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Research Article

Electromagnetic Emission in the kHz to GHz Range Associated with Heat Production During Electrochemical Loading of Deuterium into Palladium: A Summary and Analysis of Results Obtained by Different Research Groups

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Abstract

There is a small literature on the combination of low energy nuclear reactions (LENR) experiments and radiofrequencies (RF). The papers are worth attention in case they can teach anything about the mechanisms behind LENR. Application of RF to LENR electrochemical cells in the mid-1990s clearly showed increases in the production of excess power. More recently, RF have been measured in LENR cells. However, it is still possible that those data are artifacts of the operation of the system, and not indicative of LENR. It has been suggested that the appearance of RF in LENR experiments is the cause of LENR, and not merely a manifestation of such reactions. That possibility has significant implications. In the present paper, we summarize and analyze the results obtained by different research groups concerning the application and emission of RF in the kHz to GHz range associated with heat production during electrochemical loading of deuterium into palladium.

Keywords: Electromagnetic emissions, Electromagnetic radiation, Excess power, LENR, Heat production

1. Introduction

There have been two fundamental approaches to obtaining information of the production of low energy nuclear reactions (LENR) in electrochemical and other experiments. These are aimed at both understanding the mechanisms

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LENR experiments:
Electrochemical, Gas Loading, ...
and Various Metals with P or D

	Input Stimuli	Output Measurements
Heat	✓	✓
Inpurities	✓	
Transmutation Products		✓
Neutrons	✓	✓
Ion Beams	✓	
Energetic Ions		✓
Gamma Rays		✓
X-Rays		✓
Ultraviolet Radiation		✓
Visible Light	✓	
Infrared Radiation		✓
Radio-Frequency EMF	✓	✓
Teraherz Radiation	✓	
Sound		✓
Ultrasound	✓	
Electric Fields	✓	✓
Magnetic Fields	✓	✓

Figure 1. List of the input stimuli and output measurements for LENR experiments. P is for protons and D for deuterons.

behind LENR and controlling the production of excess power. In the first method, various stimuli are applied to the experiments in order to observe their response. In the second, diverse measurements are made during experiments. Numerous applied stimuli and observations have been exercised. Figure 1 shows graphically which of the many possibilities have been used. This paper is focused on the use of radio-frequencies (RF) to either induce or improve the production of excess power, or else to indicate something about what is happening within and during an experiment.

This study has three goals. The first is to review and compare the frequencies reported in papers on RF stimulation or observations, and their results. This is done in Sections 2–4. The second goal is to attempt to determine whether the observations are artifacts, or useful reflections of the electro-chemistry and -physics of cell operation during production of excess power. Section 5 addresses this issue. Finally, we seek to enumerate and evaluate mechanisms, which might permit coupling of applied RF frequencies into an LENR cell to enhance power production or else appear as a result of excess power production. Mechanisms and their assessment are discussed in Section 6, prior to a brief in Section 7.

2. Early RF Stimulation Results

The earliest paper by Bockris et al. [1] reported on application of RF to an electrochemical LENR cell by using a coil around the cell driven by an RF generator. Peaks in the production of excess heat were observed at specific applied frequencies. Figure 2 shows the setup and results of their experiments. It is seen that the RF fields produced by the coils had two effects. At some frequencies, they quenched the production of excess power. However, at others, the RF caused an increase in the power due to LENR. The stimulation of power by RF was observed for D_2O, but not H_2O.

