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Dual Mode Electron Paramagnetic Resonance: A New Probe for the Investigation of High-Power Microwave Processes

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Abstract. A new X-band continuous wave Electron Paramagnetic Resonance (EPR) cavity is presented, capable of simultaneous EPR measurement during high-power microwave irradiation. This new capability provides the opportunity to use a new chemical probe to unravel the complex mechanisms taking place in microwave driven chemical processes. Here we highlight recent work detailing the design and construction of the EPR probe for high power microwave processes and demonstrate the principle of rapid sample heating by measuring the EPR trace of spin labelled micelles whilst being heated by microwaves [1]. The key concept of the design is the use of a cavity resonator allowing EPR detection (at 9.5 GHz) and sample heating (at 6.1 GHz).

Keywords: Dielectric Heating, Electron Paramagnetic Resonance (EPR), T-jump, Kinetics, Resonator Design.

1 Introduction

In order to probe the fundamental processes taking place during microwave heating, innovative approaches to measurement and monitoring techniques are necessary. Conventional heating has its own challenges when attempting to measure chemical processes in situ, but under microwave irradiation, there are often additional challenges. Electron Paramagnetic Resonance (EPR) offers widespread opportunities for exploring reactions with paramagnetic species or reaction intermediates (radicals). For example, in microwave driven catalysis, EPR can be a powerful tool for investigating the structure, the location and dispersion of active sites in solid catalysts as well as their interaction with reactant molecules [2]. Here, we demonstrate the operation of a dual mode device that can provide rapid dielectric heating whilst simultaneously measuring EPR spectra. In order to fully exploit the benefits of microwave heating in chemistry there is a need to fundamentally understand how it can drive and accelerate reactions. To explore this, a unique dual-mode EPR resonator was developed to enable rapid in situ heating. One mode of the resonator operates at 6.1 GHz and is used to heat the sample (in the TM_{010} mode), whilst the second mode operates at 9.5 GHz for EPR detection (TM_{110}). MW radiation can locally raise the temperature of the desired sample volume very rapidly, unlike conventional heated systems that are dependent on conduction and convection. In this article, we describe the basic principles of the resonator, designed for simultaneous heating and EPR experiments, and demonstrate how rapid heating can be achieved using spin-labelled micelles. In addition to direct studies of microwave driven processes, the advantages of rapid and volumetric heating can be utilised to explore fundamental thermodynamics of chemical processes. This can be carried out by measuring EPR spectra during a rapid temperature jump caused by microwave heating. Such 'T-jump' measurements can reveal important information about the underlying reaction mechanism and kinetics [3]. In this article, we demonstrate the principle of controllable microwave heating during EPR measurements and consider its application in catalysis and T-jump experiments.

2 Experimental

For the dual mode resonator, the MW heating mode must be resonant well below the cut-off frequency of the X-band waveguide used to couple to the EPR detection mode (i.e. below 6.5 GHz, assuming a waveguide "long" dimension of 22.9 mm) to ensure

that high power microwaves are not coupled to the sensitive detection chain. To meet this condition, resonant frequencies for the heating and EPR modes in the ratio of around 1.0 to 1.6 are easily achieved by designing the dual mode resonator to be near square or cylindrical. A short length of waveguide feed then acts as an almost perfect high pass filter for our dual mode resonator, rejecting the heating frequencies around 6 GHz whilst transmitting the EPR frequencies around 9.5 GHz. For a perfectly cylindrical cavity resonator of internal radius R, the resonant frequencies of the TM_{010} and TM_{110} modes can be calculated very precisely using the following equations:

$$\begin{cases} f_{010} = \frac{p_{01}c}{2\pi R} \\ f_{110} = \frac{p_{11}c}{2\pi R} \end{cases} \quad (1)$$

where c is the speed of light in vacuum, $p_{01} = 2.405$ and $p_{11} = 3.832$ (i.e. the first roots of the Bessel functions $J_0(x)$ and $J_1(x)$, respectively). The TM_{010} and TM_{110} modes each have antinodes of electric and magnetic field, respectively, in the sample region (on the axis) and so are ideal for heating and EPR, respectively. The TM_{110} mode is doubly degenerate, with the two degenerate modes having orthogonal fields. To lift this degeneracy, so that the resonant frequencies of this mode are spectrally separated by at least 500 MHz at 10 GHz (i.e. by 5%), we design an elliptical (rather than cylindrical) geometry. Whilst we can achieve a similar splitting of the degeneracy using a near square, rectangular cavity, the separation of the two quasi TM_{110} degenerate modes in the elliptical case is greater. There is also then a slightly better separation of the electric and magnetic fields near the cavity axis, which is important for maintaining a high quality factor (Q) for EPR measurements when lossy dielectric samples are being studied (e.g. species within any polar solvent). Whilst analytic expressions exist for the resonant frequencies of an elliptical cavity, simple, first-order approximations can be deduced from perturbations of the cylindrical cavity. For an ellipse of semi-major and semi-minor axes a and b, respectively, the resonant frequencies of the quasi TM_{010} and TM_{110} modes can be estimated using the following equations:

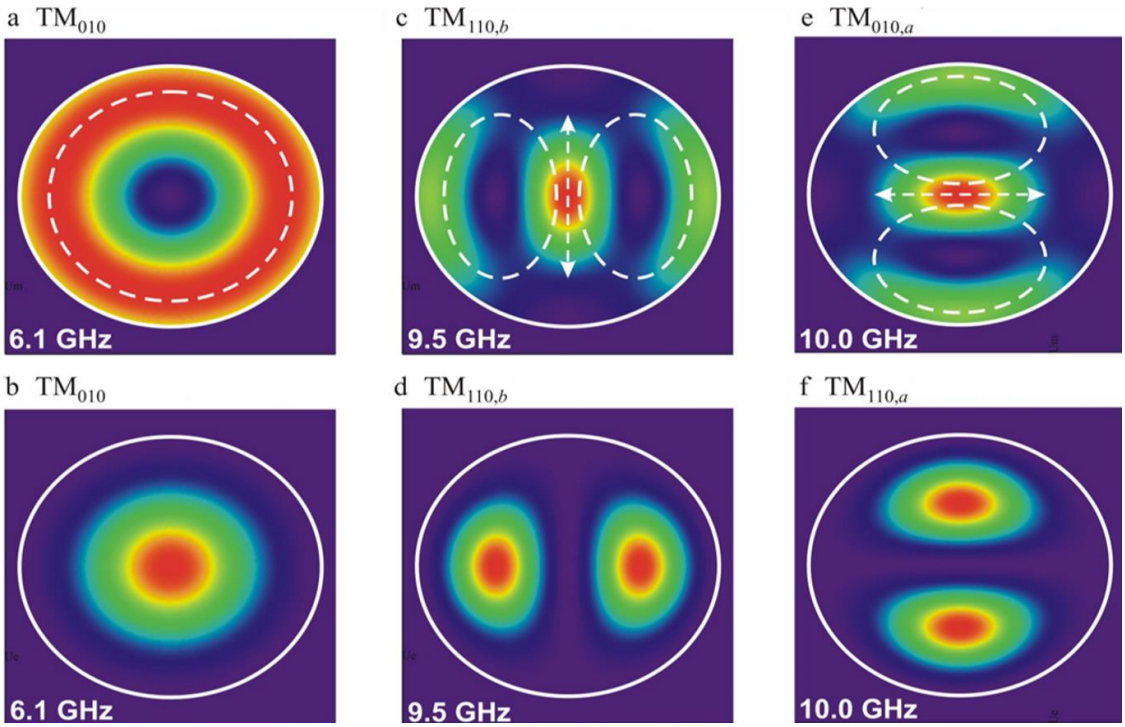

Figure 1: Magnetic (a, c, e) and electric (b, d, f) energy densities (H^2 and E^2, respectively) of an elliptical cavity. The approximate resonant frequencies are shown for semi-major and semi-minor axes of a = 19.7mm and b = 17.8 mm. The H fields are in the plane of the page, whereas the E fields are perpendicular to the page. The dielectric heating mode TM^{010} has an E-field antinode at the sample region. The EPR mode TM_{110}, b has an H-field antinode at the sample region.

$$\begin{cases} f_{010} \approx \frac{p_{01}c}{\pi(a+b)} \\ f_{110,b} \approx \frac{p_{11}c}{2\pi(a-\Delta)}, f_{110,a} \approx \frac{p_{11}c}{2\pi(b+\Delta)}, \Delta = \frac{1}{2}(a-b) \end{cases} \quad (2)$$

The internal dimensions of the elliptical cavity to be used as the dual mode resonator are a = 19.7mm and b = 17.8 mm, giving approximate resonant frequencies from Equations 2 of $f_{010} \approx 6.1$ GHz, $f_{110,b} \approx 9.5$ GHz and $f_{110,a} \approx 10.0$ GHz. Finite element models of these resonant modes and their field orientations are shown in Figure 1. The internal length of the cavity is chosen to be 11 mm, which is large enough to ensure high unloaded Q of the TM_{010} and $TM_{110,b}$ (approximately 7000 and 8000, respectively, when the cavity resonator is constructed from aluminium), but short enough to maintain the uniformity of the modulation field and to ensure that TE modes are pushed to higher frequencies (e.g. above 14 GHz for TE_{111}). Another special feature of this cavity resonator is its construction in two parts, rather than the usual three. As can be seen from Figure 2, all of the wall currents flow parallel to the single metal-metal join, meaning that Q is independent of the pressure applied to this contact and the resonator can be easily taken apart (separated) for occasional cleaning, whilst retaining near identical performance. Finally, it should be noted that the side walls of the cavity are very thin (around 1mm thickness) so that the modulation field at the sample is not compromised by the skin effect in the cavity walls.

To obtain the required phase sensitive detection at 100 kHz, a set of Helmholtz coils were designed and constructed in order to modulate the external magnetic field B_0. The coils were made of resistive copper wire of 0.25 mm gauge, appropriately wound so that the wire becomes two solenoids in series. The coils were designed to have a radius equal to the separation of the coils. The resistance and inductance of the designed Helmholtz coils were 3.48 Ω and 217 µH respectively. The experimental assembly for the simultaneous microwave-assisted rapid heating and EPR detection is schematically illustrated in Figure 3. The assembly consists of: a microwave signal generator (EXG 5173B, Keysight Technologies), a DC power supply (not shown in the Figure, EA PS 2042-20 B, Elektro-Automatik), a power amplifier (1131-BBM5K8CGM, EMPOWER RF SYSTEMS), a circulator (Mini-circuits), attenuators (Mini-circuits), a power sensor (U2021XA, Keysight Technologies), a thermal imaging camera (TIM640, Micro-Epsilon) and a Bruker EMX EPR spectrometer, housing the dual mode resonator equipped with Helmholtz coils described in the previous section. The MW bridge employed is a Bruker ER041X X-band Gunn diode bridge. The resonator was designed with an observation hole to one side in order to capture real-time thermal images of the sample under test during microwave heating and can also be used for in situ irradiation experiments. The power amplifier has a saturated output power of 40 W and 10 W at 1 dB compression point, which is more than enough to induce thermal gradients greater than 50°C in a few seconds. A circulator is added to protect the power amplifier from the reflected power and also to monitor the power delivered to the sample. For the purposes of the initial heating experiments described in this work, a thermal imaging camera was used to record the temperature.

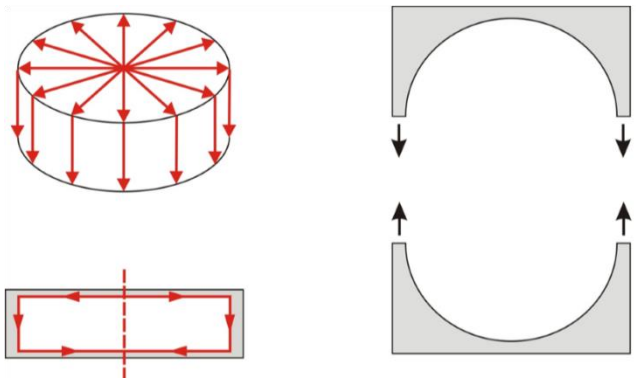

Figure 2: Design and construction considerations of the elliptical cavity. It is manufactured in two sections to ensure that there is no current flow across metal-metal join in both the heating mode and the EPR mode (the internal surface microwave currents are shown for the TM_{010} heating mode). The metal thickness of the opposing elliptical surfaces is very thin (1 mm) to minimise the reduction in the modulation field owing to the skin depth in the cavity walls at modulation frequencies up to 100 kHz.

To test the dual mode capabilities of the resonator for simultaneous heating and EPR measurement an organic spin label was prepared. Full details of sample preparation can be found in reference [1]. An aliquot of a spin labelled micelle

solution was introduced into a Q-band EPR tube (1.6 mm outer diameter, 1.1 mm inner diameter suprasil tube, product number: WG-222T-RB Wilmad Labglass) for measurement with the dual-mode MW-EPR reactor-resonator. EPR spectra were simulated using the Easyspin package [4] running within the Mathworks Matlab environment.

3 Results and Discussion

The resonance frequencies for both TM_{010} and $TM_{110,b}$ modes were obtained using an S5180 network analyser (Copper Mountain Technologies), giving f_{010} = 6.180938 GHz, with a reflection coefficient of -32 dB and $f_{110,b}$ = 9.587420 GHz with a reflection coefficient of -31 dB. When a Q-band tube filled with deionised water is placed in the sample region, we obtain f_{010} = 6.124125 GHz, with a reflection coefficient of -15 dB and $f_{110,b}$ = 9.585420 GHz with a reflection coefficient of -28 dB. We found that a compromise between the two TM modes during critical coupling was very important. Indeed, whilst we were able to achieve a reflection coefficient of −50 dB on the EPR mode (i.e. $TM_{110,b}$), this limits the reflection coefficient of the heating mode (i.e. TM_{010}) to below −15 dB. In contrast, by limiting the EPR mode to around −30 dB, this allows us to maintain −15 dB to −30 dB for the heating mode, which is preferable for power delivery to achieve the desired temperature increases.

