NOVEL TECHNIQUES USING FEM FOR MATERIAL PRODUCTION AND PROCESSING*

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Abstract

The objectives of this European project are to use high frequency microwave technology to develop focused energy sources for industrial applications. The microwaves, generated in the 10GHz to 20GHz frequency range by using a table top FEM has been used to investigate novel solutions for material processing and material production, including microwave heating of substrates, microwave chemistry for increasing the speed of thermal reactions, microwave plasma chemistry for aiding gaseous reactions in the reduction of combustion pollutants and the production of UV/ozone for germicidal activities. In this paper we report unique results and analysis in using tuneable FEM system compared with the conventional magnetron 2.45 GHz system.

INTRODUCTION

A research project assessing the use of microwave radiation for industrial applications at higher frequencies than the standard 2.45GHz produced by most magnetrons is being undertaken as part of the European Community Competitive and Sustainable Growth programme. The basic principals of the FEM system is that as electrons passing through the Industrial Free Electron Maser (IFEM) resonant cavity oscillate from side to side due to the static magnetic field produced by the wiggler magnet array [1-3]. These oscillating electrons emit electromagnetic energy, which forms what is referred to as a radiation field. The radiation field combines with the wiggler field to produce a pondermotive or beat wave. This pondermotive wave then promotes axial bunching of the electrons in the electron beam allowing a more coherent radiation output from the electrons. To allow such an interaction to take place, and energy to be extracted from electrons in the electron beam, the electron velocity must be matched to the phase velocity of the electromagnetic field in the cavity. This condition is often referred to as beam wave synchronism. For the synchronism case, Eq. 1 shows one form of the basic FEL resonance equation. This equation describes the wavelength output from a FEL, and has been reported previously many times.

$$\lambda_r = \lambda_w \frac{(1-\beta_e)}{\beta_e} \qquad (1)$$

where, λ_r : Electron output radiation wavelength, λ_w : is the wiggler magnet period, $\beta_e = v_e/c$, which is the ratio of the electron beam velocity, v_e to the speed of light, c. Apart from the electron velocity, another factor which is

used to describe the energy of an electron in an electron beam is the relativistic mass factor γ. This quantity relates an electrons rest mass to the effective mass of the electron when it has been accelerated to a particular energy, $\gamma=1+E/511$, where, γ: is the electron relativistic mass factor; E: is the electron energy in kilovolts and 511: is a factor relating to the rest mass of an electron (mc^2). As the relativistic mass factor may also be defined as $\gamma = (1-\beta_e^2)^{-1/2}$ then for highly relativistic electrons with a large value of γ, then $\beta_e \approx 1$. For this case equation 1 may be approximated as:

$$\lambda_r \approx \frac{\lambda_w}{2\gamma^2} \qquad (2)$$

What is significant about Eq. 2 is that the radiation output wavelength from an FEM varies in proportion to the wiggler period, and inversely with the electron energy. Although Eq. 2 is the standard relation in most FEMs work, Eq. 1 is more suitable for FEM, where $\beta_e \ll 1$.

The FEM is operated in an oscillator configuration. The FEM interaction region is a rectangular waveguide resonant cavity terminated by copper irises. It has frequency tuneability between 8-12.4GHz. This cavity is placed in the centre of an NdFeB permanent magnet undulator with 33 periods [4]. The electron beam source is a travelling wave tube (TWT) type dispenser cathode electron gun. After passing through the interaction region the electron beam is recovered using a single-stage depressed collector. The FEM system set up is shown in Figure 1.
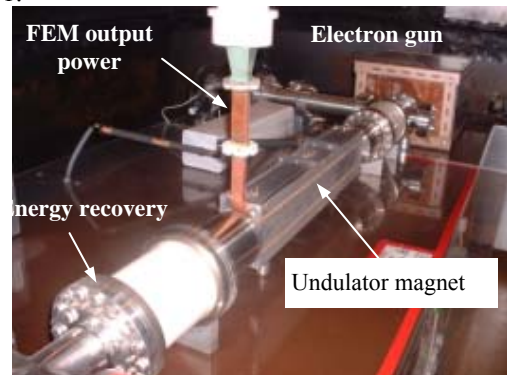

Figure 1: X-band FEM System setup seen from the collector end

The FEM characteristics are governed by the behaviour and capabilities of various components. The pulse length is limited to about 200μs by droop of the cathode supply voltage. The output power is limited to 1kW by the beam current. The pulse repetition frequency (PRF) is limited to

2kHz by the pulse generator. Average power is limited to 50W by vacuum degradation considerations because the electron beam trip level on the vacuum gauge has been set at a conservative 1×10^{-6} mbar to avoid any risk of poisoning the gun cathode. Various experiments in the following areas have been performed including Microwave UV/ozone chemistry, Focussed microwave heating, Microwave thermal chemistry, Microwave plasma chemistry and Microwave plasma material processing.

