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January 8, 1998

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William Caton, Acting Secretary
Federal Communications Commission
1919 M Street, N.W., Room 222
Washington, DC 20554

Re: Appeal of Discrimination Complaint of Feb. 2, 1997
ET Docket 93-62
Disabilities Issues Task Force

Dear Mr. Caton:

Enclosed are Comments in the above-referenced matter, an original and 4 copies. Copies have been mailed this day to Robert Cleveland, Office of Engineering and Technology, and to Pam Gregory, Disabilities Issues Task Force.

Sincerely,

Arthur Firstenberg

Arthur Firstenberg
President

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List A B C D E

Before the
FEDERAL COMMUNICATIONS COMMISSION
Washington, DC 20554

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In the Matter of	)	
	)	
Complaint of Discrimination on the Basis of Handicap Filed by the Cellular Phone Taskforce on Feb. 2, 1997	)	Disabilities Issues Task Force
	)	
Guidelines for Evaluating the Environmental Effects of Radiofrequency Radiation	)	ET Docket 93-62

Comments

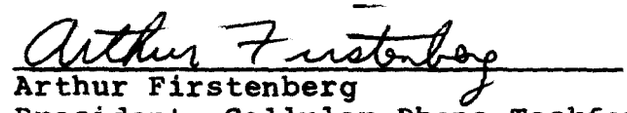
1. Attached as an Exhibit is a journal article by W. Grundler and F. Kaiser describing work that has been ongoing in Germany during the past two decades which is remarkable in its elegance and precision and repeatability; and also in the development of a theory of biological mechanism for non-thermal effects which has been used successfully to design experiments and predict results. In these experiments, cellular growth rate was increased or decreased, reliably, at precise millimeter microwave frequencies--some frequencies having the effect of as much as doubling the duration of the cell cycle--at power densities as low as 5 picowatts per square centimeter. The magnitude of the effect is the same at all exposure intensities, but the frequency window narrows. It will be noted that similar independence of exposure intensities, and narrowing of the resonant frequency, occurred in work published by I.Y. Belyaev et al. on the genome conformational state of *E. Coli*, all the way down to 10^{-19} Watts per square centimeter, which was submitted in ET Docket 93-62 as Exhibit 167 by the Ad-Hoc Association of Parties on July 7, 1997.

2. The FCC denied the Cellular Phone Taskforce's Discrimination Complaint by referring to the Second Memorandum Opinion and Order in ET Docket 93-62, which in paragraphs 31 and 111 denied Commission expertise in health and safety matters. Since the Commission has no expertise in these matters, and was not created by the Congress with authority in health or environmental matters, therefore the Congress improperly delegated to the Commission such authority in 47 USC 151, 253(b), 254(c)(1)(A), 332(a)(1), 332(c)(7)(B)(iv) and in Section 704(b) of the Telecommunications Act of 1996. Those sections are therefore unconstitutional, and rather than accept jurisdiction over matters it cannot evaluate, the FCC should instead have referred the complaint to an agency which does have such expertise, as required by 47 CFR 1.1870(e). Indeed the constitutional conflict is reflected in conflicting statements by the FCC itself: thus, Robert Cleveland, Jr. of the Office of Engineering & Technology wrote to Lucinda Grant of the Electrical Sensitivity Network on January 23, 1997 that "Since the FCC is not a health and safety agency, we have neither the <u>jurisdiction</u> or the resources to investigate the biological effects you describe." (Exhibit A, Comments of the Cellular Phone Taskforce in WT Docket No. 97-197, submitted October 6, 1997). Injured parties are therefore being denied due process guaranteed under Amendment V of the U.S. Constitution. In addition, the unconstitutional grant of preemption power in areas of health and safety to the FCC over the States should not be exercised, as it denies to the citizens of the various states who are electrically sensitive the equal protection of

the laws guaranteed under Amendment XIV of the U.S. Constitution.

3. Congressional mandating of technology which is injurious to the public, and especially to that segment of the public which is most sensitive to the resulting harm, in 47 USC 151, 157, 303, 309, 332 and 714, and in Sections 704, 706 and 708 of the Telecommunications Act of 1996, is an unconstitutional violation of the Civil Rights of the citizens represented by the Cellular Phone Taskforce. These sections of the Communications Act and Telecommunications Act, upon which the Report and Order FCC 96-326 in ET Docket 93-62, and the Second Memorandum Opinion and Order FCC 97-303, and accompanying OET Bulletin 65 and Supplements, are authorized, and in particular the clauses preempting states and local governments in the area of health and safety are authorized, violate the protection against being deprived of life and liberty without due process of law guaranteed under Amendments V and XIV of the U.S. Constitution and should not be enforced.