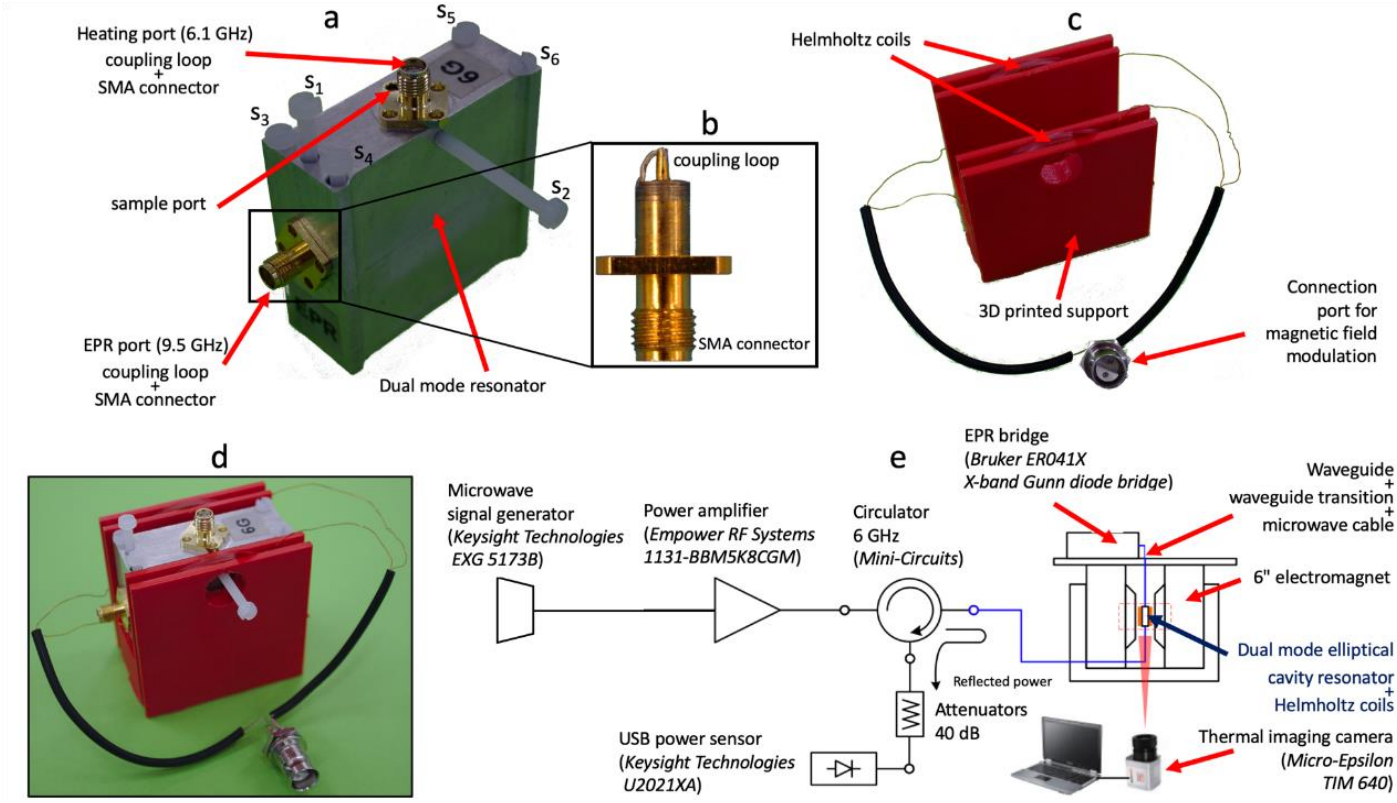

Figure 3: (a) Details of the dual mode cavity resonator. s_1 and s_2 are two PTFE screws to hold in place the coupling loops once the two modes (TM_{010} and $TM_{110,b}$) are critically coupled. s_3, s_4, s_5 and s_6 are PTFE screws to hold the two parts of the resonator together. Details of the coupling loops + SMA connectors used for matching both resonant modes are shown in (b). (c) Details of the Helmholtz coils used to achieve modulation of the external magnetic field. A picture of the resonator inside the support with the Helmholtz coils is shown in (d). A schematic diagram of the experimental setup for running EPR and dielectric heating simultaneously is shown in (e).

The Q factor was obtained by taking S21 measurements. This was first monitored with a weakly coupled resonator so that the measured Q could be considered unloaded. The measured Q factors were 6007 for the TM_{010} mode and 7349 for the $TM_{110,b}$ mode. The efficiency of the MW induced heating was shown using an IR thermal imaging probe and 50 µl of water in a Q-band EPR tube when setting the MW source to deliver a nominal power of 1 W at 6.1 GHz. Figure 4 shows the temperature ramp achieved. The initial slope of the curve indicates a temperature ramp of 1.57 K/s. Power losses in the cables connecting the MW source to the amplifier and subsequently the amplifier to the resonator, plus the power loss within the resonator itself (associated with the Q-factor at 6.1 GHz) would decrease the actual power available to heat the sample. In simple terms, considering that the specific heat capacity of water is equal to 4.18 kJ kg^{-1} K^{-1} and assuming >99% absorbance of the MW radiation, it can be deduced that 1W of nominal power would cause a temperature rise of 4.78 K/s on 50 µl of water, if no power was lost. Hence, we can estimate that the power transfer efficiency in the entire system is 1.57 K s^{-1}/4.78 K s^{-1} = 0.33. Even with this low power transfer efficiency, it can be calculated that when using 10 µl of water rather than 50 µl (i.e. which is the case for many solution samples analysed by EPR spectroscopy in Q-band tubes), a T-jump of 5 K in just over 20 µs would require a MW power of 30 W at 6.1 GHz, which is already possible with our hardware (currently the maximum power deliverable is ca. 31 W). After interfacing the dual mode resonator to the Bruker bridge, the modulation coils and the spectrometer signal channel were calibrated at 100 kHz modulation frequency using a BDPA (3-bisdiphenylene-2-phenylallyl) X-band EPR standard. This procedure ensured ease of operation by enabling the dual mode resonator to be controlled through the Bruker WinEPR software. Lorentzian fitting subsequently returned ca. 60% of the expected value, which matches results obtained with a set of search coils positioned inside the resonator, highlighting that only 60% of the modulation field generated by the Helmholtz coils actually enters the cavity.

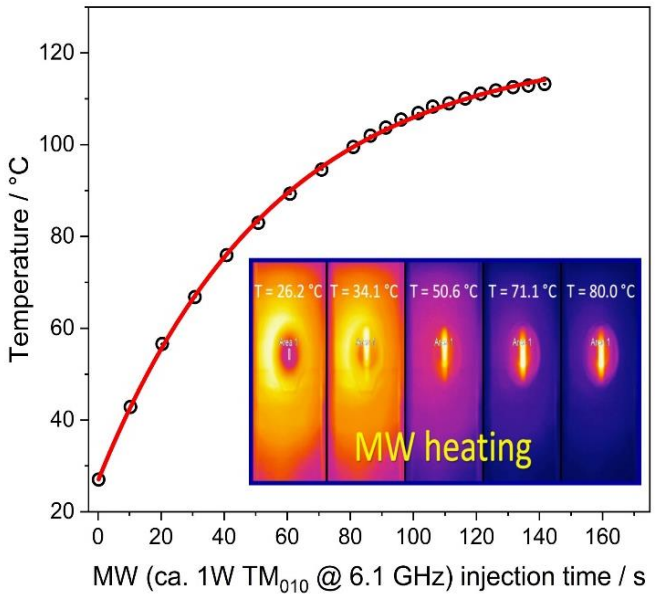

Figure 4: Typical temperature ramp profile achievable upon continuous wave MW injection of 1 W of nominal power at 6.1 GHz. The inset shows five thermo-camera images of a water-filled EPR tube inside the cavity being subjected to dielectric heating.

A demonstration of dielectric heating was performed using sodium dodecyl sulfate (SDS) micelles in water, spin-labelled with 16-doxylstearic acid methyl ester (16-DSE). Figure 5(a) shows the X-band CW EPR spectrum of the spin-labelled micelle at room temperature. The spectrum can be fitted to a model of anisotropic rotational diffusion, with a rotational diffusion tensor exhibiting axial symmetry, i.e. with a preferential rotation mode. Following 20 s of 1.5 W (nominal power) MW injection at 6.14 GHz, which causes the temperature of the sample to rise to about 58°C, the EPR spectrum changed to that shown in Figure 5(b). This second spectrum can still be simulated and fitted to a model of anisotropic rotational diffusion, but at a much faster rate compared to the original room temperature case. Interestingly, the rotational diffusion not only increases at higher temperature, but also becomes more anisotropic. Faster rotational diffusion rates are expected at higher temperature, given the reduced viscosity of the solvent.

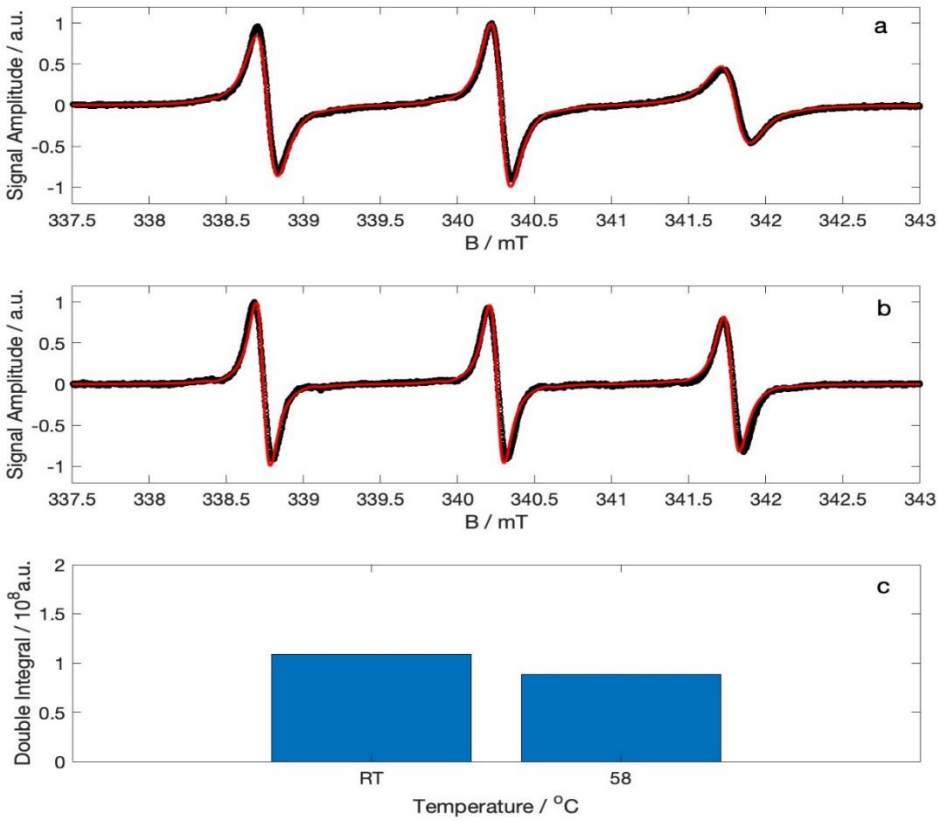

Figure 5: X-band CW-EPR spectra of 16-DSE spin-labelled SDS micelles in water recorded at (a) room temperature, and (b) 58◦C. Spectra were recorded using the dual mode resonator operating at 100kHz field modulation frequency, 0.1 mT field modulation amplitude, 5.024 10^{+4} receiver gain and 4096 points. (c) Double integrals of the spectra in (a) and (b).

4 Perspective for microwave heated EPR experiments

From a chemical perspective, another advantage of using MW for rapid heating comes from the fact that enhancement of rates and selectivities of chemical reactions can be achieved. Reported benefits of MW in chemical reactions include shorter reaction times, higher rates, enhanced product selectivity and control of material properties [5]. Certainly, in organic reactions, the rates can sometimes be significantly faster and in some cases the observed accelerations cannot be obtained by conventional heating methods [6]. However, in order to fully exploit the numerous benefits, there is a need to fundamentally understand how MW heating can drive and accelerate reactions. In situ methods such as EPR are critical to develop our understanding of the complex mechanisms of microwave driven reactions. Rapid heating can change not only the selectivity of some reactions, but also provides a simple and effective means to study the kinetics and dynamics of the reacting system itself via the temperature-jump relaxation approach. Most chemical reactions involve an equilibrium process, with the rate of the forward and reverse reactions controlling the overall concentration of reactants and products at any given point in time. The chemical or conformational equilibrium can be easily perturbed and shifted in either direction, when a stress is applied. This stress may involve a change in concentration, pressure or temperature. The rate of change from the old to the new equilibrium will depend on the rate constant for the forward and reverse reactions or the conformational change, so that analysis of this rate is extremely informative in chemical kinetics and dynamics. It is important that the perturbation is applied more rapidly than the relaxation time, and usually on a time scale that is faster than the mixing times involved. Rapid heating

by microwaves (creating a T-Jump) using a suitable resonator, could therefore be used as a novel means of studying reaction kinetics and dynamics, as well as investigating the fundamental mechanism of how MW influence chemical reactions. Successful in situ heating was evidenced by the changes in rotational correlation time (monitored simultaneously by EPR). The use of pulsed MW sources at 6.1 GHz will enable us to deliver faster temperature rises, to study by EPR spectroscopy dynamics and kinetics in chemical systems. Crucially, this resonator is simple to produce and easy to use on a standard Bruker EPR spectrometer, offering a facile method for in situ EPR heating studies.