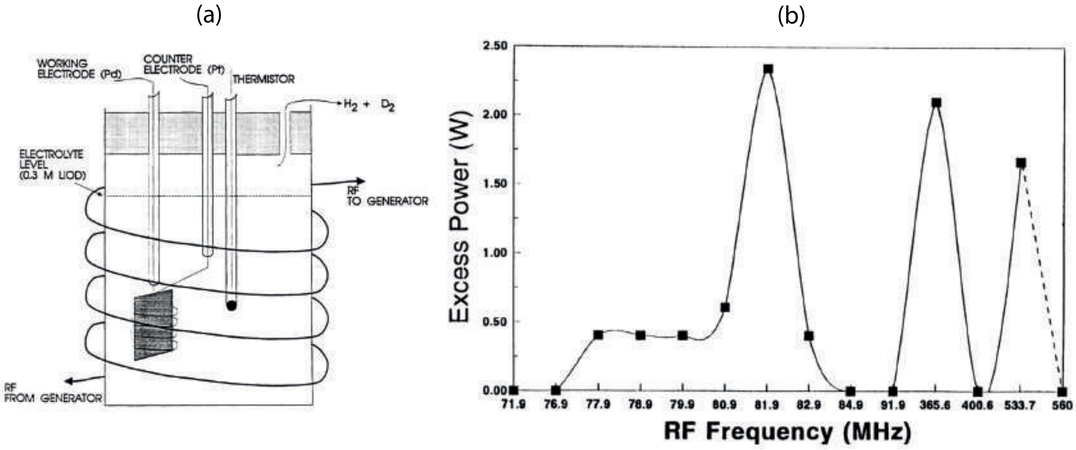

Figure 2. Setup of the RF stimulation experiments by Bockris, Letts and their group, with the response of the system to various frequencies.

The authors noted that "heating by RF was precluded". That is, the increase in generated power was not due to thermal effects of the applied RF.

A similar study was conducted by Cravens in the same time frame [2]. The imposition of RF fields in the range of 80–84 MHz was found to trigger some anomalous heat reactions. This is done by pulsing (both sine and square seemed to work) the magnetic field at the cell by wrapping the cell with a coil of wire and connecting it to a RF unit. The excess heat was enhanced by the application of the RF magnetic field. The apparent excess was roughly proportional the power level of the applied field. The effect was most pronounced when the RF coils were impedance matched at about 81.9 MHz.

Cravens' work was done at 200 mW of power and 5–10 turns on the field coils. Assuming a reasonably working cell was used (already at about 30% excess power production), the effect usually was quickly seen (within seconds or minutes). If the cell was run at above 70 or 80°C, the additional power levels were often large enough to cause rapid boiling. The increases were typically from the initial 30% to the 100–200% range and remained as long as the RF field was applied to the cell.

The two early experiments indicated that application of RF EM frequencies in the 77–534 MHz range to operating LENR electrochemical cells increased the production of excess power. The increase could be due to either of two causes: (a) coupling of the RF energy into the measurement system or (b) the effect of RF on the mechanism causing LENR. The first is ruled out by two observations: (a) the increase in excess power is less than the total RF power and (b) there is no increase in apparent power when the electrolyte is H_2O rather than D_2O. So, there is strong evidence that RF applied to LENR electrochemical cells does improve the production of excess power. Whether or not RF excitation can *initiate* excess power is an open question.

The effect of incident RF on increase in the production of LENR does not require the reverse effect, that is, the production of LENR does not necessarily generate RF within an experiment. However, some recent experiments have found the appearance of RF within the circuit or near the electrodes of electrochemical experiments. That occurred sometimes during production of excess power, but sometimes without power production. These newer experiment are discussed in the next section.

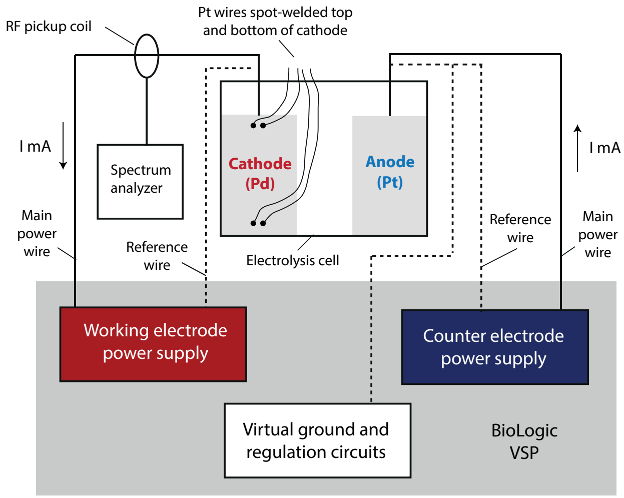

Figure 3. Schematic of the experiment at the NRL, in which RF frequencies were sometimes observed.