Respectfully submitted,



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January 7, 1998

Verification: I declare under penalty of perjury that the foregoing is true and correct. Executed on Jan. 7, 1998.

Arthur Firstenberg

Certificate of Service

I, Arthur Firstenberg, hereby certify that on this 8th day of January, 1998, I mailed copies of the foregoing Comments Express Mail, postage paid, to the following persons:

Pam Gregory
Disabilities Issues Task Force
Federal Communications Commission
2025 M Street, N.W., Room 7130-N
Washington, DC 20554

Dr. Robert Cleveland, Jr.
Office of Engineering and Technology
Federal Communications Commission
2000 M Street, N.W., Suite 266
Washington, DC 20554

Arthur Firstenberg

Arthur Firstenberg

Nanobiology (1992) *1*, 163–176

Experimental Evidence for Coherent Excitations Correlated with Cell Growth

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Two decades ago it was proposed by H. Fröhlich that electric vibrations with frequencies in the GHz region should be excited coherently in active biological materials through metabolic processes. Excitations of the proposed type could have important biological consequences as they would lead to long-range interactions of, for example, biomolecules. Verification of the theoretical conjecture posed considerable experimental difficulties. Biological investigations must be performed using high accuracy in physical parameters, especially in terms of frequencies and field intensities. In our experiment we have controlled these parameters by using a new precision irradiation chamber, which has a fixed well-defined intensity distribution, and attenuation that extends over nine decades. Irradiation experiments with growing yeast cells (microscopically observed for two generations) generated the following results: (1) the cell growth rate depends on frequency and either increases or decreases by 10%–20%, (2) the overall frequency dependence shows a resonance-like structure and (3) the shape of the resonance curve can be changed by the use of radiation of different intensities. These observations, along with those of others also showing a non-linear response, may be explained in a general sense by the theory of non-linear dynamics. As a hypothesis to adapt this theory to our results, we suggest that only non-linear self-sustained oscillators can respond in the way we have experimentally observed. If this hypothesis is true, then in our yeast system there may indeed be one or more active internal oscillators that are normally coupled to cell growth in an unknown manner, but which are interfered with by an external electromagnetic field.

Keywords: *Microwave, resonance, low level bioeffects.*

INTRODUCTION: THEORETICAL CONSIDERATIONS AND FORMER RESULTS

As the active subunits of biological systems, living cells exhibit a high degree of information processing and communication as well with neighbour cells as with the cell-internal subunits enclosed by the plasma membrane. In this context, the information is usually described from many different viewpoints: ion fluxes, chemical gradients, protein channel openings, conformation changes of biomolecules, etc. However, the cytoplasm within living cells is now appreciated to be close to the 'solid state' due to an extensive cytoskeletal structure, and ordered water-

embedding membranes and organelles (Hameroff, 1987). These highly ordered structures are mostly charged, polarized and of dynamic nature. They may be the candidates for oscillators proposed theoretically by bioenergetic models capable of supporting cooperativity and dynamic information processing.

Over the past two decades one of the most remarkable models for cooperative functions in biological systems has been proposed by the concept of coherent excitations (Fröhlich, 1968, 1986). It provides mechanisms for long-range order and cooperativity, characteristic parameters useful for biomolecular communication and information processing. In short, one of two possible types of Fröhlich's coherence is based on an ensemble of oscillating dipoles (i.e. biomolecules or cellular structures) excitated to a collective, coherent vibration of the whole system provided the energy flux density S through the system is greater than a critical value S_0 ($S > S_0$). The necessary energy supply is proposed to be delivered by metabolic processes. The collective vibration of the system is characterized by one (or a few) modes possibly influencing molecular conformational stages or stimulating long-range interaction with other molecules or structures and, by this way, steering biochemical reactions. This idea, applied primarily to biological membranes as the possible oscillator, leads to electric vibrations with frequencies of the order of $10^{11}-10^{12}$ Hz. The given frequency range is to be considered as a very rough order of magnitude (Fröhlich, 1978).