MICROWAVE UV/OZONE CHEMISTRY

The purpose of this experiment was to assess whether there is any benefit to be gained using higher frequency microwave radiation as the power source for UV fluorescent tubes [5,6]. Microwave driven fluorescent tubes can operate at much higher power per unit length than conventional mains driven tubes because there is no need for electrodes, which wear out at high currents. For the initial experiments, commercially available 16mm diameter UV tubes were used. The waveguide used at the workstation is WR90 (22.86mm x 10.16mm). This is 23mm across, so it was possible to simply drill a 16mm hole through the centre of the broad faces of the waveguide and push the tube through. Unfortunately the measured reflected power was as highest 60% of the forward power. Widening the waveguide around the tube to give the 8GHz microwaves a more "square" field distribution increased the efficiency, but reflected power was 30%. For this reason we changed to a waveguide surfatron [7,8], to launch surface waves along the inner surface of the quartz tube. Using the surfatron, it was possible to achieve almost 100% transmission of microwave power into the UV tube. The waveguide surfatron is a microwave structure for launching surface waves within a plasma column. Microwave power is supplied via a rectangular waveguide the coaxial section with tuning short circuit enables optimised the microwave power launching.

For 2.45GHz operation, the variable power magnetron was coupled to a WG9A (86mm x 43mm) waveguide. A small antenna coupling on the next waveguide section enabled forward power to be monitored via crystal microwave detector diode [HP423B]. The microwaves next pass through a circulator onto the tuning section. This section consists of a waveguide surfatron mounted on the wide section of the waveguide, this part of the waveguide is tuned by a stub tuner and movable short circuit, see Figure 2. Any reflected power from this section goes back into the circulator and is dissipated in a dummy load mounted on the circulator's third port. A small antenna coupling mounted on this port provides reverse power measurement via crystal detector. The waveguide surfatron is it's self-tuned for minimum reflected power and maximum plasma column length by correct positioning of the coaxial short circuit plunger.
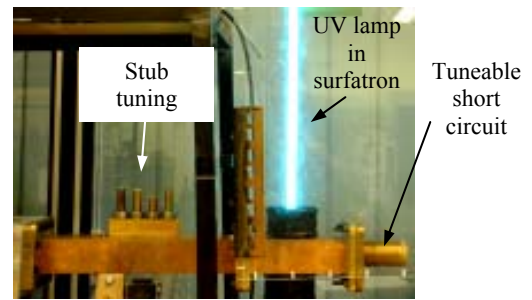

Figure 2: The 2.45GHz Microwave UV lamp demonstrator system

THEORETICAL AND EXPERIMENTAL CONSIDERATIONS

A Monte Carlo algorithms [9] have been used to simulate the effect of microwaves on gases discharges at frequencies ranging from 2-10GHz. Figs. 3 and 4 show simulation results for the 2.45GHz and 10GHz using conventional microwave oven (magnetron) and FEM systems respectively. It can be clearly seen that as the microwave electric field increases, at 10kV/cm region that the 185nm radiation increases as the 254nm line decreases.
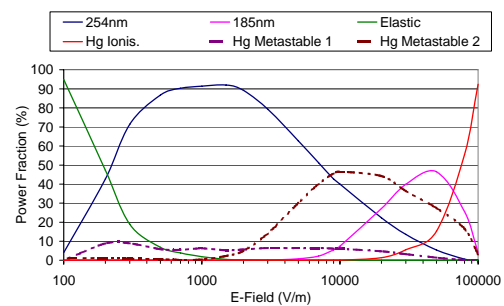