5 Conclusions

In this newsletter article, we have highlighted recent results describing a novel dual-mode EPR resonator capable of performing standard X-band EPR measurements whilst simultaneously enabling microwave heating of a sample. We have demonstrated the successful EPR detection of a spin-labelled system under rapid microwave heating, as evidenced by the changes in the rotational diffusion dynamics of the paramagnetic species in solution. This resonator can be easily interfaced to a Bruker EPR microwave bridge and operated using the standard Bruker instrumental software. This new probe enables the study of a wide range of reactions containing paramagnetic reactants or radical intermediates under microwave heating. The method also allows for modest temperature-jumps experiments to investigate chemical systems perturbed from equilibrium. Further development will enable this technique to probe emerging applications in microwave driven catalysis.

6 Acknowledgement

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For further readings

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About the author

Daniel R. Slocombe received the Ph.D. degree in Electronic Engineering from Cardiff University, UK. From 2002 until 2006 he was an engineer in the Royal Air Force and from 2012 until 2015 he was a Research Fellow in the Inorganic Chemistry Laboratory at the University of Oxford, UK. He is currently Head of Teaching for the Department of Electrical and Electronic Engineering at Cardiff University and is a member of the Centre for High Frequency Engineering. He has carried out research in many areas of microwave science and high frequency materials including microwave activation of catalytic processes, synthesis of functional oxides, dielectric spectroscopy and new methods using Electron Paramagnetic Resonance

Andrea Folli obtained his Laurea degree in Industrial Chemistry from the Universita' degli Studi di Milano, Italy (1998 - 2004). After a few years in industry working for Sasol, Andrea received his PhD from the University of Aberdeen (2007 - 2011) as part of an EU Marie-Curie Research Training Network. Prior to his current position at Cardiff University, Andrea was a research consultant for the Danish Technological Institute (2010-2015) where he served as the principal investigator on a European FP7-funded project investigating TiO2 photocatalysis. Andrea's main research interest lies in the application of magnetic resonance techniques to understand the role of

magnetism and electron spin dynamics in chemical reactions and catalysts involving paramagnetic species.

Michael Barter received his Ph.D. from Cardiff University in 2019. He is currently working as a Post-Doctoral Research Associate in the Centre for High Frequency Engineering at Cardiff University. His research focuses on microwave characterisation of materials, specifically the development of a dual-mode EPR reactor-resonator for high temperature materials characterisation. He is also involved in several cross-disciplinary projects linking to neutron and X-ray diffraction, catalysis, and advanced materials.

Jaafar Harari is a second year PhD student working on the development of new methods in Electron Paramagnetic Resonance at the Centre for High Frequency Engineering, Cardiff University.

Emma Richards was appointed as a University Research Fellow in EPR spectroscopy at Cardiff University in April 2015, and promoted to Lecturer in August 2019. Following her BSc(Hons) Natural Sciences at the University of Bath (2004), she completed her PhD on the EPR characterization of oxygen radicals on polycrystalline TiO2 at Cardiff University (2007). Her research involves utilising time-resolved EPR and hyperfine spectroscopy to investigate catalytic redox processes involving transition metal and main group systems, and photoexcited triplet states for new technologies. She is co-author of the OUP Oxford Chemistry Primer "Electron Paramagnetic Resonance" and currently serves as a committee member of the RSC EPR Interest Group.

Damien Murphy is Professor of Physical Chemistry at Cardiff University. After obtaining his Chemistry degree from the Dublin Institute of Technology in 1990, he moved to the University of Turin to undertake his PhD in EPR of surface defects on polycrystalline materials. Following successive PDRA appointments at the IST, Lisbon (1994) and Université P. et M. Curie, Paris (1995), he was appointed to a lectureship in Cardiff University, School of Chemistry in 1996, where he is currently Head of School. He is a Fellow of the RSC, Fellow of the Learned Society of Wales and a Royal Society Wolfson Research Award holder. His research interests are broadly focused on the applications of advanced EPR methods for catalysis research.

Adrian Porch is the Research Leader of Cardiff's Centre for High Frequency Engineering. He has 34 years of research experience in the fundamental properties, electromagnetic modelling and applications of materials at microwave frequencies. He is a champion of interdisciplinary research, with research interactions across all of the physical and biomedical sciences. In recent years his research has expanded into the area of medical microwave devices, for example the Wellcome Trust funded project to develop a non-invasive blood glucose meter using his patented microwave technology, now undergoing commercialisation. In other funded projects he is developing new methods in EPR (with Prof Damien Murphy, School of Chemistry at Cardiff) and assessing energy storage materials using simultaneous microwave characterisation and neutron diffraction (with Prof Martin Jones, Rutherford Appleton Laboratory). He has long-standing industrial collaborations with Merck KGaA and Renishaw Ltd., for the latter investigating the use of RF and microwave technologies to aid additive manufacturing.

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From Lab Concept to Railway Demonstrator: Microwave Plasma Track Treatment

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1 Background

Braking conditions are a fundamental issue for the railway and have been a limiting factor in network capacity & timetabling. This work was focused on taking high power microwave generated plasma out of the laboratory into a railway environment.

The Imagination Factory with no experience in microwave-generated plasma has partnered with experts in this field to develop a mobile system which delivered 15 kW 2.45 GHz microwave generated plasma. Over a 3-year development program, the project moved from initial concept feasibility to an on-track demonstrator tested on live UK rail Network.

Figure 1: Full-scale demonstrator lab on test track

Figure 2: Road-Rail Demonstrator Prototype on UK Rail Network

Development partners:

- Microwave Technologies, France
- Industrial Microwave Systems, UK
- The National Physical Laboratory, UK
- British Steel, UK
- Network Rail, UK

2 Introduction

Effective railway acceleration and braking is reliant on the small contact patch between wheel and rail. This is roughly 1 cm^2 and must support high loads under numerous different conditions. Traction in the contact is generated because of torque being applied through the driving wheelsets and low levels of traction, often known as low adhesion, between wheel and rail can occur under certain conditions and cause difficulties when accelerating or braking.

The wheel-rail contact is an open system and therefore exposed to several conditions and contaminants, usually referred to as 3rd layer, that may influence adhesion. This can include natural contaminants such as leaves and organic debris, iron oxides and wear particles, as well as artificial contaminants such as sand, oil and salt. Some of the causes of low adhesion in the wheel-rail contact are well understood and can be predicted and mitigated, whilst others remain hard to prevent. Different environmental conditions such as temperature, precipitation and humidity change the properties of this third body layer and therefore change adhesion conditions on the railway. Low adhesion can lead to wheel slides and slips during acceleration and deceleration, which can cause large amounts of damage to the wheel and rail as well as causing safety issues and delays if a train cannot accelerate or decelerate when necessary.

The use of microwave-generated plasma in the treatment of the railhead is hoped to remove any contaminant through thermal ablation, chemical reaction with active species and retard any further creation of biological matter through sterilization. The system will eventually be developed into a track cleaning system & as a braking aid on vehicles.

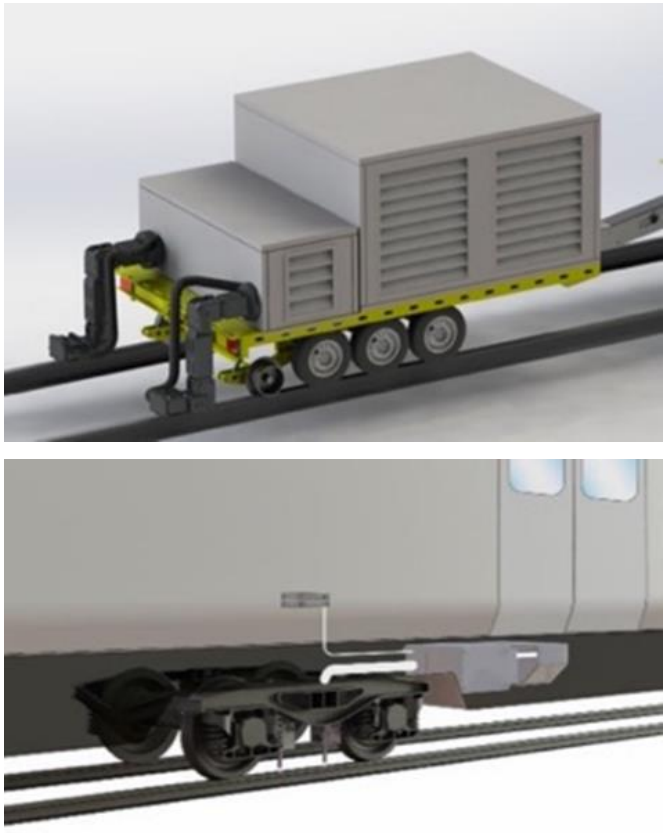

Figure 3: Product vision of track cleaning (top) and on-board train braking assistance (bottom)

3 Microwave plasma & testing equipment

The atmospheric pressure plasma was created within a dielectric tube placed in a TE_{01} monomode microwave cavity; the atmospheric plasma sustained in different inert gases (nitrogen, argon) as well as mixtures of inert gases with reactive molecules was jetted directly onto the railhead as to change the conditions for the wheel-rail interface – Figs. 4 & 5. This technology is hoped to be a game changer in enabling predictable and optimized braking on the railway network. Challenges encountered during the demonstration phase will be discussed.

4 Challenges

Thermal performance

The focus of this work was to understand the relationship between gas flow rate and power input. While testing in the lab, a block of aluminum was used to measure the rate of temperature increase during the plasma treatment as to evaluate the relationship between flowrate, gas flow dynamics & microwave power input – Fig. 6.

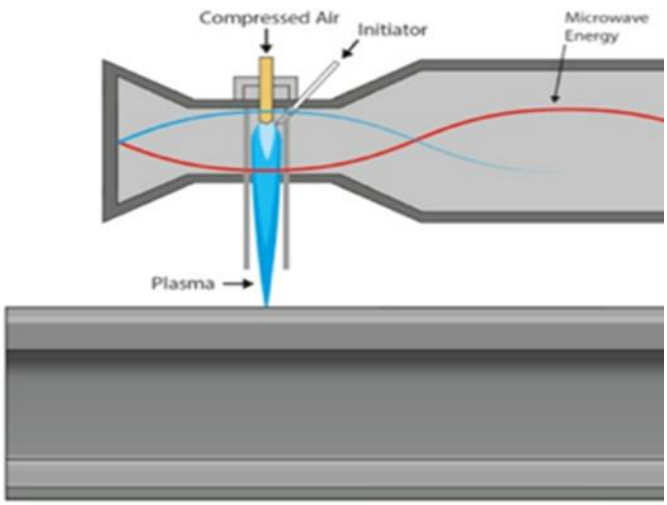

Figure 4: Plasma head cross-section schematic

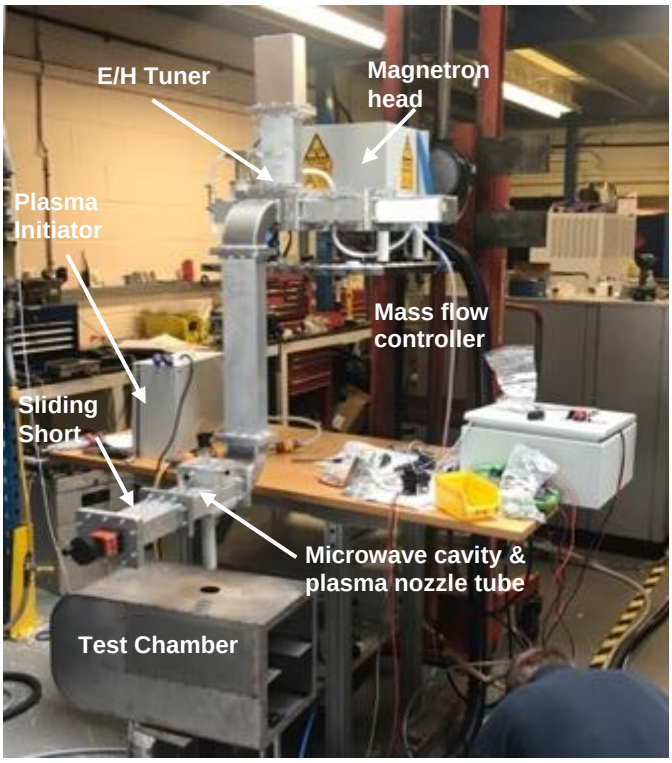

Figure 5: Laboratory set-up

Figure 6: Effect of gas flow on plasma afterglow delivery at 2kW

The main objective of the work was to develop a downstream plasma with an intensity and concentration as high as possible. The quartz tube initially used to contain the gas flow/ignited plasma had limitations with temperature vs. microwave power input. It was therefore decided to embark on investigation into alternative 'microwave transparent dielectrics' which could support this goal. In addition to quartz, non-oxide ceramics such as silicon carbide (SiC), aluminium nitride (AlN) and boron nitride (BN) were investigated. Out of numerous tested dielectrics, sintered BN proved to the best choice in terms of thermal shock (cycles plasma on/off) and microwave 'transparency'; in addition, BN could be machined into various forms enabling rapid iteration and development of plasma tube designs. The final 15 kW system was able to 'focus' the afterglow out of a 3 mm inner diameter tube.