In order to find an experimental evidence of this proposed conjecture, in principle, two approaches may be applied. (1) If vibrational states with these frequencies are strongly excited by metabolic processes, then corresponding Raman lines (Brillouin scattering) should be found when the system is metabolically active. (2) An alternative approach would be to attempt to interfere with the biological processes by exciting the systems from outside.

Approach (2) has been chosen by us in testing the proposed existence of actively oscillating 'receptors', by analysing the influence of millimetre microwave (40 GHz) radiation on cell growth in three experimental series, performed with a step-like improvement of the applied techniques. In a first experimental series, we analysed the growth behaviour of yeast cultures in aqueous suspension by monitoring the visible light extinction. We found an exponential growth rate reproducible within ± 4% limits. When the cultures were irradiated by continuous wave microwave fields of a few mW per cm^2, the growth rate either stayed constant or was considerably enhanced or reduced depending on the frequency around 42 GHz. A spectral fine structure with a width of the order of 10 MHz was observed. Careful temperature monitoring excludes a trivial thermal origin of this effect (Grundler *et al.*, 1977; Grundler & Keilmann, 1978). Repetition of this experiment has confirmed that the growth of aqueous yeast cultures is indeed affected by weak microwave radiation in a frequency-selective manner (Grundler *et al.*, 1983; Grundler & Keilmann, 1983). To exclude any possible influence of uncontrolled experimental parameters, many improvements were added in these studies. These include refined frequency stabilization, refined power recording, impedance matching elements, two geometrically different antenna structures and two recording photometers. Laser thermometry was employed to locate any hot spots (Keilmann, 1983). The results of this study using two different types of antennae and described above are shown in Figure 1. These data prove that the microwave irradiation leads to fairly reproducible effects, increasing or decreasing the growth rate by up to about 10%, depending on the frequency of irradiation.

The results, however, are obtained as an average reaction of nearly 10^6 cells. No exact measurement can be made of the power actually applied or of the time during which a cell is affected by irradiation. To overcome these disadvantages inherent in the photometer experiment, a new method was developed for studying microscopically the kinetics of single cell growth during the influence of microwave radiation.

Each cell develops into a microcolony of eight cells. To apply the radiation the microwaves are guided through a sapphire plate (multimode chamber) on to which the cells are spread in a monolayer. The data obtained from this second experimental series with frequencies in the 41 780 MHz resonance (Figure 1) again prove the existence of a microwave effect on the growth on yeast cells (Grundler *et al.*, 1988, 1989).

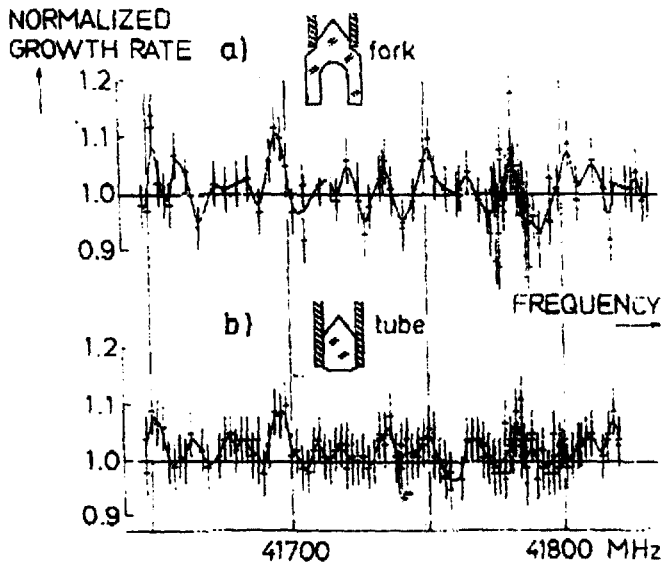

FIGURE 1. Normalized growth rate of yeast cultures versus microwave irradiation frequency using (a) fork-shaped or (b) tubular antennae. The curves were obtained by single three-point smoothing.