3. Recent Results on Excitation of RF in LENR Cells

Dominguez [2], Kidwell [3] and their colleagues from the Naval Research Laboratory (NRL) picked up oscillations at high frequencies within the circuit of an electrochemical cell in a calorimeter. Their experimental setup is shown schematically in Fig. 3. It is seen that a pickup coil around one of the wires between the power supply and the cell was used to detect the presence of RF within the electric circuit of the cell. That is, the RF reported was not emitted and picked up with an antenna. Actually, what was done was to run one of the wires from the cell through a ferrite toroid. A two to three turn link was then also wound on the same ferrite and connected between the center conductor and braid of a length of coaxial cable whose other end was then connected to the input of an RF spectrum analyzer. This approach turned out to be much better than simply placing a whip antenna near the cell, where it could pick up RF interference from many other sources in the laboratory. Various RF frequencies were observed, some of them correlated with the appearance of excess power. An example is shown in Fig. 4. The excess powers during this run were small, generally less than 10 mW. An interesting effect is the rapid variation in the resistivity ratio during the time of RF emission. It is seen that the RF at 4.8 MHz persisted throughout the period exhibited. However, a slightly lower frequency, appeared, then disappeared for most of one day, then reappeared.

Violante and his team [4] from the Italian Agency for Energy and Economic Development (ENEA) did impedance spectroscopy of RF and other frequencies in electrochemical LENR experiments. A schematic of their setup is given in Fig. 5. In contrast to the arrangement at the NRL, the ENEA group did intercept and measure radiated RF. They could be measured in either of two ways. If the DWC 80 GHz down-converter in the circuit was turned OFF, then the spectrum analyzer would measure frequencies in its range from 20 kHz to 3.5 GHz. When the DWC was ON, it would subtract 80 GHz from the frequencies presented to its input and pass the difference to the spectrum analyzer. Then, the spectrum in the 80.02–83.5 GHz range would be recorded.

Some of the results reported by Violante et al are shown in Fig. 6. Regardless of whether or not excess power was being produced, or whether or not the DWC was ON, white noise at about -95 dbm was observed. There was very little $1/f$ noise at the lowest frequencies. However, when excess power was produced, substantial $1/f$ noise appeared. The reason for the appearance of that $1/f$ noise is not known. The origin(s) of the peaks in the spectra for the various

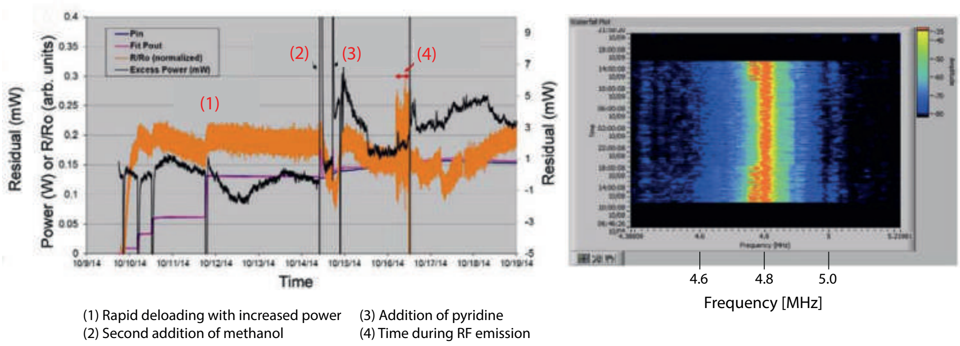

Figure 4. (*Top*) Time histories of the input, output and excess (*residual*) powers, plus the resistivity ratio (R/R_O). The time during which RF frequencies were observed is indicated. (*Bottom*) Variation of RF frequencies and intensities (*indicated by color*) as a function of time (*vertically*).

