and Exploitation

Project Aims and Objectives (Associated Tasks)

WP No.	Tasks associated with specific objectives
1 (DCU)	WP1-O1: Design and construction of a prototype standoff LA and LIBS system. WP1-O2: In the field tests of the efficacy and efficiency of remote LA and LIBS. WP1-O3: Optimisation of the standoff system.
2 (DCU/ UCD)	WP2-O1: Determine the optimum laser / focussing parameters for LIBS on blades. WP2-O2: Catalogue emission profiles of different turbines and contaminant types. WP2-O3: Incorporate advanced chemometric techniques (such as principal component analysis, convolutional neural networks, etc.) for fast, reliable classification of turbine or contaminant spectra.
3 (UCD)	WP3-O1: Determination of optimal laser and optical focusing parameters for laser ablation of contaminants with zero damage to blade surfaces. WP3-O1: Incorporate optical, atomic force and electron microscopies for surface inspection. WP3-O3: Develop a reliable visual indicator for the 'end-point' of ablation process.
4 (DCU)	WP4-O1: Evaluate femtosecond (fs) laser irradiation for the classification, quantification and removal of contaminants. WP4-O2: Evaluate femtosecond (fs) laser filaments for the classification and quantification of contaminants in standoff (remote) operation.
5/6	**Desk based activities (UCD and DCU)**

Project Partners

DCU. John Costello and Lazaros Varvarezos

UCD. Paddy Hayden and Padraig Dunne

ESB. *David Burke* with Colm de Burca, Cathal Lally, Robert Farrell and Carlos Kuzatko

SEAI. Lucy Corcoran and John McCann

Remote/Standoff LIBS expert advice from Javier Laserna/ Jose Vadillo (Malaga) and Rick Russo (Berkeley).

Large international LA/LIBS network established over decades

Project laboratories under preparation (Mar 2020)

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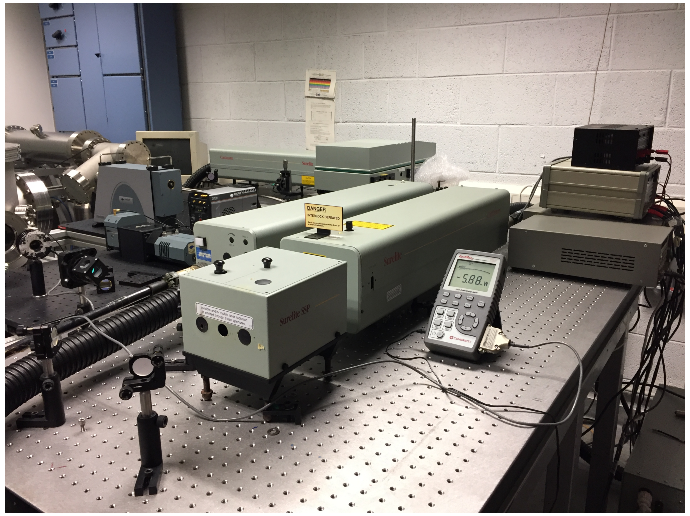
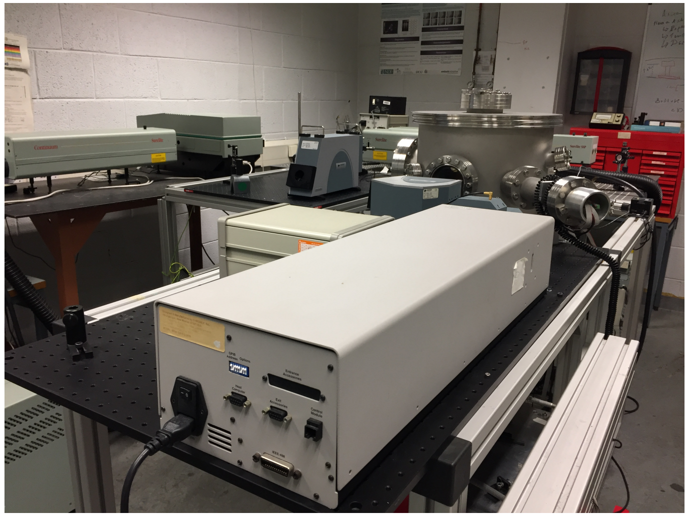
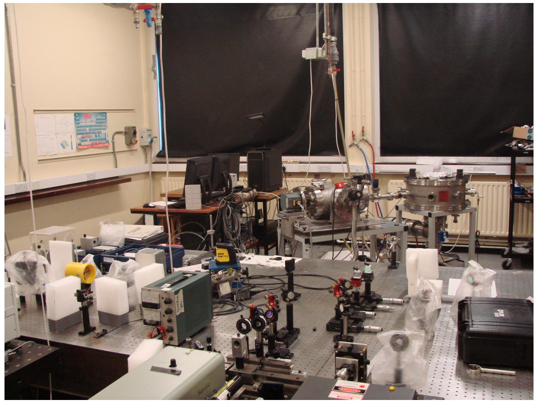