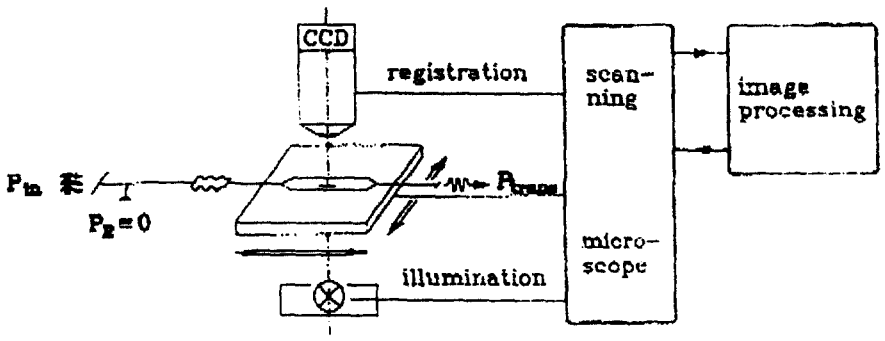

FIGURE 2. Schematic drawing of the experimental set-up for observation of kinetics of single cell growth.

Due to difficulties in reproduction of the observed cells reactions further improvements seem to be necessary, since, apart from highly stabilized frequencies, the theory demands a knowledge of the intensity for the irradiation of every single cell and a definable orientation of the biological object in respect to the field.

Then due to the frame of the theoretical concept outlined above, resonantly applied external microwave radiation should function as a trigger for the system's transition from the less ordered ($S < S_0$) to the highly ordered state ($S > S_0$). Extended theoretical studies of the non-linear dynamical behaviour of this phase transitions demonstrate their high sensitivity to slight changes of the external physical parameters (Kaiser, 1984, 1988).

How we meet these requirements experimentally and what the first observations are will be treated in this paper.

METHOD: IRRADIATION PROCEDURE AND SINGLE CELL OBSERVATION

Long time frequency stability ($\pm$ 10 kHz) can be achieved even in the GHz region by using high quality, commercially available equipment and the usual stabilization procedures (phase

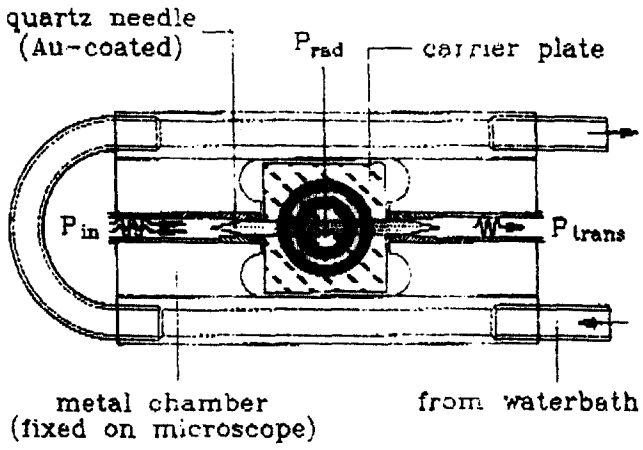

FIGURE 3. Thermostatted irradiation chamber (top view) and the removable dielectric (quartz needle and carrier plates).

lock technique). Short wavelength radiation, however, creates great difficulties in defining the intensity qualitatively for an irradiated single cell, for instance, as the reacting biological unit. Figure 2 demonstrates schematically the experimental set-up developed by us for this purpose.

The irradiation chamber, coupled by a flexible waveguide with a standardized millimetre wave set-up (Grundler *et al.*, 1983), is mounted on the stage of a scanning microscope. Between the fixed illumination and registration systems the movable stage enables the observation of individual cells (40 at maximum) by the use of a CCD camera. The pictures of the selected cells and their progenies are stored by an image processing system at fixed time intervals (e.g. 7·5 min) over an observation period of about three cell cycles.

Irradiation System

The incoming radiation is guided through the thermostatted chamber by means of a tapered quartz needle broadened by transparent quartz plates (carrier plates) on both sides (Figure 3). The quartz needle is part of the microwave circuit, in fact it is the dielectric in a dielectric-filled metal waveguide. The needle is mostly covered with gold to confine the microwaves, except at the ends and within a radiating slot (0·4 mm × 1·7 mm). A similar but broader opening is provided at the opposite surface to allow microscopic viewing, but this is covered with a fine metallic mesh structure which completely (−50 dB) suppresses leakage of microwaves.

The yeast cells are fixed to the lower surface of a thin transparent agar layer (0·2 mm) filling the inner part of the smaller plastic ring (shown as dark rings in Figure 3). The agar layer and the cells now rest on the quartz needle and the carrier plates. To apply the radiation, the microwaves are guided through the gold-coated quartz needle and radiated out of the slot on which the cells are spread in a monolayer.