conditions is (are) also unknown. Since what seem to be harmonics of the strongest line appear when the DWC was on, there is a question about its possible non-linear behavior. However, Peak B appears when the DWC is off, as shown by the graph on the left-hand side of Fig. 6. Also, the two graphs on the right-hand side of Fig. 6 show that the ratio of the harmonics is different depending on whether or not excess power is being produced. Clearly, there is need for further measurements like those in Fig. 6 in order to understand the origin of the individual spectral characteristics.

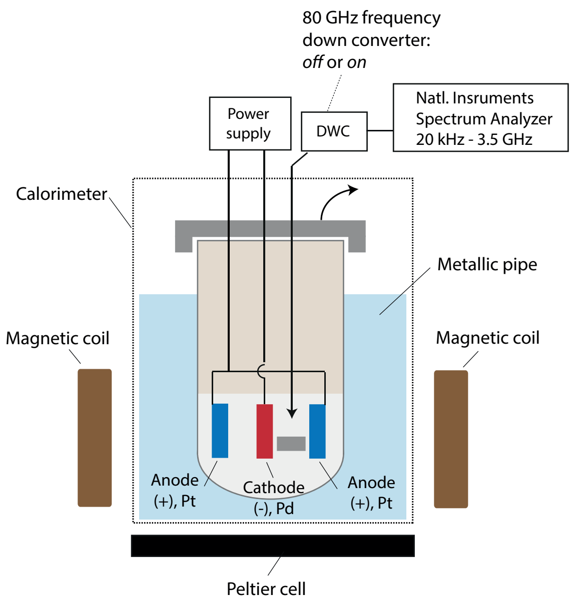

Figure 5. Schematic of the experimental setup used by the team at the ENEA. It did measure emitted RF, which was picked up by a piece of metal in the electrolyte. That was connected to the 80 GHz DWC down converter. When turned off, the DWC passed unaffected frequencies to the spectrum analyzer with the acceptance range shown.

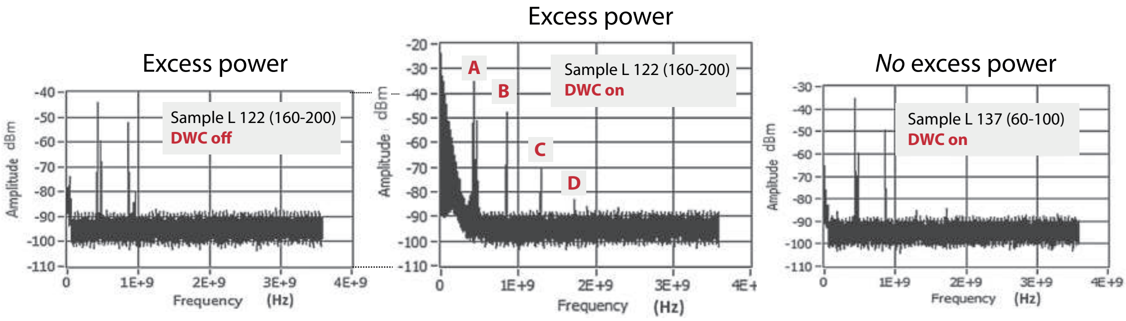

Figure 6. RF spectra from experiments at the ENEA during periods with or without excess power generation with the DWC down-converter either OFF or ON, as indicated. Peaks labelled B, C and D are at multiples of the frequency of peak A, so they appear to be harmonics.

More data might help determine if the features can indicate anything about what is happening in the electrochemical cell, with or without production of excess power.