DCU – Nano Lab

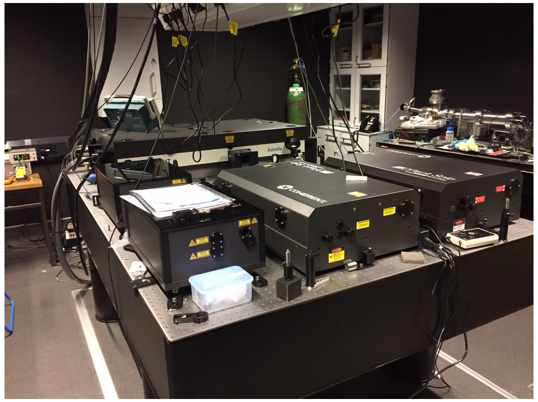


DCU – Nano Lab

DCU – Femto Lab



UCD – Nano Lab



DCU – Femto Lab

PhD Funding

3 PhD funded PhD positions. 1 x UCD and 2 x DCU

WP1 (PG1), WP2 (PG2) and WP3 (PG3)

Scholarships cover fees of E5,500 plus stipends to the value of E18,500 per annum (tax free)

Scholarship top-ups of ca. E1,500 for demonstrating and tutoring to full stipend of E20,000 p.a. (DCU).

Funding will cover 4 years fees and 3.5 years of stipend (potentially longer if SEAI can award NCEs)

Applicant Qualifications

Essential

Have, or expect to gain, *at least* a mid range (~65%) upper second class honours degree in physics, chemistry (with a substantial physics chemistry and/or analytical sciences component), engineering (with a substantial lasers and optics component), or materials science

Desirable

Deep knowledge of lasers, optics & spectroscopy

Deep knowledge of atomic, molecular & quantum physics

Strong writing and communications skills

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Application Procedure

Cover letter summarising academic career and achievements to date along with motivation for pursuing research and a research degree

Up to date CV summarising educational achievements and subjects taken with grades to date, including grades achieved at the end of each undergraduate year. Expected degree grade / completion date

The names of at least two academic referees. Please make sure that they are willing and able to provide references.

Any evidence of research experience and outputs to date

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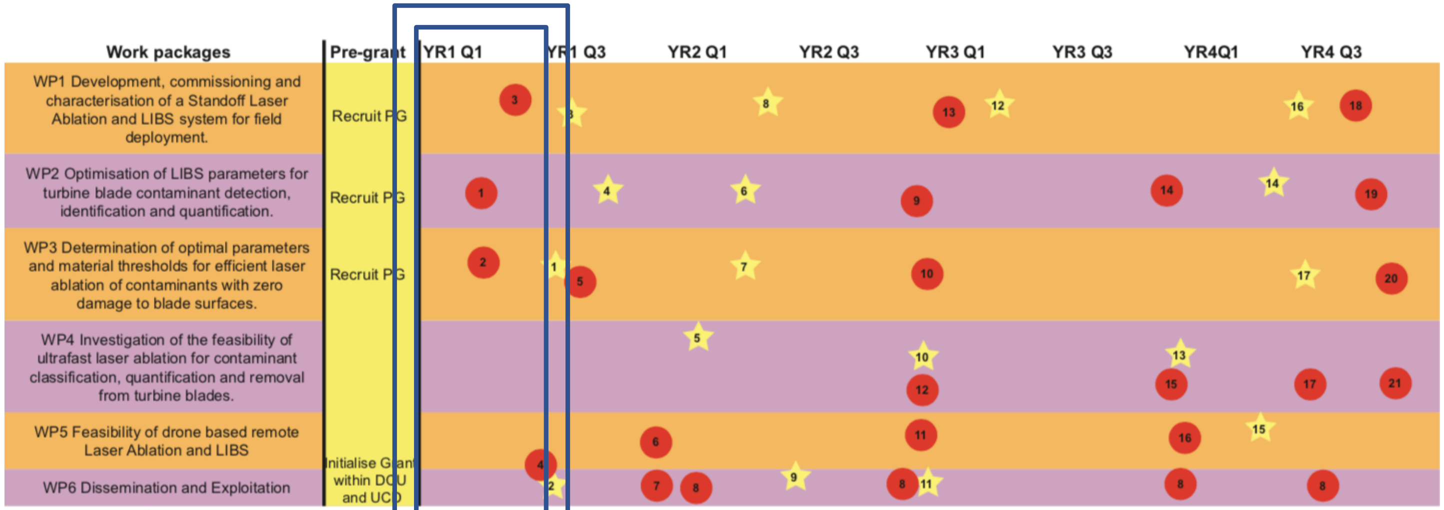
Scope of Work, Timelines for Milestones/ Deliverables