Figure 3: The 2.45GHz microwave discharge simulation
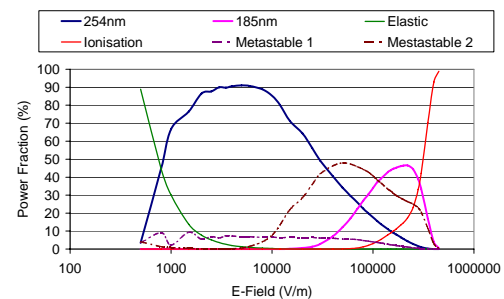

Figure 4: The 10GHz microwave discharge simulation

Furthermore, Figure 4 shows that the fractional power curves have shifted right i.e. the maximum 254nm radiation curve has now moved from 1000 v/m to approximately 10,000 v/m. This is a very important point in order to maintain the germicidal efficiency at high power densities, i.e. higher output power per unit length. This theoretical result is confirmed in the experimental measurements shown in Figs. 5 and 6, which indicated that as the microwave power increases, i.e. the electric

field so does the 185nm to 254nm radiation ratio. Also in agreement with theory is the fact that at higher powers, the 2.45GHz powered UV gradient levels off while the 8GHz powered UV is relatively steeper. It is estimated that the IFEM operating at 8GHz will become more efficient, than the 2.45GHz system, at producing UV at 254nm and Ozone at approximately 400 Watts. As the microwave frequency increases so does the UV power density. However, there are limits to the theoretical model as electric field can only be increased so far before dielectric breakdown and arcing occurs. Wavelengths higher than 254nm have not been included in this simulation.
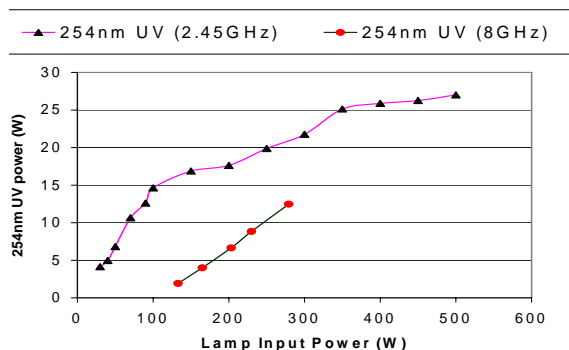

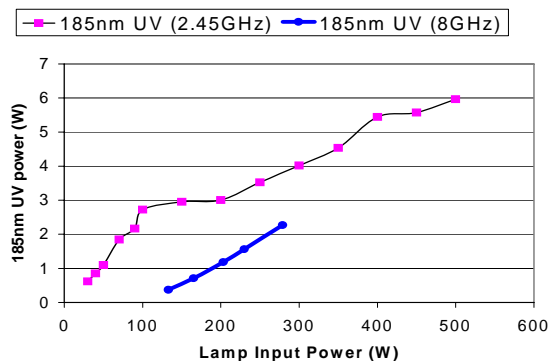Figure 5: UV Output at 185nm for 2.45 GHz and 8GHz.

Figure 6: UV Output at 254nm for 2.45 GHz and 8GHz.

The FEM system was set up to generate a 100μs pulse required for the plasma column to reach the ends of a 30cm UV tube, as in Figure 7. Figure 8 confirms the trend shown by this theoretical model. High power (high E field), narrow pulses yield more ozone than low power, wide pulses. If high UV power density required, for example at 254nm, one can increase the microwave power but a point is reached where the power fraction, at 254nm, decreases as shown in figure 6. The theoretical model indicates the solution to obtain high power densities is to increase microwave frequency [9].
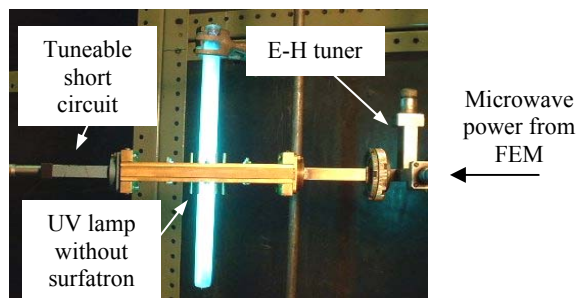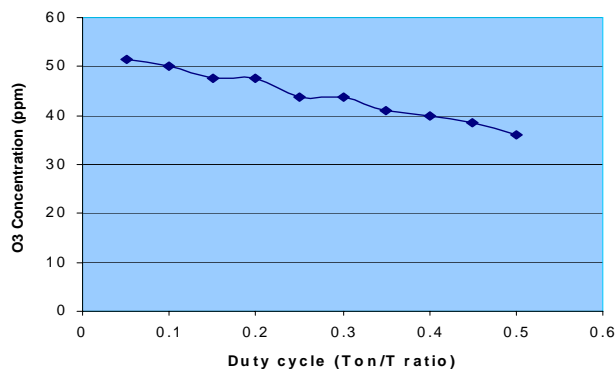

Figure 7: 100μs pulses fill a 30cm UV tube.