4. Comparison of Frequencies

Particular frequencies were observed in the experiments in the mid-1990s to increase production of excess power. Also, specific frequencies appeared in the more recent experiments, sometimes coincident with excess power production. It is natural to ask how the various frequencies compare with each other. Hence, the frequencies for both cases are shown in Fig. 7. It is seen that both the Bockris group and Cravens found that frequencies near 100 MHz increased excess power. The Bockris team also reported the effectiveness of frequencies near half of 1 GHz, similar to what the Violante group reported.

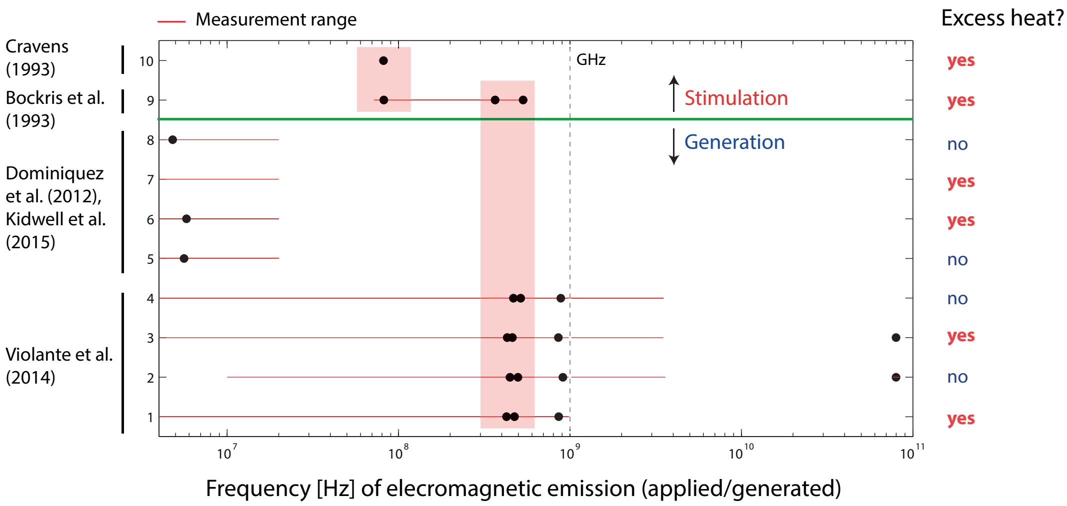

Figure 7. Compilation of the frequencies reported in both stimulation and generation experiments, which are divided by the horizontal green line. Frequencies in similar ranges are boxed.

The two recent experiments showed that operating LENR electrochemical cells can exhibit RF frequencies with or without the production of excess power. Frequencies of 450–480 kHz and 4.8–5.8 MHz were measured at the NRL. Frequencies of 430, 475 and 850 MHz, plus 1.28, 1.75, 2.45, 3.05 and 77–83 GHz were reported by ENEA. That is, frequencies found in the work at the NRL are lower than were observed in any of the other experiments.

It is worth noting that the wide variety of frequencies shown in Fig. 7. They span somewhat over two orders of magnitude. There are two challenges to theory in these data. The first is to explain why RF should increase excess power or appear in LENR cells, sometimes with and sometimes without production of power. This is basically a question of mechanisms for either coupling RF energy into a cell or generating such frequencies during operation of a LENR cell. The second challenge is to understand why specific frequencies are effective or else appear spontaneously. This issue also has to be related to the underlying mechanism. We discuss possible mechanisms in Section 6, after considering the character of the data surveyed above in Section 5

5. Comments on the RF Data

It is hard to understand how the data on application of RF to cells presented and discussed in Section 2 above could be artifactual. Still, more experiments of that type are desirable, and discussed in Section 7. It seems easier to imagine how the frequencies observed in and near the circuits within electrochemical cells could be due to extraneous effects not intrinsic to the LENR mechanism(s). There are two possibilities. The frequencies might originate in the power supplies used to drive the experiments at the NRL and the ENEA. Both groups used potentiostats from the company BioLogic. However, those sources should not involve any frequencies in the range of about 500 MHz to 1 GHz. The second possibility is some interaction of the power supplies with the cells. But, here again, the near-GHz frequencies present a problem. The round-trip transit time of electrical signals between the power supplies and experiments was probably on the order of a few to 10 ns eliminating frequencies near 1 GHz. However, this second possibility can be further examined.