Milestones

1. WP3-M1: Modification of the UCD laser ablation system for handling wind turbine samples.
2. WP6-M1: Dissemination database established
3. WP1-M1: Begin laboratory testing of individual system components.
4. WP2-M1: Database of spectra and lines of interest for turbines and contaminants established. To be updated and maintained throughout.
5. WP4-M1: Complete initial LIBS data direct laser – sample arrangement.
6. WP2-M2: Begin fluid/plasma/atomic modelling.
7. WP3-M2: Full suite of diagnostic tools in operations for calibration.
8. WP1-M2: Begin incorporating individual components into complete system.
9. WP6-M3: First manuscripts submitted for peer review
10. WP4-M2: Complete initial experimental data for ablation of contaminated turbine samples.
11. WP6-M2: Begin process of seeking additional funding to further develop the research
12. WP1-M3: Begin in-the-field testing of the complete system, with input parameters from WP2 and WP3.
13. WP4-M3: Complete initial LIBS data filament – sample arrangement.
14. WP2-M3: Optimal laser, optical and spectrometer parameters determined for LIBS of turbine blade fouling.
15. WP5-M1: Determination of the feasibility of drone based remote laser ablation and LIBS
16. WP1-M4: Complete evaluation of full standoff system for both LIBS and laser ablation cleaning of turbine blades.
17. WP3-M3: Determination of preferred conditions for contaminant removal without blade damage, with a suitable 'end point' test.

Deliverables

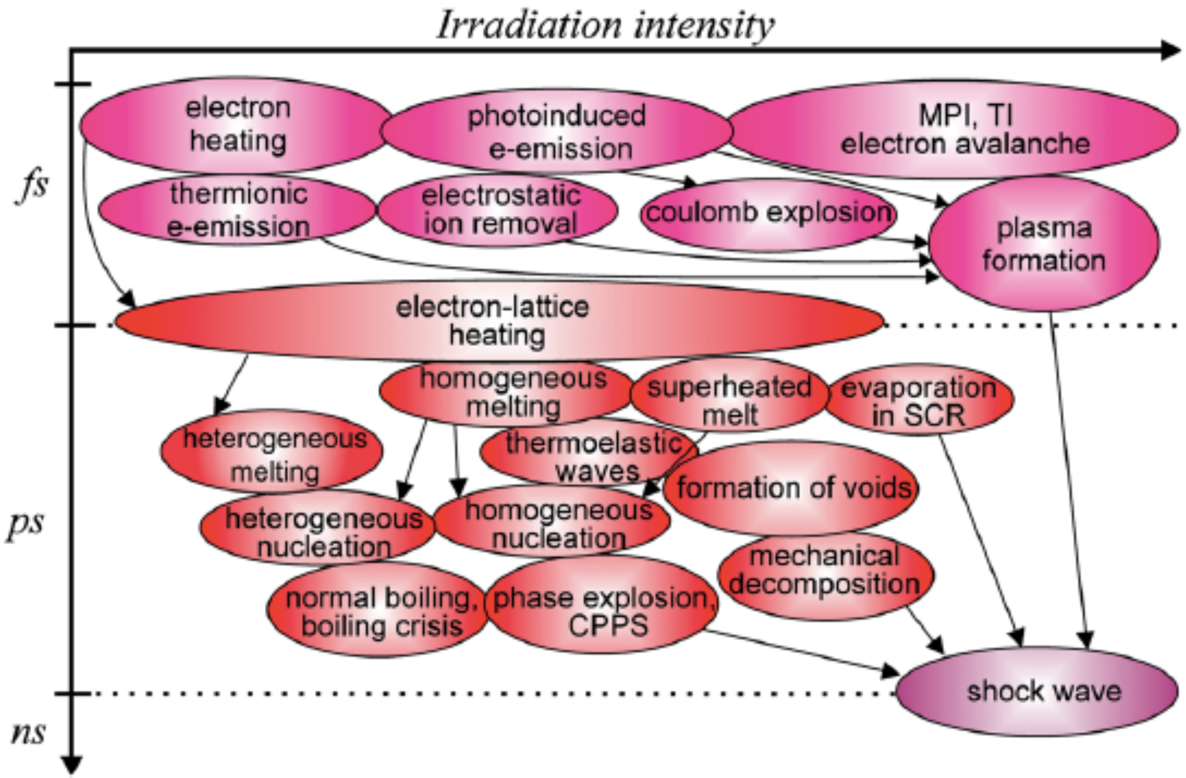
1. WP2-D1: Refine existing DCU LIBS systems to incorporate appropriate samples
2. WP3-D1: Comprehensive literature survey of existing knowledge on laser cleaning.
3. WP1-D1: Initial design of Standoff system.
4. WP6-D1: Dissemination plan completed
5. WP3-D2: Optical set-up for laser beam characterisation for on target irradiance determination
6. WP5-D1: Report on future wind energy challenges.
7. WP6-D2: IP plan completed
8. WP6-D3–D6: Annual report on D&E activities
9. WP2-D2: Supply of provisional parameter range to WP1.
10. WP3-D3: Supply of provisional parameter range to WP1.
11. WP5-D2: Report on current optical components.
12. WP4-D1: Comparison of direct fs and ns LIBS performance.
13. WP1-D2: Completed Standoff LA and LIBS system.
14. WP2-D3: Experimental dual pulse LIBS data for clean and contaminated turbine samples.
15. WP4-D2: Comparison of direct fs and direct ns contaminant removal.
16. WP5-D3: Report on current drone technology.
17. WP4-D3: Comparison of filament fs and direct fs LIBS performance.
18. WP1-D3: Final Report on WP1.
19. WP2-D4: Final Report on WP2.
20. WP3-D4: Final Report on WP3.
21. WP4-D4: Final report on WP4.