Aggressive railway environment

When passing from the static lab testing to the real-world mobile testing, in order to protect the test equipment (especially the magnetron) from shock & vibration damage, a mobile platform using sprung AV mounts was built. Limitations of DMU (diesel multiple units) speed control & repeatability of braking cycle led to the exclusion of brake deceleration testing from the evaluation methodology for on-track testing. The track lateral movement and relative vertical movement limited the test site to the straight and testing within a 20 m zone with vertical movement less than 8mm. The plasma nozzle was pre-set to a maximum height of 25 mm from the railhead, Fig. 7. During the testing, the track has been temporarily marked at meter increments to aid in analysis.

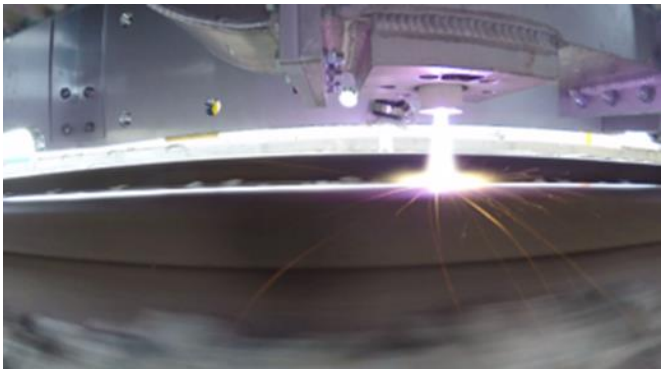

Figure 7: Go-Pro image of plasma on the rail during mobile testing

Testing was completed for 3 mm, 5 mm, 7.5 mm ID plasma tubes at low (5 km/h), medium (10 km/h) and high (15 km/h) speeds with power ranging from 9-15 kW. The test area was marked with cones to aid the driver in getting to speed, maintaining speed during plasma delivery and braking to a safe stopping point.

5 Results & Conclusion

An understanding and optimization of 2.45 GHz microwave generated atmospheric plasma in the context of track treatment has been demonstrated. The effect on 3rd layer contamination has been demonstrated in the laboratory and on the track, Fig. 8.

Figure 8: Clean (left) and dirty (right) track

Currently, 15 kW is the maximum power magnetron available at 2.45 GHz. In order to achieve a higher power microwave source, two main approaches are considered: *i)* using generators at 896 MHz, max. power 100 kW/unit, *ii)* using two 2.45 GHz microwaves generators in series. Knowing that when transitioning from 2.45 GHz to 896 MHz, the plasma density is believed to reduce by a factor of approximately 20, more testing will be needed as to validate the most viable solution (CAPEX, cost of ownership) and to maintain realistic electrical energy supply for onboard train systems.

About the Author:

Julian Swan, Co-Founder and Engineering lead at The Imagination Factory. He has worked on a diverse range of products including medical devices, sports equipment, drinks packaging and ruggedized film equipment. He graduated from Queens University Belfast with a Bachelor of Aeronautical Engineering and an MSc in Computer Aided Mechanical Engineering Design.

Power-to-X Applications based on Microwave Heating and Microwave Plasma Technology

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1 Introduction

In periods with high output, electrical energy extraction from renewable energy sources (e.g. photovoltaics, wind and water) can easily exceed the load and gets wasted. For maintaining stability of the public mains supply, surplus energy from renewable sources has to be stored, which poses a big challenge. Power-to-X is a general term summarizing technologies for conversion of this kind of surplus energy from renewable sources into matter that either can be stored and reconverted when required, or that will serve as basic materials for the production of e.g. more complex substances in chemical industry or synthetic fuels replacing fossil fuels in the transport sector. Figure 1 shows some examples of Power-to-X applications based on microwave plasma technology.

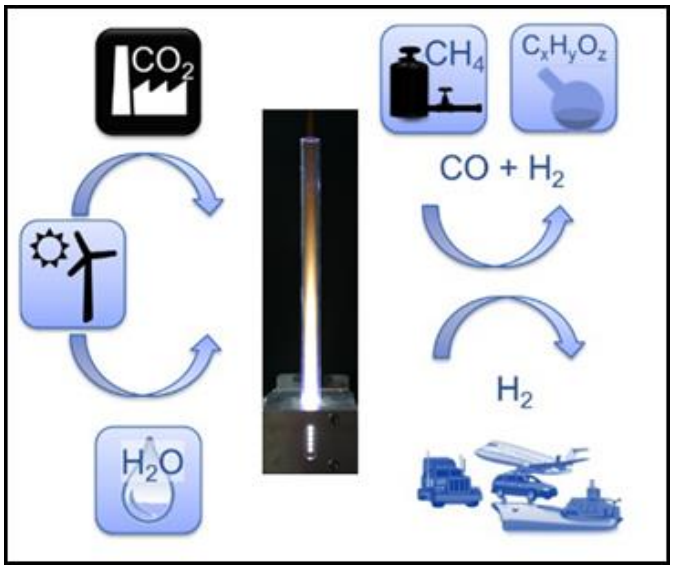

Figure 1: Some examples of Power-to-X applications based on microwave plasma technology.

Examples of Power-to-X applications based on microwave heating and microwave plasma technology are presented in the following chapters.

2 Power-to-Liquid applications based on microwave heating technology

Microwave-driven depolymerization processes (pyrolysis) are ready to be used for Power-to-Liquid applications, e.g. production of bio-fuel. Standard applications can be found in biomass-to-liquid or waste-to-liquid plants.

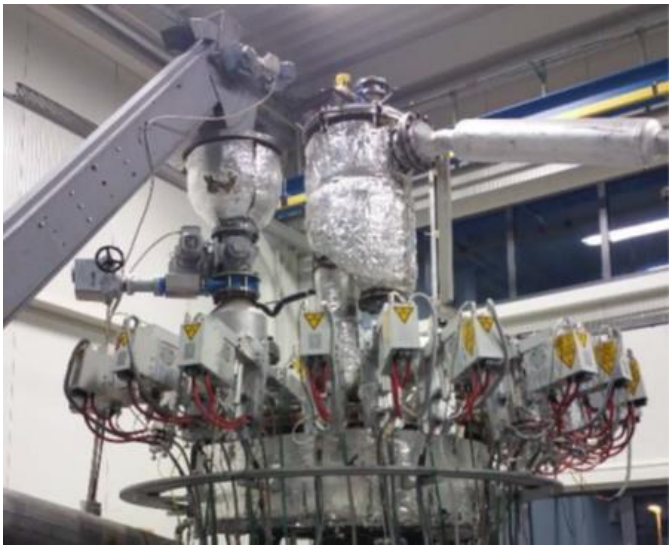

Figure 2: Microwave pyrolysis reactor for Power-to-Liquid applications (installed at Bionic Laboratories BLG GmbH, Germany, www.bionic-world.eu).

Microwave-assisted pyrolysis processes are well suited to recycle a large variety of carbonaceous waste fractions such as tires, sewage sludge, agricultural waste, waste wood, electronic scrap, cables, plastic waste etc. to liquid fuels like heavy

oil, diesel, gasoline and jet fuel. The processes often rely on rapid heating of waste in an oxygen-free environment. The feedstock is introduced into the pyrolysis reactor of Figure 2 through air locks purged with inert gas to prevent oxygen to enter the reactor. Then it is heated by means of microwaves to a temperature level just beyond the threshold for separation of solid and volatile compounds of the feedstock. In a subsequent condensation process, part of the volatile compounds can be transformed into fluids for additional separation. At the end of the pyrolysis process, bio fuels, oils and monomers are extracted via condensers and separated from the remaining char.

Microwave heating is very homogeneous due to the high penetration depth of microwaves into the feedstock, providing a low temperature gradient from the surface to the core of the feedstock.

3 Power-to-Chemicals applications based on microwave plasma technology

Storage of surplus electrical energy from renewable sources is a crucial factor for maintaining stability of the public mains supply. Carbon dioxide (CO_2) conversion is a promising approach for storing surplus renewable energy. The concept of CO_2 conversion is based on splitting CO_2 into oxygen (O) and carbon monoxide (CO) radicals in an atmospheric pressure microwave plasma process, see Figure 3. Carbon monoxide (CO) is an industrial gas, which has numerous applications in chemical manufacturing. It can be converted into base chemicals and chemical energy stores such as methanol or methane in existing infrastructures using conventional chemical processes.

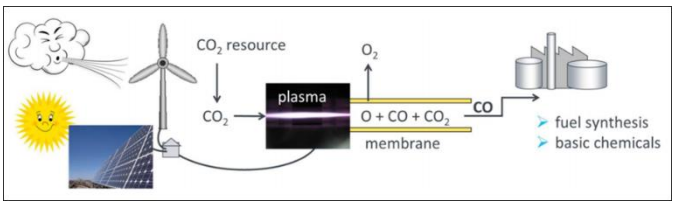

Figure 3: Schematic of CO_2 conversion for Power-to-Chemicals applications

CO_2 conversion can be efficiently performed with a high-power microwave plasma torch using excess electrical energy from regenerative sources. By separation of the oxygen from the gas mixture, for example via a perovskite membrane – as shown in Figure 4 –, the remaining CO gas can be utilized for the conversion into syngas or higher hydrocarbons. Hence, a zero emission carbon cycle can be established.

The process can be applied wherever CO_2 is produced in enriched form: in combustion processes in power plants, in the cement and glass industries, and in breweries where CO_2 is a by-product of alcoholic fermentation.

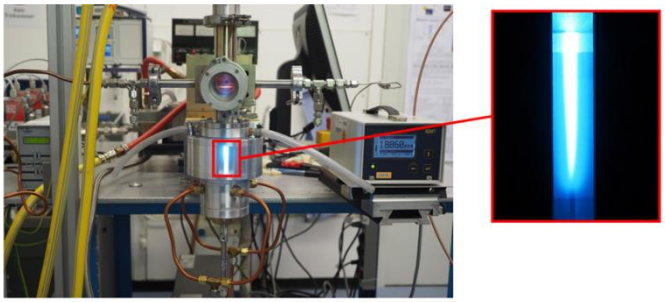

Figure 4: Laboratory setup for CO_2 conversion by application of an atmospheric microwave plasma torch and subsequent separation of CO by means of a perovskite membrane.

4 Power-to-Gas applications based on microwave heating technology

The new generation of MUEGGE's microwave powerheads, generators and tuning elements enable compact plasma sources at atmospheric pressure for surface and volume treatment. The Atmospheric Plasma Source (APS) from MUEGGE operated at the microwave frequencies of 2.45 GHz and of 915 MHz, respectively, is a feasible tool for production of syngas via CH_4 and CO_2 conversion. Figure 5 shows microwave plasma torches operated with 6 kW (left) and 3 kW (right) of microwave power, respectively. Microwaves with a frequency of 2.45 GHz are fed into the plasma source resulting in a high field concentration in the middle of the cavity. In this region, the plasma is ignited and sustained. Several kilowatts of microwave power can be injected into the plasma, resulting in gas temperatures of up to 3500 K determined by optical emission spectroscopy.

MUEGGE's microwave plasma torches are igniting at atmospheric pressure and generate a contact-free plasma while ensuring stable operation in a wide parameter range concerning type of gas,

working gas flow and microwave power. Whatever microwave frequency is selected, 2.45 GHz or 915 MHz, microwave plasma torches from MUEGGE are well suited for both synthesis of special gases and supporting chemical reactions with highly reactive gas species, which is key for many Power-to-X applications, e.g. Power-to-Chemicals and Power-to-Gas.

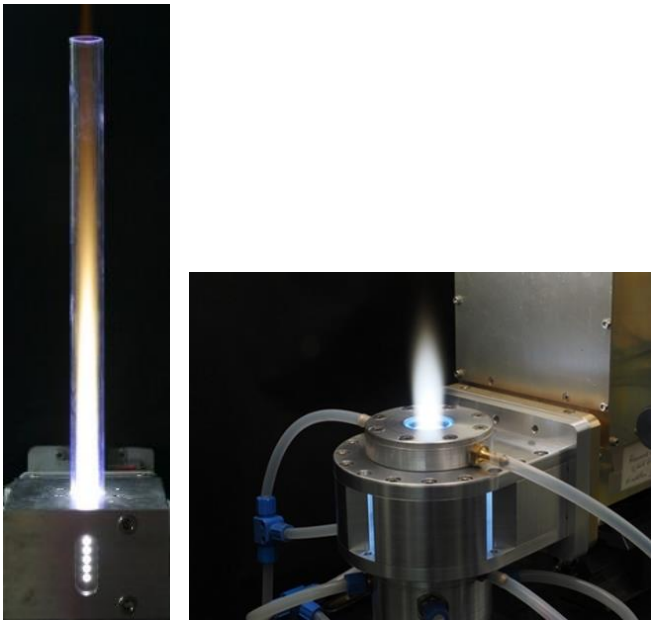

Figure 5: 2.45 GHz microwave plasma torches operated with 6 kW of microwave power (left) and with 3 kW of microwave power (right).

A high-power downstream-plasma-source operated at the microwave frequency of 915 MHz at a few mbar is presented in Figure 6. This device is characterized by its high microwave power input of up to 75 kW, enabling the treatment of high gas flows.

Efficient CO_2 dissociation combined with high conversion rates of CH_4 – being a prominent example of Power-to-Gas applications – can easily be performed by such highly energetic microwave plasma sources. The H_2/CO mole ratio of the syngas is relatively easy to control by adjusting the ratio of CO_2/CH_4 in the feeding process. Furthermore, the syngas produced by this sources is not only usable for the production of e.g. acetic acid or methyl formate, but also satisfies the H_2/CO mole ratio required for the production of various substances when combined with wet syngas processes. The process efficiency can be significantly enhanced by additional application of a suitable catalyst.