6. Possible Mechanisms for RF Generation

Conceivably, a resonant RC circuit could have existed in the electrochemical experiments. The capacitance might be due to the double layer at the surface of the cathode. That region of the cell is shown two ways in Fig. 8. The schematic on the right shows that the capacitor at the surface consists of two “plates” one the metal of the cathode and the other the arrangement of solvated cations at the Outer Helmholtz layer. At the boundary between the cathode and the electrolyte, two layers of ions with opposing polarity form, when a voltage is applied. The two layers of ions are separated by a single layer of solvent molecules that adheres to the surface of the electrode and acts like a dielectric in a conventional capacitor. That is, the dielectric consists of polarized water molecules. The two plates of the capacitor are close to each other because the Inner Helmholtz layer has a thickness on the order of the size of water molecules, namely about 0.1 nm. Using the usual formula for capacitance with the dielectric constant of water (80.4) gives about 10 F/m^2. For a 1 cm^2 cathode, the capacitance is then about 10^{-3} F, a very large value. Even if the output impedance of the potentiostat were as high as 10 MΩ, the RC time constant would be 10^4, so that the highest frequency that could occur in the resonator between the double layer capacitor and the potentiostat impedance would be on the order of 100 μHz. This is an extreme estimate, assuming a very small separation for the two layers and full coverage of the square centimeter.

We note that the Impedance Spectroscopy by the ENEA group showed that a resonator developed during the production of excess heat and remained as long as the voltage was applied to the cell [5]. However, the value of the capacitance in the effective circuit was not published. Hence, it is not possible to compare it with the estimates above.

It can also be wondered if the oscillation of charges across the double layer on the cathode surface could, by themselves, generate RF. The double layer is very thin, about 1 nm. Hence, even low velocities can span it in times

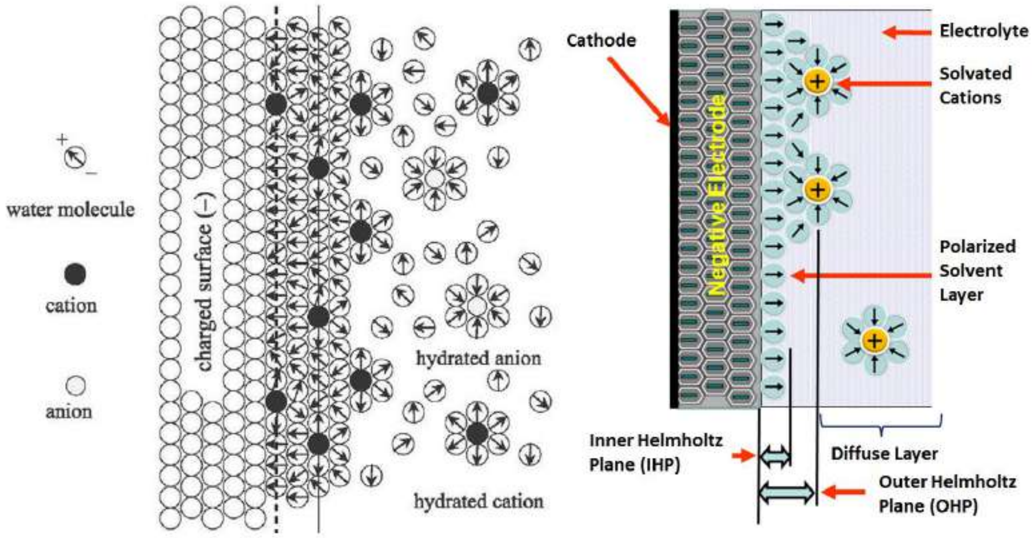

Figure 8. Two schematic versions of the arrangements of charges, ions and water molecules near the surface of a cathode in an LENR electrochemical experiment. The arrows indicating the polarity of water molecules happen to be opposite in the two versions. The diagram on the left emphasizes the randomness of molecules near the cathode. The drawing on the right gives a clearer picture of the capacitor at the surface of the cathode. Images sources: what-when.how.com (http://tinyurl.com/mozskvy) and wikipedia.org (http://tinyurl.com/zpkoejf).