Many thanks to:

1. SEAI (RDD Programme)
2. ESB
3. HEA and SFI for Infrastructure

Ultrafast Fundamentals and Applications

Just a selection of the many processes stimulated by the interaction of high peak power, ultrafast lasers, with solid surfaces



J. Anal. At. Spectrom. **31** 90 (2016)

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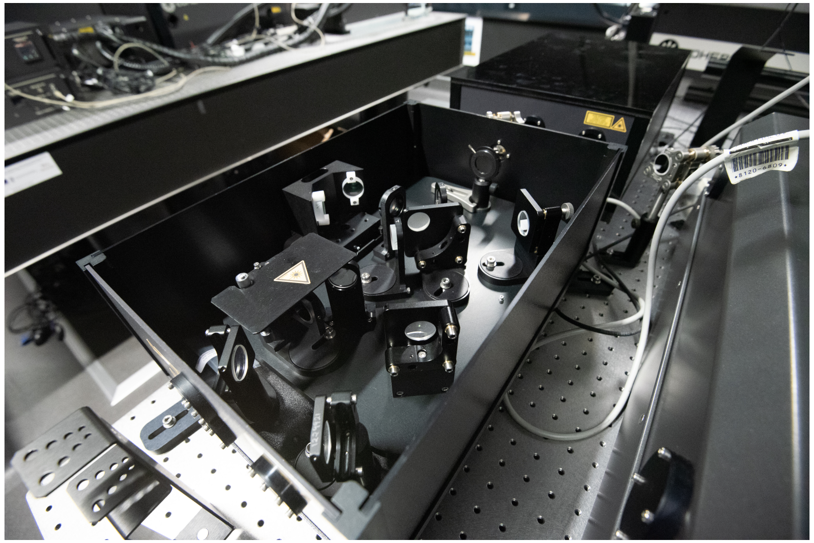
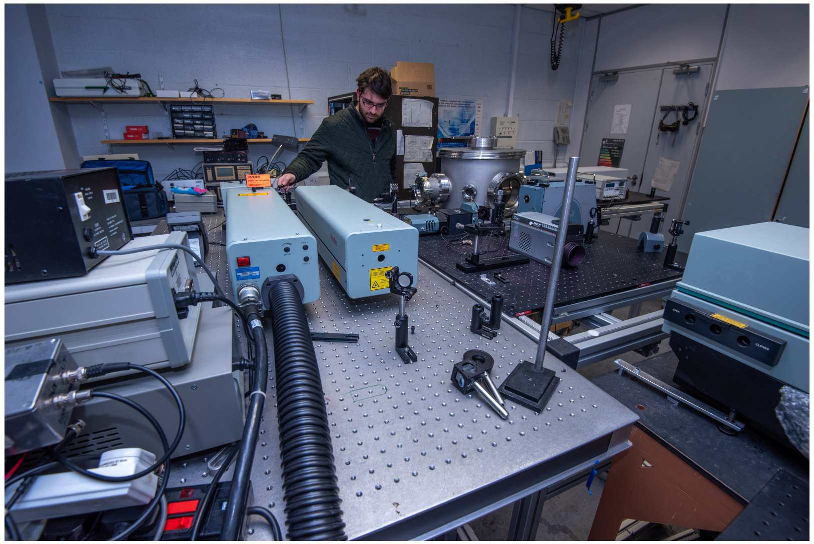
More photos from the DCU ns and fs laboratories.