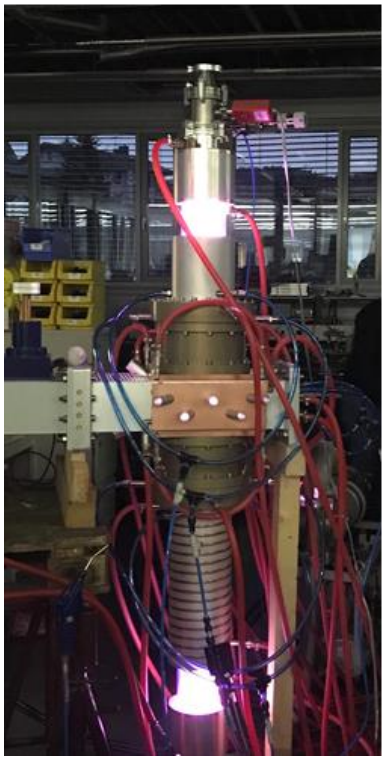

Figure 6: Microwave plasma torch operated with 30 kW of microwave power at 915 MHz.

The same microwave plasma source-equipment can be used to create a plasma environment to decompose alcohols. When introduced into a water vapor plasma discharge, methanol and ethanol, respectively, decompose to hydrogen. In fact, nearly 100% decomposition of methanol can be achieved in an atmospheric microwave plasma process. The steam reforming reaction

$$C_2H_5OH + H_2O \rightarrow 2CO + 4H_2$$

is the most likely source of H_2 production in this case, which is confirmed by the fact that no formation of solid carbon was observed. This kind of atmospheric plasma process by application of a microwave plasma torch is very efficient for H_2 production from methanol and ethanol, respectively.

A carbon-free, circular economy is required to decrease greenhouse gas emissions. Hydrogen economy is a commonly proposed alternative to the carbon-based economy. However, storing and transporting hydrogen is difficult. Ammonia (NH_3) as a carbon-free hydrogen carrier is a relatively safe

alternative to hydrogen. Especially in the long term, it is more economic to store ammonia than hydrogen.

High-energy electrons and ions as well as highly reactive radicals in an atmospheric microwave torch plasma significantly enhance chemical kinetics. However, the high level of activation energy necessary for the dissociation of the nitrogen molecule is rate limiting in ammonia production.

Plasma catalysis uses the synergy effects of plasmas and catalysts for the synthesis of various compounds. In case of ammonia synthesis, plasma catalysis helps to overcome the rate-limiting step of nitrogen dissociation prior to NH_x formation. In this perspective, the combination of plasma and catalyst for using their synergies shows high benefits in ammonia production from renewable energy sources.

5 Summary

In general, Power-to-X combines all available options for the effective and flexible use of surplus energy from renewable sources. Power-to-X technologies based on microwave heating and microwave plasma processes are innovative solutions for conversion of electrical energy from renewable sources into material resources such as hydrogen, carbon monoxide, and synthetic gases for storage and recycling – e.g. conversion of electrical energy into gaseous or liquid fuels or chemicals for long-haul trucking, shipping and aviation. Therefore, Power-to-X contributes to the objective of decarbonising the energy systems, and at the same time helps to reduce the proportion of fossil fuels in the key leading markets of transport, travel and chemicals, thus generating ecological, economical and social benefits.

About the author

Robert Mueller received his Chemistry diploma and PhD degree from the Ludwig-Maximilians-University, Munich, Germany. He has > 20 years of semiconductor experience, working on various positions in etch&strip, CVD and RTP. He joined the MUEGGE group in October 2016 and he currently heads Gerling Applied Engineering, the US branch of MUEGGE GmbH.

Microwaves in a Multidisciplinary Future

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1 Background

The science and engineering of microwave power is continuing to grow in scope. As new innovations emerge, researchers in industry and academia are witnessing an explosion in multidisciplinary applications of microwaves. The advantages of microwave energy are finding new appreciation in many diverse areas, but despite these emerging applications, there are still many open questions surrounding the fundamental mechanisms of microwave irradiation, leading to a rich scientific landscape for those involved in microwave power.

The Centre for High Frequency Engineering (CHFE) is a large microwave engineering research group based at Cardiff University in the UK [1], with 13 academic staff, led by Professor Adrian Porch. Research activities in the group span the breadth of microwave energy applications, including in chemistry, physics, biology and medicine, power amplifier device design, modelling and characterisation, microwave and mm-wave hybrid circuits and microwave microfluidics. Recent expansion into compound semiconductor materials for microwave power applications has seen the Institute for Compound Semiconductors being established, with state-of-the-art equipment and facilities for microwave device fabrication and characterisation. The group has strong international industrial links with a diverse range of companies, including IQE, MACOM, Arelis Thompson Broadcast, DSTL, Diamond Microwave, European Space Agency, Kelvin Nanotechnology, NXP Semiconductors, Oxford Instruments Plasma Technology, Plessey Semiconductors, Merck KGaA (Darmstadt), Microsemi and Renishaw.

2 Microwave Multidisciplinarity

For over 20 years, the group has worked developing innovations in microwave power and measurements. CHFE carries out a range of interdisciplinary research with industrial and academic partners. Key projects include:

- Microwave methods in hydrogen storage and production
- Additive manufacturing
- Microwave detection and treatment of bacteria and bacterial spores
- Non-invasive blood glucose measurements
- In situ measurements during microwave heating, using magnetic resonance, infra-red, neutron and x-ray scattering measurements.

Here we look at some recent work emerging from the group applying microwave innovations across a range of disciplines.

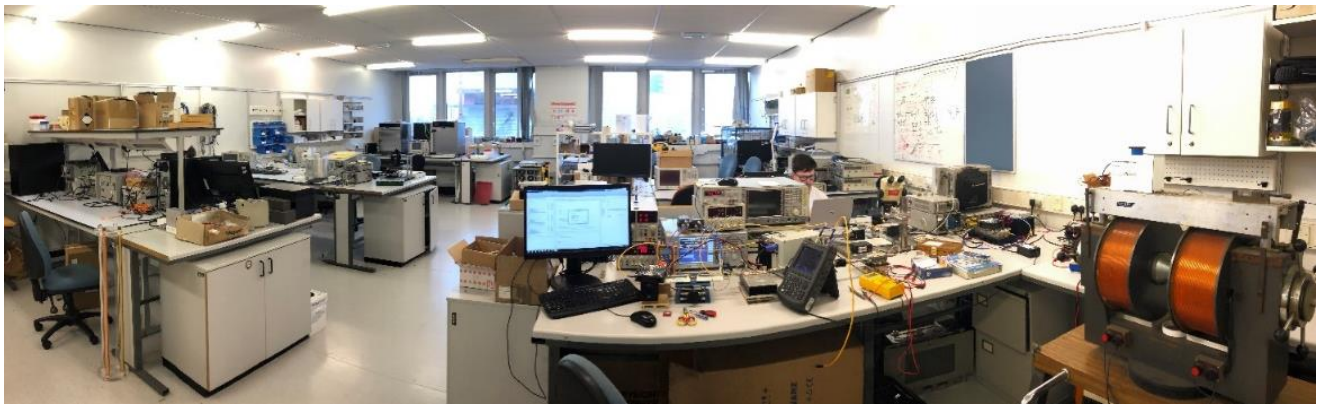

Figure 1: The interdisciplinary microwave characterization laboratory, Centre for High Frequency Engineering, Cardiff.

3 Microwaves in the production and storage of hydrogen.

Hydrogen as an energy carrier promises a sustainable energy revolution. However, one of the greatest challenges for any future hydrogen economy is the necessity for large scale hydrogen production not involving concurrent CO_2 production. The high intrinsic hydrogen content of diesel and other liquid-range alkane hydrocarbons offers a route to CO_2-free hydrogen production through their catalytic deep dehydrogenation. Using microwaves, results show that high-purity hydrogen can be liberated from fossil fuels by microwave-promoted catalytic dehydrogenation. Using Fe and Ni particles supported on silicon carbide, a H_2 production selectivity from all evolved gases of some 98% is achieved, with less than a fraction of a percent of adventitious CO and CO_2. The major co-product is solid, elemental carbon. [2-4]

4 New in-situ measurements for microwave heating

Microwave heating experiments often present impressive results under very different heating conditions. The complexity of heating heterogeneous materials in microwaves leads to many fundamental questions. Experiments to simultaneously heat and measure materials under microwave irradiation can help to shed light upon these complex mechanisms:

(i) Electron paramagnetic resonance (EPR) measurements are a useful tool to explore radical chemistry. A unique dual mode X-band continuous wave EPR resonator for simultaneous EPR measurement and rapid MW induced sample heating has been developed in Cardiff. This is currently generating unprecedented results in microwave driven catalysis and in fundamental chemistry via temperature-jump experiments to measure the properties of chemical systems far from thermodynamic equilibrium [5].

(ii) In situ neutron scattering experiments can reveal details of structure and phase changes taking place during microwave irradiation. Using a microwave resonator with a thinned-down aluminum cavity wall, scattering experiments can be carried out for either material processing using high power microwaves or dielectric measurements. Figure 2 shows one of the devices used for in situ spectroscopy under microwave irradiation. In this example, neutrons are used to reveal the absorption and desorption of ammonia with simultaneous microwave dielectric measurements. Also shown are the superimposed data of the absorption/desorption cycles showing a surface plot of Bragg diffraction during ammonia absorption and desorption within a metal-organic framework under ammonia (ND3) and argon (Ar) flows. The intensity of the Bragg lines is represented by the colour scale on the right. The results of these studies allow the identification of materials with useful ammonia storage properties and provide a new metric for the measurement of gas absorption within mesoporous solids using microwaves. [6]

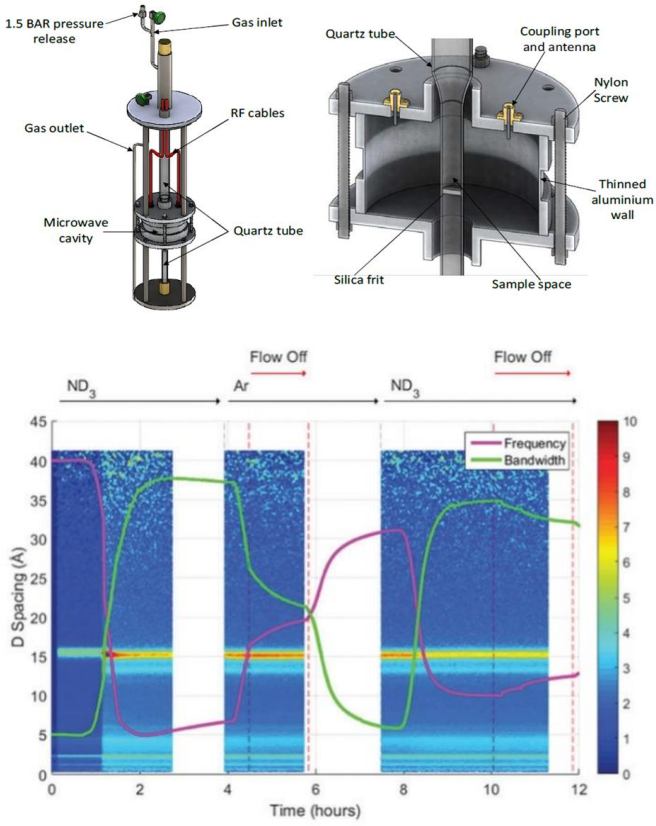

Figure 2: Schematic diagram of the experimental housing for the Microwave Cavity Resonator in the neutron diffractometer and a superimposition of the surface plot of Bragg diffraction and dielectric data (frequency and bandwidth) during ammonia absorption and desorption under ammonia (ND3) and argon (Ar) flows.

5 A new theoretical framework for heating of catalysts and powders

Recent work has established new approaches to microwave heating of powders. Analytical models of dipole absorption in conducting spheres reveal that by simple selection of the size and conductivity of a powder, the heating rate and dominant heating mechanism can be controlled [7]. As shown in Figure 3, for poorly conducting materials, the optimum heating is dominated by the interaction of the electric field *E*, is size independent, and occurs at a conductivity of $\sigma = 3\omega\varepsilon_0$, where ω is the angular frequency and ε_0 is the permittivity of free space. For highly conducting materials, the heating is dominated by the magnetic field H, is size dependent, and is optimum at a particle-radius to skin-depth (a/δ) ratio of 2.41. This knowledge provides a framework for selecting powder materials for heating applications and enables a deeper exploration of the very different mechanisms in electric- or magnetic-field driven heating.

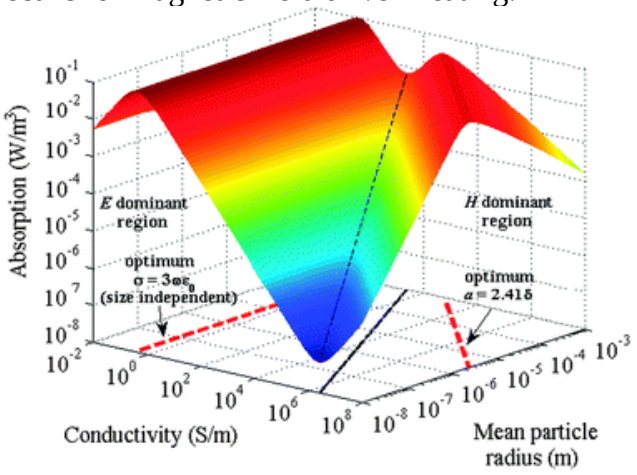

Figure 3: Heating rates in powders of different particle radius and conductivity.