Figure 8: Experimental measurements to investigate the effect of duty –cycle on Ozone production.

MICROWAVE THERMAL CHEMISTRY

This experiment involved the acceleration of chemical synthesis by microwave irradiation. Small samples of dissolved chemical were placed in a sample vessel as shown in Figure 9. This was placed in an irradiating chamber mounted in X-band waveguide, Figure 10. The waveguide section was terminated in a tuneable short circuit and reflected power minimised using a matching transformer. The procedure used was to tune the transformer and short circuit with a measured quantity of the solvent in the sample tube prior to irradiating the chemical product. During the heating process, an infrared probe at the base of the sample tube monitored the temperature.
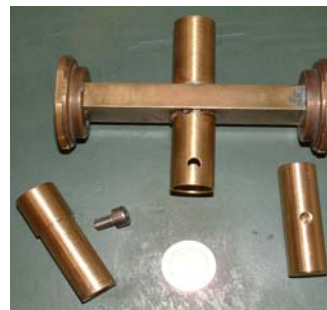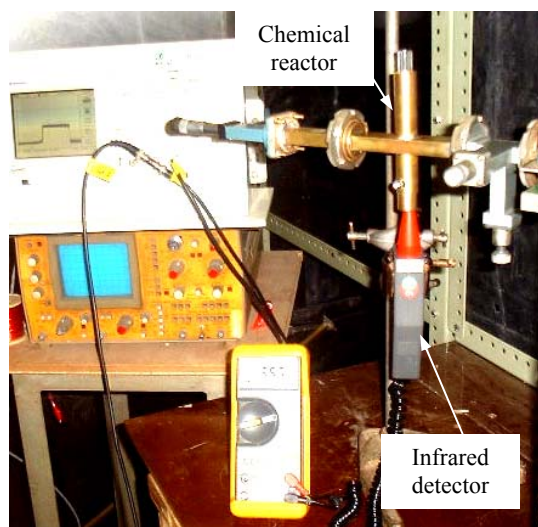

Figure 9: X-Band chemical synthesis reactor.

Figure 10: FEM chemistry experimental setup.

Figure 11 shows some types of chemicals have been used in the FEM system. This model is particularly suitable owing to the fact that according to the conditions, the results are different. At room temperature (8days) or under conventional heating (2 days in an oil bath at 80°C) cyclohexene **4** and alkene **3** are formed, but under microwaves (2.45 GHz) only the alkene **3** is observed at 80°C (3 minutes). The mechanism of the formation of the cyclohexene has been established, the first step being the formation of the alkene **3** (Scheme 4). The FEM experiments led to the synthesis of products that have not been seen using a conventional laboratory microwave oven as the heat source [10,11]. Previously these products have only been seen after eight days at room temperature or five days in an 80° oil bath. In the FEM experiment the production took three minutes, this may be due to the use of higher frequency radiation but it could also be due to the fact that the FEM power is applied in a "pseudo continuous" manner, the "off" periods are around a millisecond, whereas the oven cycles on and off over several seconds just like a domestic oven.
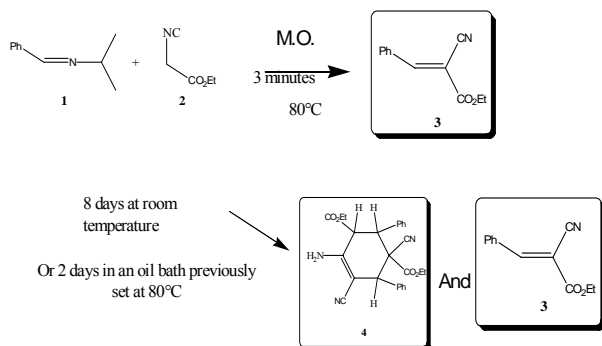

Figure 11: Types of chemicals have been used in FEM system

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