Ultrafast Fundamentals and Applications

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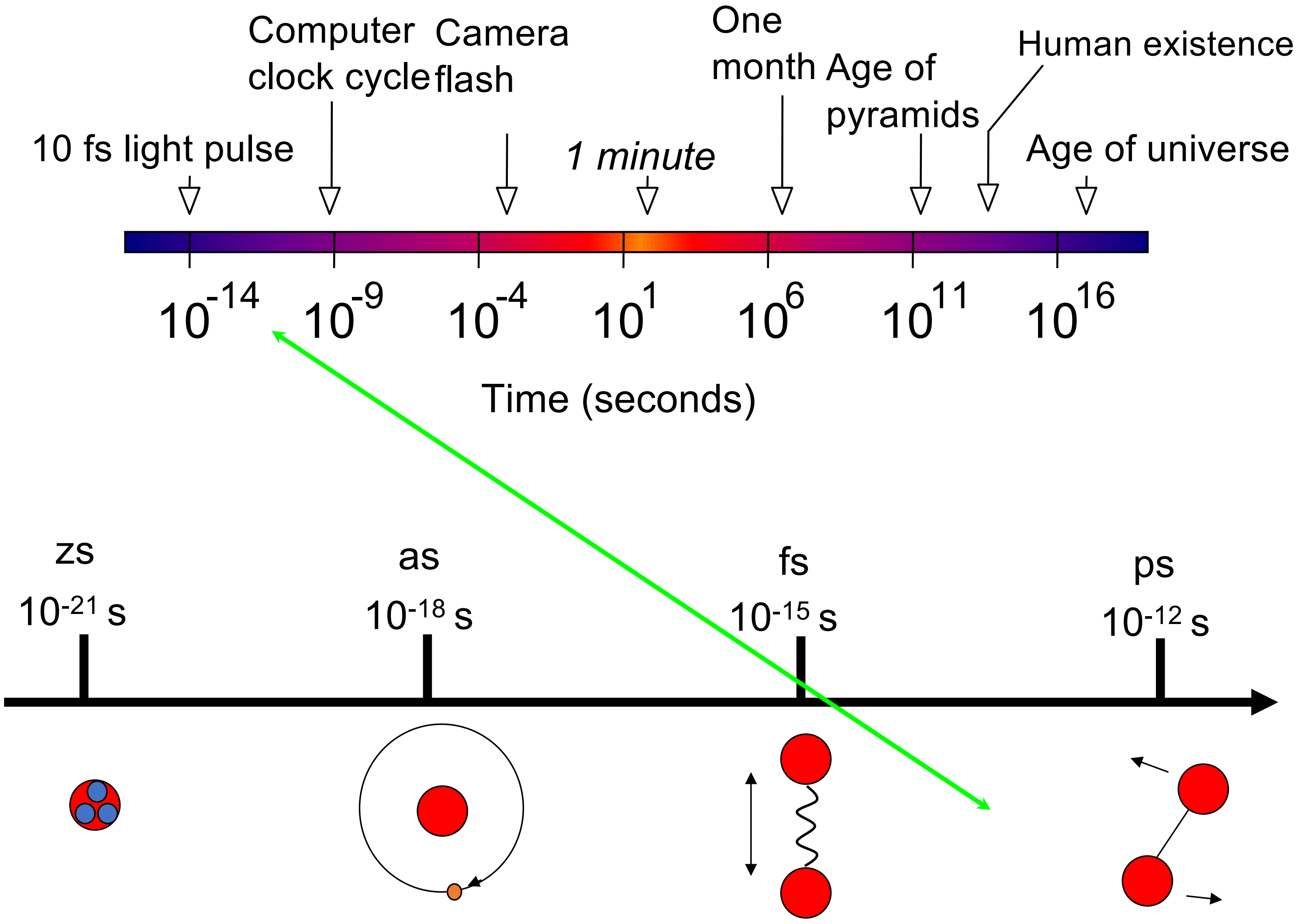
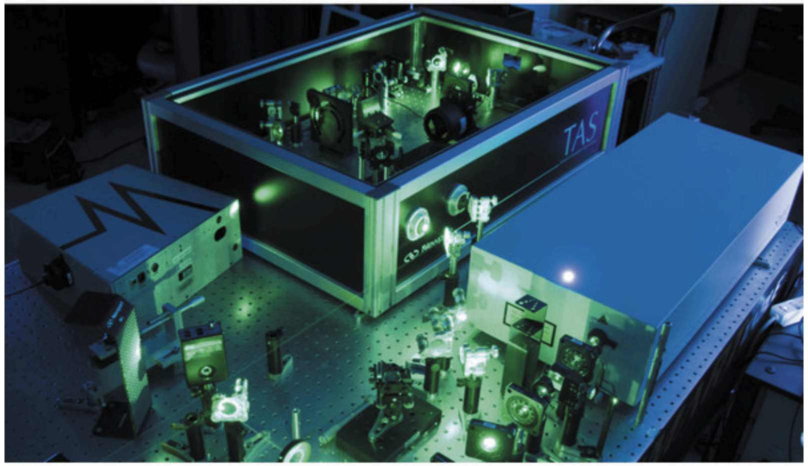