6 Non-invasive measurements of blood glucose

One in eleven adults has diabetes (463million people) and 10% of global health expenditure is spent on the diabetes. Three in four of people with diabetes live in low- and middle-income countries. Affordable self-monitoring techniques usually involve the use of finger-prick devices, test strips and the glucose meters, which can be painful and only give discrete readings. Using microwaves, the Centre for High Frequency Engineering at Cardiff University has been pursuing non-invasive and continuous monitoring of blood glucose [8] and is now working towards commercialization of the sensor device.

Figure 4: The microwave non-invasive blood glucose sensor

7 Future plans

Rapid expansions are taking place in Cardiff related to microwave device fabrication and characterization. In addition, the Centre for High Frequency Engineering is recruiting academic staff to expand the multidisciplinary research portfolio. We continue to explore new partnerships in diverse areas of microwave chemistry, medicine and energy materials. In particular, in microwave catalysis and new in situ measurements to develop a deeper understanding of scientific and engineering challenges in microwave chemistry. Given the buoyant research climate in the field of microwave power applications, and the important unanswered questions that characterize microwave research, we expect this trend to continue.

For further readings

1. Cardiff - Capital City of Wales: https://www.youtube.com/watch?v=UqicqIMGGpI
2. Gonzalez-Cortes S. et al., Wax; A benign hydrogen-storage material that rapidly releases H2-rich gases through microwave-assisted catalytic decomposition. *Scientific Reports* 6, article number: 35315, 2016.
3. Jie X. et al.; Rapid production of high-purity hydrogen fuel through microwave-promoted deep catalytic dehydrogenation of liquid alkanes with abundant metals. *Angewandte Chemie - International Edition* , 2017, **56**(34), 10170-10173.
4. Jie X. et al; The decarbonisation of petroleum and other fossil hydrocarbon fuels for the facile production and safe storage of hydrogen. *Energy and Environmental Science*, 2019, **12**(1), 238-249.

5. Folli, A.et al.; A novel dual mode X-band EPR resonator for rapid in situ microwave heating. *Journal of Magnetic Resonance*, 2020, **310**, article number: 106644.
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8. Choi, H.et al.; Microwave noninvasive blood glucose monitoring sensor: penetration depth and sensitivity analysis, IEEE International Microwave Biomedical Conference (IMBioC 2018) Philadelphia, PA, US. IEEE, 2018, 52-54.

About the author

Daniel R. Slocombe received the Ph.D. degree in Electronic Engineering from Cardiff University, UK. From 2002 until 2006 he was an engineer in the Royal Air Force and from 2012 until 2015 he was a Research Fellow in the Inorganic Chemistry Laboratory at the University of Oxford, UK. He is currently Head of Teaching for the Department of Electrical and Electronic Engineering at Cardiff University and is a member of the Centre for High Frequency Engineering. He has carried out research in many areas of microwave science and high frequency materials including microwave activation of catalytic processes, synthesis of functional oxides, dielectric spectroscopy and new methods using Electron Paramagnetic Resonance.

Ricky's Afterthought:

Quantum Entanglement and Cryptography

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Were you aware that of all Einstein's papers the one most read (ever apparently) is the so called EPR paper published in 1935 by Einstein, Podolsky and Rosen in the American Physical Review when they were colleagues at the Institute of Advanced Study near Princeton? Einstein, then director at the Institute, regarded Podolsky and one of the most brilliant young theoretical physicists of his generation who had published papers with Paul Dirac, famous for his elegant equation that predicted the existence of antimatter [$(i\partial\!\!\!/-m)\psi=0$ where $\partial\!\!\!/$ is Feynman's slash notation, ψ is a wave function, m its rest mass and (x,t) the space-time coordinates]. Dirac, by the way, was Lucasian Professor of Mathematics at Cambridge University and a Fellow at St John's College in the 1930's. This incidental fact does make me wonder whether he ever occupied one of the five rooms I have resided in, a notion that instigates quivers of excitement. However, I will not rush to check in case I find that it is but wishful thinking.

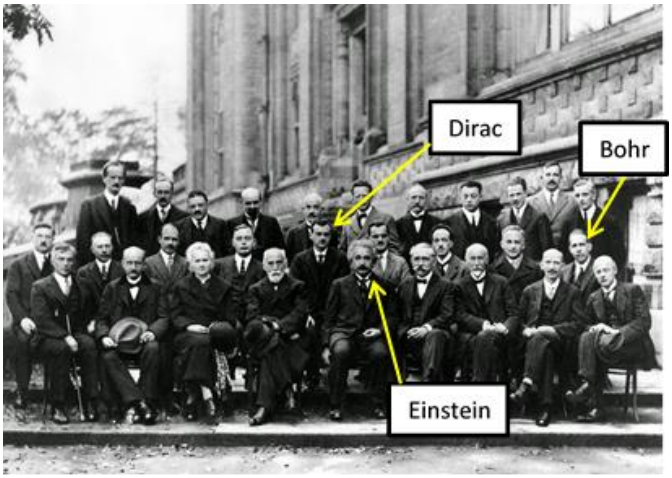

Fig.1: The iconic group photo of the 1927 Solvay meeting

The group photo taken at the 1927 Solvay conference on electrons and photons, where they discussed issues related to quantum mechanics, shows Einstein amongst most of the famous scientists at the time. Einstein mentioned time and time again that quantum mechanics gave excellent agreement with what happens in the subatomic level but more needed to be done to give it physical reality such as one finds with classical physics. Einstein debated this issue with Bohr, who aided by his colleagues, was able to answer all the Einstein's questions so Neils Bohr felt all was well with quantum mechanics.

Where was I? Oh yes, the EPR paper. So when in 1935 the EPR paper was published it essentially shook the whole foundation of quantum mechanics. This is because in that paper Einstein and his colleagues use their arguments to cast doubt on Niels Bohr's interpretation of entangled (or linked) functions. To put the problem in its more simplistic form, say we have two photons, which originate from the same source and find themselves one in Cambridge and one in Valencia (well you could take two photons in different galaxies in the cosmos but let us be more realistic) then measurement of one entangled particle will instantaneously determine what is measured at the other entangled particle, regardless of how far apart they are, that is, they are linked or to use a more scientific term the quanta, or more generally wave functions, are entangled. Einstein referred to this notion as "spooky action at a distance" when he came across quantum entanglement. The EPR paper implied that if the two entangled photons were able to communicate instantly then this had to be done faster than the speed of light which goes against Einstein's special theory of relativity. So the argument rested for a while and in the following couple of decades we see the development of the laser, disc drives, the transistor and the digital revolution commences, all relying heavily on the principles of quantum mechanics which Einstein insisted was incomplete. Of course Bohr and Einstein despite their disagreement had high respect for each other.

In the early 1960's the Irish physicist John Bell claimed that the EPR paradox had not been addressed. He continued to reflect on the Einstein/Bohr debates and in 1964 published a remarkable paper in which he proposed a "thought experiment" to resolve the issue of causality and locality that lies at the heart of quantum mechanics versus classical physics as regards the interpretation of quantum entanglement. He is well known for his so called Bell's theorem which basically seeks to find out whether particles (the photons I described above) talk to each other faster than the speed of light. If they do not then that disproves quantum mechanics. He found that they do, so at the time he could only say that quantum mechanics was not wrong. But it violates Einstein's special relativity in that it introduces a violation of locality. Another explanation that Bell put forward was that when the photons were born they had in them an "embedded DNA" with some hidden variables that would govern precisely what happens to each throughout the entirety of their existence. Since Einstein and his colleagues believed explicitly in classical physics, they would have aspired to this second explanation. But Bell's inequality proved that the notion of the embedded DNA was not true hence the only explanation was that particles do communicate faster than the speed of light. In his paper Bell put forward an expression that could be tested experimentally and could therefore ascertain whether Einstein or Bohr was correct.

However, the paper remained hidden and unnoticed from the scientific community for a number of years. Then in 1972 John Clauser of the University of California read Bell's paper and found it fascinating while pondering why nobody had thus far tested Bell's inequality. He, and his colleague, Stuart Freedman carried out the first "Bell Test experiment" by firing a laser onto calcium atoms producing entangled particles which they then passed through polarisers and checked how often the answers correlated. Their experiment was what one would describe as a "Heath Robinson device", meaning a device that was simultaneously absurdly ingenious and impracticable and could have loopholes which cast doubt on the validity of the results obtained. So what was needed was a more rigorous approach.

After numerous attempts on the "Bell's Test experiments" by other scientists, a collaborative experiment was conducted in 2015 under the direction of Anton Zeilinger's group of the Quantum Optics at the University of Vienna and performed in a sub-basement at the Vienna Hofburg Palace using

a source which created entangled photons. These were distributed, one in each of two optical glass fibres, to measurement stations called Alice and Bob. After many observations quantum entanglement was confirmed. However, physicists still questioned whether all the possible loopholes were covered and in that respect Prof Zeilinger spent the best part of the following a few years devising an amazing experiment which included light emanating from two distant quasars. This time his colleagues teamed up with researchers at MIT and many other institutions and conducted quantum entanglement experiments on the island of La Palma in the Canaries, using two large telescopes the Telescopio Nazionale Galileo and the William Herschel Telescope. Essentially this created a giant "Bell Test experiment" where a source of entangled particles was equidistant (500m) from the two telescopes.

A laser created a pair of perfectly timed photons which travelled through the air reaching the receivers of the two telescopes. At the same time light from two distant quasars and from opposite sides of the cosmos, arrive at the two telescopes and as they had travelled such vast distances it was highly unlikely to influence the randomness of the test. The quasars were used as random number generators and determined which filters the photons were passing through. Variations of the colour in the quasar light were then used to control which kind of measurement was performed on the two photons from an entangled pair created in a mobile laboratory on Las Palmas. Finally, they examined the polarisation of each entangled photon emanating from the light fluctuations from each distant quasar. After conducting many experiments and recording the results quantum entanglement was confirmed.

Now, you may think that all this is academic and has no bearing to any practical use. In fact superposition and entanglement is at the heart of research into quantum computers. Instead of storing data in bits, as in today's computers, quantum bits or qubits are used to do so. The qubits could be in states 1 or zero or both and groups of qubits could be linked to form a quantum computer. By using entangled qubits real problems can be tackled much faster than using digital computers, for example, in cryptography where one-time pad, that is, a set of random numbers-the key-is used in order to encode and decode messages. Putting it simply both parties would have the same cipher thanks to quantum entanglement. Should a hacker attempt to secretly listen to the conversation, the symmetry would be broken and the parties would instantly realise that something was wrong. Chinese scientists have launched the Micius satellite setting up intercontinental quantum communication amongst multiple locations on earth with a maximum separation of 7.6 km. None other than Anton Zeilinger from Vienna is involved in this project with his Chinese colleagues, led by Jian-Wei Pan at the University of Science and Technology of China in Hefei, China.

So, can one categorically state that Einstein was wrong? Remember, he only stated that quantum mechanics was incomplete. I let our readers draw their own conclusions.

For further reading

https://journals.aps.org/pr/pdf/10.1103/PhysRev.47.777

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Afterthoughts of the workshop Challenges in Plasma and Catalysis, 17th & 18th October 2019, Le Havre, France Plasma-Assisted Catalysis of CO_2 Methanation

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Abstract. The main objective of the project CO_2 VIRIDIS was to study interactions between catalysis and different types of plasmas. The methanation of CO_2 with hydrogen on different catalysts was used as a model reaction.
To investigate how plasma-assisted catalysis could help the activation of CO_2 in an energy efficient way, CO_2 Viridis has started two years ago as a collaboration among four laboratories in Normandie, France:

- CORIA (COmplexe de Recherche Interprofessionnel en Aérothermochimie) Rouen, involved with the optical emission spectroscopy for the measurement of species formed in different plasmas (DC, microwave, low pressure, atmospheric pressure), which helped to build theoretical models based on collisions, vibrational excitations and energy levels of the formed species, particularly using CO_2 plasmas;
- LCS (Laboratoire Catalyse et Spéétrochimie) Caen, in charge with the development of highly efficient catalysts for CO_2 methanation and with the testing of the obtained catalysts in DBD plasma;
- LOMC (Laboratoire Ondes et Milieux Complexes) Le Havre, looked at mechanisms and kinetics of CO_2 dissociation;
- LSPC (Laboratoire de Sécurité des Procédés Chimiques) Rouen, developed a microwave plasma pilot and tested CO_2 conversion using microwave plasmas.

The workshop benefited from talks given by international guests working on similar subjects and who have been invited to share their experience and to contribute with ideas towards the understanding of the complex system involving plasma-assisted catalysis; a list of participants and their shared expertise is given at the end of the article.
The workshop's main goal was to disseminate the results of the carried-out research during the project - system modelling, catalyst development/selection, plasma type - and to assess the results in view of process scale up.

1 Introduction

Over the last 10 years or so, several technologies have been developed to utilize renewable sources to produce value added chemicals, and CO_2 has been discussed widely as a potential renewable source[1-4]. The utilization of CO_2 not only contributes to the decrease of greenhouse gas emissions, but also produces useful chemicals such as C1 building blocks, syngas, and higher hydrocarbons. However, its activation generally requires high temperatures (>540 °C to obtain more than 50 % CO_2 conversion in CO_2 reforming with methane) because of its large ionization potential and a small electron affinity, which leads inevitably to a massive energy consumption. This disadvantage limits practical applications even if renewable sources are used, therefore, energy efficient improvements are necessary for CO_2 utilization technology.