compatible with RF frequencies. Some simple estimates are instructive. Two relationships are employed: f = frequency = $1/T$ = 1/(transit time) and D = Distance = Velocity $\times$ Time $= V \times T$. Hence, f (Hz) $= 1/T = V/D = V$ (cm/s)/10^{-7} (cm). Then, for 1 MHz, $V = 0.1$ cm/s, and for 1 GHz, $V = 100$ cm/s. These are relatively low velocities. But, what would drive synchronized motions of many charge carriers (ions) across the double layer for many hours? Also, how many charges would have to move coherently in order to produce RF frequencies of the magnitudes measured? One possibility is the surface plasmon polariton, a coherent oscillation of surface charge that can occur in many conductive materials. Some LENR theories, including the Widom Larsen Theory, specifically invoke surface plasmon polaritons for the purpose of increasing the effective mass of the surface electrons in the host lattice material.

These are semiconductor devices with areas of negative resistance that are used to generate RF in many systems. It can be asked if semiconductors might be deposited on the surface of cathodes to create such devices. There are four requirements that make such deposition and operation unlikely: (a) the doping profiles in both Esaki (tunnel) diode and Gunn device have to be very specific, (b) even if they could be deposited with the needed doping profiles, the entire cathode would have to be coated or the devices would be shorted, (c) if such a complete coating were achieved, the current through the cell would be drastically affected and the Impedance Spectra would be very different, and (d) there are neither the needed voltages nor required circuits for RF oscillations due to such devices.

The drawings in Fig. 8 and the calculations above, based on the assumption of a flat cathode surface, are suggestive, but unrealistic. Many publications have presented micrographs of the surfaces of Pd and other cathodes from electrochemical LENR experiments. They show diverse technologies on scales ranging from nanometers to micrometers and larger. Some particularly instructive images and data on surface roughness are given in the ENEA paper [5]. In general, the areas in cm^2 of actual surface per cm^2 of the macroscopic cathode surface area are much larger than unity. That might mean that the area of the double layer is significantly greater than estimated from the macroscopic cathode surface area. However, the electric fields near a rough surface vary greatly, being concentrated at the tips of protruding structures. Hence, the double layer character and thickness might vary, possibly significantly, with the type and scale of the surface roughness. It is also noted that both the shape and size of surface structures vary during an electrolysis run, so that the capacitance of the double layer is variable. If that capacitance is part of a resonant circuit that generates RF, the frequencies being produced at any time during an experiment must also vary.

Kidwell and his colleagues speculated "The RF frequency is too high to originate from electrochemistry, but may be due to deuteron hopping between lattice sites in highly loaded Pd." [4]. If the RF is associated with a phenomenon having the same spatial periodicity as the basic FCC lattice, then dividing the Pd lattice constant by the observed RF period for 5.3 MHz, we get a velocity near 0.25 cm/s, consistent with known diffusional velocities. The fact that there are hopping and diffusional frequencies within D loaded Pd similar to the frequencies reported from LENR experiments does not guarantee the generation of relatively monochromatic radio frequencies over long times (hours). What can cause the frequency stability and the long times?