Pump-Probe Spectroscopy from the UV to Mid-IR

UV – NIR Pump-Probe Transient Absorption Spectrometry



TR - 2D NIR - MIR Correlation Spectrometry

Q3 2018 – Pump-Probe Spectroscopy from the UV to Mid-IR

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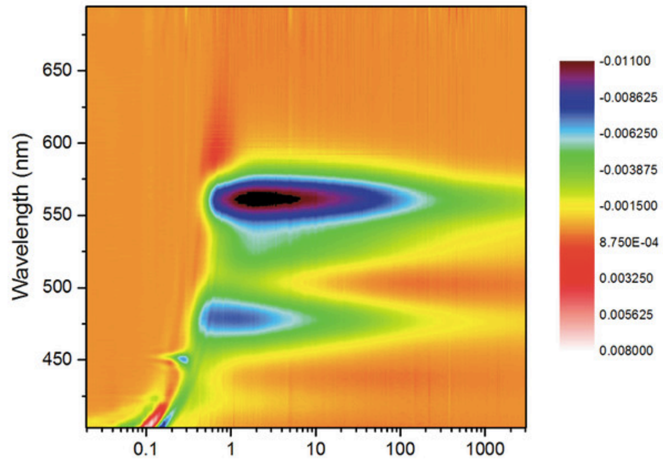
UV – NIR Pump-Probe Transient Absorption Spectrometry (350 – 1600 nm)



TR - 2D NIR - MIR Correlation Spectrometry (2 – 12 um)

Femtosecond Pulse Shaping Enables Rapid Two-Dimensional Infrared Spectroscopy

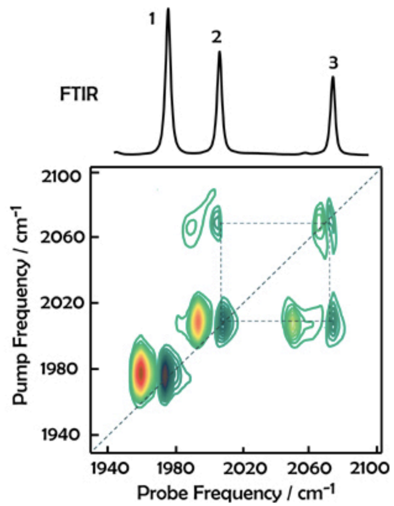


Figure 1: Experimental FT-IR and 2D IR spectra for a mixture of W(CO)6 and a rhodium dicarbonyl (RDC). For each peak in the FT-IR spectrum, the 2D IR spectrum exhibits a pair of diagonal peaks. The cross peaks in the 2D IR spectrum reveal that the two higher frequency peaks are coupled to one another, which is because peaks 2 and 3 are from a rhodium dicarbonyl (RDC) whereas peak 1 is from W(CO)6. W(CO)6 and RDC do not have cross peaks between them because the mixture is too dilute. (Data collected by Tianqi Zhang.)