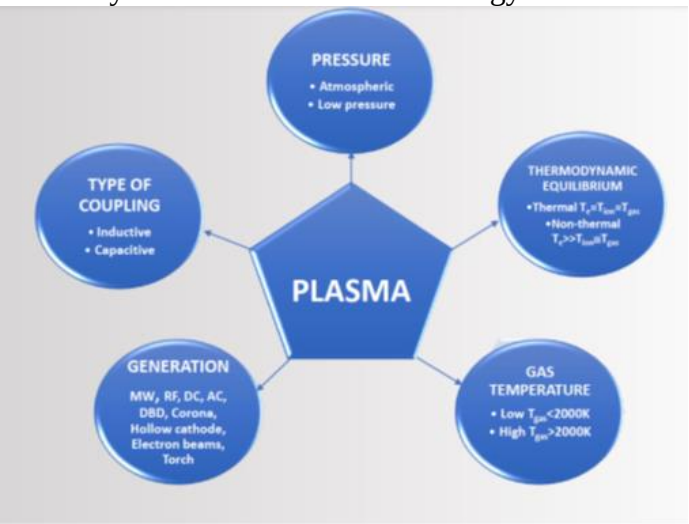

Figure 1: Plasma classification

At present there are a few strategies for the conversion of CO_2 that could be an effective alternative to a thermochemical reactor system. These alternative strategies include the use of an electric field, microwave dielectric heating, plasma–catalysis hybrid system, and a light assisted catalytic system. These methods, however, also require excessive energy input to overcome the activation energy of the target reaction and although some papers reported a reduced operating temperature with high efficiency conversion, up to present these processes can only be operated on a small scale that is suitable only for localized CO_2 conversion and is not acceptable for industrial production[1-3].

Understanding the interaction between plasma and catalyst is not an obvious subject: essentially, plasma is an ionized gas containing an equal number of positive ions as of electrons and negative ions. Plasma is electrically neutral, and its degree of ionization can range from very low, i.e., partially ionized, to 100%, or fully ionized. Technically, plasma can be created by a variety of discharge techniques (electrode or electrode-less), which initiate a breakdown of the gas and create a range of reactive species such as electrons, ions, dissociated and excited species leading to chemical transformations. Plasmas can be characterized by the pressure regime in which they operate, either low pressure (< 1 atm) or high pressure (>1 atm). Low-pressure conditions favour surface collisions making catalytic effects easier to notice and they also minimise the deactivation of the excited states produced in the plasma through gas-phase. Another distinction concerns the degree of thermal equilibrium in the plasma. It may be thermal with all the degrees of freedom including the electrons, ions and neutral species having the same temperature as the bulk gas (typically > 1000 K). In contrast, non-thermal plasma has a high degree of disequilibrium between the light electrons and the heavier particles (ions, radical and molecules). Little kinetic energy is transferred between the light electrons and the heavy atomic and molecular species that remain close to their ambient temperature. Thus, a non-thermal discharge can create excited and reactive species that can normally only be produced in an equilibrium system such as an arc or flame at very high temperatures. Hence, plasma typically produces ionised, excited and reactive gaseous species in relatively low concentrations compared with the bulk neutral atomic and molecular species providing the means by which the key components in the gas stream are destroyed or converted into other potentially useful chemicals. In plasma-catalysis, these ionised, excited and reactive gaseous species can also interact with a catalyst at near ambient temperatures for which conventional thermal catalysis would be inactive.

2 Main topics of the workshop

2.1 Plasma modelling

Several research teams have presented their work on CO_2 plasma modelling. Most of the developed models have been based on the various energy levels of the possible excitation states of CO_2. Some models have integrated the dissociation of CO_2 in CO and O, which helped to predict the distribution of the excited species within the plasma as a function of energy levels, electric field intensity etc. In connection with the vibrational states, the cross sections calculations are very important, and they were found to depend on the excitation type, i.e. rotational, vibrational or electronic. As an example, Bultel and co-authors have simulated the concentration profiles of the species obtained in a post discharge shock wave plasma.

Fundamental studies of electron collisions with larger molecules like BF_2^+ and NO_2 have been presented. As per CO_2 plasma modelling, the results of these studies emphasize the importance of accurate cross section calculations.

From all presentations, it was concluded that plasma modelling must be done via a double approach, which combines the scientific procedure with an engineering point of view. First, the fundamental properties of thermal plasmas that are required in the models are to be considered, followed by the basic equations and structures of the models. The third part must be devoted to test cases, with the objective of studying some basic phenomena to show their influence on plasma behaviour in simple configurations, and the validation of the models pointing out the roles of radiation, thermal conductivity and electrical conductivity.

In the specific case of microwave-excited plasma, one must consider that these plasmas are more complex. The charged particles are both

affected by external electromagnetic fields and contribute to them. The resulting system is nonlinear and therefore difficult to analyse. Electromagnetic waves carry energy from the plasma surface into the bulk plasma, where the major part of energy carried by the electromagnetic wave can be absorbed. Electromagnetic wave propagation in plasma is similar to the electromagnetic wave propagation in a dielectric medium, similar rules apply, and concepts developed for dielectric medium can be transferred to plasma.

2.2 Modelling of catalytic systems under plasmas

Engelmann & co-workers modelled the mechanism of non-oxidative coupling of methane to ethylene and acetylene in a plasma environment. The mechanism of the methane reforming was proposed using a *microkinetic model* for the formulation of a rate law of methane decomposition to CH_3^+, H^+ etc. and a *catalytical model* where a pure metal catalyst was used to complete the reforming reaction. The calculation of interaction forces/binding energies between formed species and different metal catalysts showed that noble metals, e.g. Ru, Pd, Pt, Rh, promote strong interactions while less noble metals, e.g. Cu, Ag, promote weaker interactions leading to the desorption of products. Furthermore, possible reaction paths were proposed on coupling reaction of methane through plasma and studied theoretically using the transition state theory; methane excitation depends on the vibrational mode and the temperature. The use of plasma allows to obtain high density excited-state populations in binding mode however, with low efficiency. The choice of temperature and catalyst can be used to 'tune' the plasma-assisted methane reforming reaction paths towards acetylene production or towards other products.

2.3 Experimental testing

Plasma-catalysis can be considered as a variant of heterogeneous catalysis where the gaseous phase of the reagents and products differs from the solid phase of the catalyst. Solid catalysts come in a variety of forms that all have the property of absorbing species onto their surface and thereby allowing possible migration into their bulk. Commonly, an active material such as a transition metal is placed onto a support material such as metal oxide or silica. The role of the support is to provide a high surface area, with defined porosity and to give thermal and mechanical stability. The species that are adsorbed onto the catalyst can remain in their gaseous form upon adsorption and be weakly bound (physisorption) or they may become dissociated into fragments and be strongly bound to the surface (chemisorption) and then react with either other species on the surface or by contact with an incoming gas-phase species. In contrast to thermal catalysis where the reactive species are formed dissociatively only on the surface of the heated catalyst, in plasma-catalysis reactive species can also be formed in the gas-phase either by dissociation within the plasma or by subsequent gas-phase reactions of plasma-excited species.

The chemical system most studied in this project was CO_2 methanation using Ni catalysts in various plasmas. The gas pressure and the type of discharge are reported to have great importance on the reaction path.

It was reported that DBD plasmas offer interesting results at low gas pressure, and not only for CO_2 methanation on Ni catalysts. The effect of various supports like alumina, silica, zeolites and the effect of a cocatalyst (Ce, Co) addition have been presented. Equally, the use of a plasma may allow the activation and the possible usage of less active catalyst like Fe of Co, which are more economically attractive to a scale-up scenario. Research was also conducted towards plasma catalytic surface treatments that may help in catalyst synthesis, in preventing coke deposition or in the regeneration of coked catalysts.

In the specific case of microwave excited plasmas, the presented results showed that more investigations are required as to find out the optimised conditions for favouring methane production; these investigations include *i)* the location of the catalyst, within or after the discharge; *ii)* gas pressure; *iii)* microwave frequency.

2.4 Challenges of scaling-up catalytic-plasma processes

Plasma-assisted catalysis of CO_2 methanation is an emerging concept towards sustainable economies

however, when evaluating the development of a new process, the production/processing capacity represents the main design guideline, thus dictating the equipment requirements. From an industrial perspective, one of the most important input parameters is that the scaling up of such system must consider the need to operate at considerably high throughput and therefore demanding high energy input.

In addition to this, challenges related to characterization of the structural and dynamic aspects of the plasma-catalyst aspects across a wide range of scales must be resolved before assessing the scaling-up. These challenges mainly concern:

Development of chemical kinetic models that can be implemented into multidimensional multiphysics models for process design, optimization, and control. Plasma-catalysis is a complex process which is non-trivial to model; in situ measurements are required to provide the fundamental information about the behaviour of the different species created in the gas-phase and on the catalytic surface that is necessary to test and develop the modelling. The modelling must also be able to incorporate the wide range of inhomogeneity in properties such as electric field, concentration, temperature etc. that are caused by the non-equilibrium nature of the plasma and the morphology of the catalyst. However, it is only by obtaining a fundamental understanding of these effects that we will be able to determine and specify the most effective composition and structure of catalysts for best performance under plasma activation and determine the optimal design, configuration and operating conditions for the plasma. The interaction between modellers and experimentalists is a vital part of understanding plasma catalysis and thereby determining and developing the full potential of the technique.

Choice of the plasma system. If plasma catalysis shall be a valuable option for CO_2 reforming, the process should be performed at atmospheric pressure due to higher space time yields and lower operating costs by avoiding the generation and sustainment of low pressures. However, at atmospheric pressure the gas has a high particle density, which makes non ionizing collisions of the electrons with the heavy particles inevitable resulting in thermal arc discharges. In comparison to the established atmospheric pressure non-thermal plasma sources such as DBD and corona discharge, microwave discharges can generate homogenous plasmas. Microwave discharges favour lower gas temperature at low pressure and quite high gas temperature at atmospheric pressure. The temperature increase can be limited via two main approaches:

- By pulsing the microwave field;
- By choosing a different microwave frequency.

Within the ISM band, microwave frequencies at 433.92 MHz, 915 MHz, 2.45 GHz and 5.8 GHz can all have potential applications in plasma assisted catalysis. At present, microwave plasmas for industrial applications are commonly excited at 2.45 GHz; some applications at 915 MHz are also reported. When choosing the frequency of the microwave field, the following factors must be correctly assessed:

- Increase in frequency decreases the transferred energy from electrons to other species leading to lower reaction temperature;
- Increase in frequency decreases the volume & cross-section of the plasma.

Another factor that must be taken into account when scaling up microwave plasma reactors is that, in contrast to dielectric heating, the scale up by use of more efficient high-power magnetrons at lower frequencies [1] is not sufficient in the case of the plasma reactor scale-up. If the power density in the reactor is important for the chemical reaction, the total power scale-up is non-trivial and can be estimated via equation 1.

Example: The equivalent power density of a 6 kW, 2.45 GHz process can be obtained at 915 MHz using ~ 115 kW – equation 1.

$$6\ kW \times \left(\frac{2450}{915}\right)^3 = 115\ kW \qquad (1)$$

[1] The availability of industrial microwave generators is directly linked to the maximum nominal power of CW magnetrons, i.e. 6 kW at 2.45 GHz (overall mains electrical efficiency ~60%) and 100 kW at 915 MHz (overall mains electrical efficiency ~80%). Due to poor performance and high cost, magnetrons at 433.96 MHz and 5.8 GHz are not discussed. Similarly, CW magnetrons at 2.45 GHz with nominal power > 6 kW are not considered suitable for industrial applications.

The main industrial applications of microwave excited plasmas include photoresist stripping in semiconductor manufacturing, deposition of barrier layers in PET bottles, high rate deposition process of quartz on polycarbonate windows, plasma photo curing of paint applied in the automotive industry, UV disinfection for water treatment, waste gas treatment for decomposition of fluorine-based components such as CF_4, C_2F_6, CHF_3, and SF_6 or ammonia, and plasma reforming to increase efficiency in wood gas engines[4-6]. Specific advantages of the technology include the enablement of a high energy density source and a highly reactive medium, operational flexibility, fast response time to inlet variations and reduced footprint. These aspects make microwave-assisted plasma a promising alternative technology to conventional thermal chemical processes provided that certain technical and operational challenges related to scalability are overcome. An important drawback of microwaves, very often not mentioned, is the high cost of equipment and the relatively low (~1 year) lifetime of the magnetrons. However, in terms of microwave technology successful implementation in industry, a more complex analysis of benefits is required: technical and economic advantages as well as those process specific must be analysed together.

Finally, understanding how microwaves can enhance plasma-assisted catalysis requires a good knowledge of not only the fundamentals of microwaves and their interaction with matter, but also of the hardware, the practical advantages and limitations of the available tools. Understanding the pros and cons of microwave energy is very important in deciding when and where microwaves can replace other plasma sources.

3 Conclusions

To understand how plasma and catalyst might interact, we need to better understand the nature of plasma and catalyst separately and to find how to bridge the fundamental knowledge of the two scientific fields.