It is possible that a high Q resonance exists within the cathode, governed either by the physical dimensions of the cathode or perhaps by non-thermal anomalies in the occupation numbers of the acoustic branch phonons within the cathode. The speed of sound in Pd is 3070 m/s. The transit time for a mechanical signal across a 50 μm thick Pd cathode is 1.6×10^{-8} s. This corresponds to a frequency of 60 MHz, near the frequencies seen in Fig. 2.. This is near the frequencies seen in Fig. 2. Those data are for Pd that had already been loaded with deuterons. For such material, the speed of sound might be faster than in pure Pd, leading to higher frequencies more consistent with the data. However, the mechanical resonator idea for a cathode of uniform thickness would not explain the appearance of peaks in the excess power at multiple frequencies. Also, there remains the question of what drives the resonator.

The great uncertainty now regarding RF in electrochemical cells, independent of LENR, is noted in the contrasting statements from the NRL and the ENEA. As quoted in the last paragraph, the NRL team thinks that electrochemistry cannot cause RF. But, the ENEA group cited stated "Nevertheless, although high frequency systems are assumed to exist in electrochemical systems, the literature explicitly mentions that proper instruments to study such specific electrochemical phenomena have not been conceived and realized yet". Instrumentation for high-frequency measurements is now commonly available. Its application to electrochemical cells for both LENR and other research should be instructive.

There is another large duality, whether LENR causes RF or vice versa. In their published paper [5] and paper at ICCF-19 [6], the ENEA group wondered about which effect is causal. In the proceedings paper, they wrote "RF signal emission has been observed during excess power production but such a signal has been obtained also when the excess power was absent, showing that RF emission is not the effect of the excess but perhaps the cause". This is a very important possibility. If RF causes LENR, then the application of such frequencies to an electrochemical cell might be a means to initiate or control LENR. It was found in the experiments in the mid-1990s discussed in Section 2 that the control was possible, if the cells were already producing excess power. If it can be demonstrated that application of RF to a cell not already generating power can cause it to do so, then this approach might lead to a reproducible LENR experiment. Such an experiment would be invaluable for parametric and other studies, especially the screening of materials.

7. Conclusion

The application of RF EM waves to LENR electrochemical cells was shown to increase excess power in two early experiments. This, by itself, makes it worth studying the intersection of electrochemical LENR cells and RF. It is conceivable that the application of the external fields could align protons or deuterons in or very near cathodes to cause an effect on the production of excess power. But, only weak RF fields were used in the Bockris and Cravens experiments, both of which used RF stimulation. The appearance of RF in LENR electrochemical experiments still has the basic question of whether or not the high frequencies reflect the occurrence of LENR (are fundamental), or are due to the power supply or its interaction with the cell (and, hence, are artifacts). If RF is due to the occurrence of LENR in electrochemical experiments, does it also appear in the operation of LENR in gas loading experiments? That might be very difficult to determine in gas loading experiments that involve the generation of plasmas. However, gas loading experiments without application of electrical power [7] and with application of only low frequencies for heating [8] might permit simultaneous RF measurements. If RF were found in such experiments, and was not due to any environmental or power line effects, the case for RF being associated with LENR would be strengthened.

There is a great deal of experimental electrochemical work needed in order to understand the origin of the influence of applied RF on excess power production and to determine the origin of RF in LENR cells. Technical details involved in the measurement of RF within the circuits of electrochemical cells need more experimental and analytical attention. These include the method used to pick up the high frequency variations and the possible non-linearity of frequency down converters. The potential synergism between the application of magnetic fields to cells and the effects of appearance of RF needs more experimentation. Variations in the intensities of the peaks that appear in RF spectra with the electrochemical current should be determined. If a cell, which is giving both excess power and RF, is poisoned to stop LENR, what would happen to the RF? The levels of the white noise in measured RF spectra from LENR experiments should be measured precisely to see if it increases during LENR. The $1/f$ noise measured in some ENEA experiments might contain information, so they should be analyzed.

In summary, the three basic questions are: (a) is RF intrinsically associated with LENR, at least part of the time, (b) if so, can the intersection of RF and LENR reveal anything about the mechanism(s) that cause LENR and (c) can the mechanism(s) for RF generation be understood independently of the cause of LENR?

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