The project CO_2 Viridis enabled to obtain satisfactory results for the modelling of single or dual gas plasmas (e.g. CO_2, CO_2 + H_2) if limited to the generated species & kinetics. To further progress, the consortium will focus on:

- Modelling & experimental validation of a solid catalyst presence within the plasma by considering more complex plasmas consisting of reagents & the reaction's products including methane, water etc., but equally considering the time evolution of different species within the plasma;
- Identification of the interaction mechanism between active species absorbed on the catalyst and the activated species formed within the plasma (electrons or activated molecules) understanding that the choice of catalyst (metal & support) is of primary importance, the energetic levels of interactions depending on both the active metals and the support. Macroscopically, one area of interest where we can see the effect of scale concerns the pores that lead from the surface into bulk of the catalyst. Pores in catalytic materials can selectively adsorb species depending on their size, which may affect the overall reactivity and selectivity of the plasma process. Penetration of plasma into the pores may specifically excite the adsorbed atoms or molecules creating localized reactive species. In the particular case of the microwave excited plasmas but not only, the electrical properties of the catalytic material can also play an important role in how the plasma interacts with the catalyst. The use of dielectric materials can have a profound effect on the electrical properties of the discharge by changing the capacitance of the plasma reactor.

A reference experiment will be designed and applied for the experimental validation of these interactions.

4 Acknowledgments

The project CO_2 Viridis was co-funded by the European Union and Region Normandy. The participation of all guests and their valuable contributions to the workshop *Challenges in Plasma and Catalysis* is kindly acknowledged by the organisers.

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6. M. Radoiu, *Radiat Phys Chem*, 2004, 69:113–120.

List of participants, invited speakers and their field of contribution

Plasma modelling: Daniela Pietanza & Vincenzo Laporta, P.LAS.M.I. Lab, Bari, Italy; Vasco Guerra, Technical University of Lisbon, Portugal; Arnaud Bultel, Université de Rouen Normandie, France; Janos Zsolt Mezei, Institute of Nuclear Physics of the Hungarian Academy of Sciences, Debrecen, Hungary; Viatcheslav Kokoouline, University of Central Florida, Orlando, US; Mehdi Ayouz, Centrale Supélec, Saclay, France.

Modelling of catalytic systems under plasmas: Yannick Engelmann, University of Antwerpen, Belgium

Experimental testing: Bachar Alrafei, Institut National de Sciences Appliquées, Rouen, Isabelle Polaert, Institut National de Sciences Appliquées, Rouen, France ; Alain Ledoux, Institut National de Sciences Appliquées, Rouen, France; Carlos Manuel Faria De Barros Henriques, Technical University of Lisbon, Portugal; Radoslaw Debek, Sorbonne Universités, UPMC, Université Paris 6, France; Federico Azzolina-Jury, Ecole Nationale Supérieure d'Ingénieurs de Caen, France; Teresa Grzybek, AGH University of Science and Technology, Kraków, Poland ; Savita Kaliya, Université de Lille, France; Catherine Batiot Dupeyrat, Université de Poitiers, France.

Challenges of scaling-up catalytic-plasma processes: Jean-Pierre Dath, Total, France; Marilena Radoiu, Microwave Technologies, France

Figure 2: Group photo of all participant of the workshop

About the Author:

Marilena Radoiu (Chartered Chemist, Member of the Royal Society for Chemistry) received her M.Sc. in Organic Technological Chemistry from the Polytechnic University of Bucharest in 1993 and her Ph.D. in Radiochemistry and Nuclear Chemistry from the same University in 1998. In 2018 she received an Executive Master's degree in Business Administration (MBA) from the Ecole de Management Lyon (EM Lyon) France. She is author or co-author of more than 50 publications in peer reviewed journals. She received the Rustum Roy Award (2016), AMPERE Medal (2019) and the award Femme de R&D of the Trophees des Femmes de l'Industrie (2019). With an international experience of more than 15 years in the development of microwave-assisted technologies with applications to chemical synthesis, biomass extraction, plasma etc., since January 2018 she has been acting as the Managing Director of Microwave Innovation for Radient Technologies Inc. Canada where she focuses on the development of new extraction solutions and the manufacturing of high-value natural ingredients and products from biomass. In February 2018 she has founded Microwave Technologies Consulting (MTC) specializing in research & process development using microwaves (915 MHz, 2.45 GHz and 5.8 GHz) for applications in the field of biotech, food technology, nanotechnology, medical technology, and the chemical and pharmaceutical industries. The focus of MTC activity is to deliver customer-specific industrial solutions, technical, environmental and economic process benefits.

Dr. Radoiu is also a member of several professional associations, including the Association for Microwave Power, Education and Research in Europe (AMPERE).

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Isabelle Polaert received her M.Sc. in Chemical Engineering from the National School of Chemical Engineering (ENSIC, France) and National Polytechnic Institute of Lorraine in 1993. During her PhD, she was involved in studying three phase catalytic reactors for highly exothermic reactions such as hydrogenations. She received her PhD in 1997 from National Polytechnic Institute of Toulouse. After four months at National Chemical laboratory, Pune, India, she got the position of Assistant Professor at the Laboratory of Chemical Engineering, LGC Toulouse. Particularly involved in environmental processes, she developed a coupled adsorption-reaction process for the depollution of phenolic effluents and co-authored a patent.

In 2003, Isabelle Polaert moved at INSA Rouen and integrated the LSPC (Laboratory of safety and chemical processes) where she developed her research activity on microwave processes and process intensification. Specialized in dielectric properties measurements, microwave processes modelling and experimental pilot scale development, she works on various applications such as green chemistry in continuous flow, new materials treatment under microwaves or biomass valorisation. Dr Polaert is also member of AMPERE Association.

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Upcoming Events

News from organizing committee of 4GCMEA

The 4th Global Congress on Microwave Energy Applications

CALL FOR PAPERS

Important Dates

Abstract Submission Deadline	Acceptance Notification	Registration Deadline	Conference Dates
April 30, 2020	May 30, 2020	July 15, 2020	August 17-20, 2020

The 4th Global Congress on Microwave Energy Application (GCMEA) will be held at Chengdu, China, during august 17-20, 2020. Some news is given by the local organizing committee.

What has been done for the 4GCMEA?

Some progresses have been made on 4GCMEA:

- The web of 4GCMEA (http://campa.com.cn/4gcmea/) has been built and the submission system is available. We already have received abstract submissions.
- All the TPC members and 5 plenary speakers have been invited and signed up.
- A workshop and four short courses will be organized in parallel on 17th August. Lecturers have been invited and the relevant information has been posted on the web of 4GCMEA.
- A Chinese national conference on microwave / RF applications will be held in parallel with the 4GCMEA. The call for paper has also been distributed in China. Lots of Chinese have signed up for the national conference.
- 2 SCI-index journals and 4 Chinese journals (one of them accept English-written papers) agree to launch special issues for these two conferences.
- A fancy hotel (CYNN) has been selected as the conference venue. We have signed the contract with this hotel and succeeded in getting special room discounts for the conference attendees.
- Until now, we have signed contracts with an exclusive sponsor, a gala dinner sponsor, 4 golden sponsors and several exhibition sponsors. Efforts for attracting more potential sponsors are still making.
- Two call for papers have been posted on the webs of AMPERE, JEMEA and IMPI with their help. They are also sent to the members of these associations by email.

What will we do for the 4GCMEA with consideration of the COVID-19?

As you all may have learnt from the media, the COVID-19 is under control in China. Much improvement and recovery has been achieved. Everything is getting back to normal now. We believe strongly that China will be safe for all participants in August, and we continue the preparation of the **4GCMEA.**

However, we will still pay close attention to the epidemic situation in other countries, particularly the situation in Europe and North America. **We keep close contact with other associations and organizations for concerted actions if necessary**.

About the organizing committee

Li-WU: General secretary of 4GCMEA local organizing committee. She was born in Guangxi, China, in 1986. She received the B.Sc. degree in electronic information engineering from Sichuan University, Chengdu, China, in 2010. She then went to further her study in the Institute National Polytechnique de Toulouse (INPT) in France and obtained the Ph.D. degree in microwave, electromagnetic and photoelectron in 2016. Her current research interests include microwave plasma discharge theory and its industrial applications, and permittivity measurement.

Hua-cheng Zhu: General secretary of 4GCMEA local organizing committee. Hewas born in Xuzhou, China, on March,1986. He received his B.Sc. degree and Ph.D. degree from Sichuan University in 2009 and 2014, in Electric Engineering and Information and radio physics, respectively. From 2015, he has been a faculty of Sichuan University. During 2012 and 2013, he was a Visiting Fellow with Department of Biological and Environmental Engineering at Cornell University, Ithaca, USA, which was supported by China Scholarship Council. His special fields of interest include microwave heating of food, biological tissues and chemical reactions.

Ka-ma Huang (M'01–A'01–SM'04) general chair of the 4GCMEA local organizing committee. He was born in Chongqing, China, in 1964. He received the M.S. and Ph.D. degrees in microwave theory and technology from the University of Electronic Science and Technology, Chengdu, China, in 1988 and 1991.He has been a Professor in the Department of Radio and Electronics of Sichuan University, Sichuan, China, from 1994, and has been the Director of the department since 1997. In 1996, 1997, 1999, and 2001, he was a Visiting Scientist at the Scientific Research Center "Vidhuk" in Ukraine, Institute of Biophysics CNR in Italy, Technical University Vienna in Austria, and Clemson University in the U.S., respectively. At these institutions, he cooperated with the scientists to study the interaction between electromagnetic fields and complex media in biological structure and reaction systems. He has published over 100 papers. His research interests are in the areas of microwave chemistry and electromagnetic theory.

Junwu TAO: 4GCMEA Technical Program Committee chair. He received the B.Sc. degree in electronics from the Radio Engineering Department, Huazhong (Central China) Universitry of Science and Technology, Wuhan, China, in 1982, the Ph.D degree (with honors) from the Institut National polytechnique of Toulouse, France in 1988, and the Habilitation degree from the University of Savoie, France in 1999. From 1983 to 1991, he was with the electronics laboratory of ENSEEIHT, Toulouse, France, where he worked on the application of various numerical methods to two- and three-dimensional problems in electromagnetics, and the design of microwave and millimeter-wave device. From 1991 to 2001 has was with the microwave laboratory (LAHC) at the university of Savoie, Chambéry, France, where he was an associate professor in electrical engineering and involved in the fullwave charaterization of discontinuity in various planar waveguides and the nonlinear transmission line design. Since September 2001 he is a full position professor at the Institut National Polytechnique of Toulouse where he is involved in the computational electromagnetics, multuphysics modeling, microwave and RF components design, microwave and millimeter-wave measurements, microwave power applications.

EuMW on Schedule for Annual Event in September 2020

Conference Website: **https://www.eumweek.com/**

March 17, 2020 (London, UK.) – Preparations for European Microwave Week (EuMW) 2020, to be held from 13-18 September 2020 in Utrecht, The Netherlands, continue on schedule. In light of the global pandemic and related measures imposed by the respective authorities, organizers are adapting the scheduling of EuMW Technical Programme planning meetings in an effort to enable all members to participate in the conference paper selection. The selection of papers will take place this month, with notifications to speakers going out on schedule in April.

"EuMW participants and technical co-sponsors should know that preparations are on track, and we expect and trust that we will run the full conference and exhibition as planned," said Frank van den Bogaart, President of EuMA. "We are excited about European Microwave Week 2020. The programme, exhibition, and venue promise to deliver a fantastic event in a historical city. We look forward to welcoming you in September."

"European Microwave Week continues to enjoy robust support from exhibitors and sponsors, and this year's exhibition floor promises to keep with the tradition of providing a network for our industry to share new products and innovations, " said Ivar Bazzy, President of Horizon House. "All of us working on the event send our very best wishes to our colleagues, friends, and customers who are directly affected by the COVID-19 virus and look forward to seeing you all at our 2020 event in Utrecht."

Important Dates

Notification of Acceptance	Deadline for grant/fellowship request	Deadline for final paper submissions
April 27, 2020	May 8, 2020	June 12, 2020

XIX International UIE Congress
Evolution and New Trends in Electrothermal Processes
UIE 2020, 9.-11. September 2020 in Pilsen, Czech Republic

Conference Website: https://edison.fel.zcu.cz/html/uie2020/

Important Dates

Abstract Submission Deadline	Abstract Acceptance	Early bird registration	Conference Dates
March 13, 2020	May 1, 2020	June 1, 2020	September 9-11, 2020

IMPI 54 - Virtual Symposium

The 54th Annual Microwave Power Symposium, June 15th - June 17th, 2020

INTERNATIONAL MICROWAVE POWER INSTITUTE

The International Microwave Power Institute (IMPI) has announced that the 54th Annual Microwave Power Symposium (IMPI 54) will be held as a Virtual Symposium from June 15-17, 2020. The event was to take place in Savannah, Georgia but is moving to a virtual format due to concerns over COVID-19.

IMPI's Technical Program Committee plans to release the revised Schedule of Events for the IMPI 54 Virtual Symposium in the next week. IMPI still plans to produce Proceedings for the event and the Student Competition will go on as planned. Registration will be open to the public on April 6th. Updates are provided daily at: https://impi.org/events/symposium/

The 55th Annual Microwave Power Symposium will be held at the DeSoto Hotel in Savannah, Georgia next year, from June 28-30, 2021. The Call for Papers for that event will be released this September.

Important Dates

Final Papers Due: April 15, 2020
Registration Deadline: TBD
IMPI 54 Virtual Symposium: June 15-17, 2020
Solid State RF Energy Virtual Workshop & Meeting: June 18, 2020

About AMPERE Newsletter

AMPERE Newsletter is published by AMPERE, a European non-profit association devoted to the promotion of microwave and RF heating techniques for research and industrial applications (http://www.AmpereEurope.org).

Call for Papers

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- Technological and market forecasts.
- Comments, views, and visions.
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- Tutorials and technical notes.
- Social, cultural and historical aspects.
- Economical and practical considerations.
- Upcoming events, new books and papers.

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