To quantitatively determine the intensity distribution, the three quantities P_{in}, P_{trans} and P_{rad} can be measured. The 1·70 mm half wavelength slot delivers a frequency-dependent radiating power resonance around 43 GHz. If using frequencies between 41 and 42 GHz, a negligible variation of intensity with frequency can be guaranteed.

In this set-up the microwave field in the radiating slot can be expected to be monomodal. This was experimentally tested as shown in Figure 4. The electric field is polarized and oscillates in the y direction only, surrounded by the magnetic field in the $x-z$ plane. The intensity radiated out is proved to be a $\sin^2$ distribution. These data (Figure 4) correspond to a fixed frequency (41 652 MHz) and a constant input power of 30 mW. In order to test both the linearity of the waveguide system and the accuracy of the experimental irradiation entities, the input power

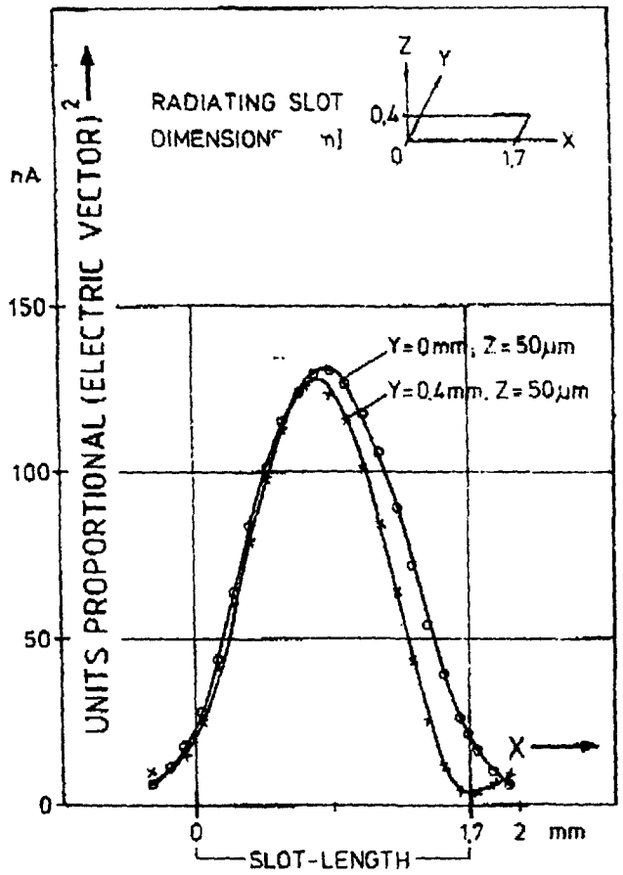

FIGURE 4. Intensity distribution of a radiating slot (1·7 mm long) measured at the long boundaries.

was systematically varied and the corresponding P_{trans} and P_{rad} values registered using standard adaption and attenuation procedures (Figure 5).

By resetting (open triangles in Figure 5) and reproduction (open squares in Figure 5) experiments, the relative accuracy was experimentally proved to amount to a factor of ± 2 due to a slightly changed geometrical coupling when the quartz needle is repositioned for a new experiment. Using high accuracy attenuators the applied energy flux densities can be varied over nine decades within an accuracy of ± 5 on an absolute scale.

Observation of Growth

For our experiments diploid yeast cells (*Saccharomyces cerevisiae*) were obtained from a stock culture of stationary state cells on solid nutrient agar (20 g l^{-1} glucose, 20 g l^{-1} Bacto agar, 5 g l^{-1} yeast extract; 4°C) and suspended in phosphate buffer. A synchronized subpopulation (early G_1 phase) was selected by volume sedimentation and used for a series of experiments. For every experiment 10 μl of a medium suspension containing 4×10^6 cells ml^{-1} was used in the cell chamber (Grundler *et al.*, 1988).

In order to run an experiment, about 20 cells were selected for observation. By the use of prescreening programs three quantities could be defined for every start cell and stored in a data file:

(1) the (x,y) coordinates, corresponding to the intensity individually achieved by a single cell;
(2) the orientation of the cell's main axis to the **E** vector direction;
(3) the cell area, which is proportional to the cell volume defining the individual state of the cell in G_1 phase.

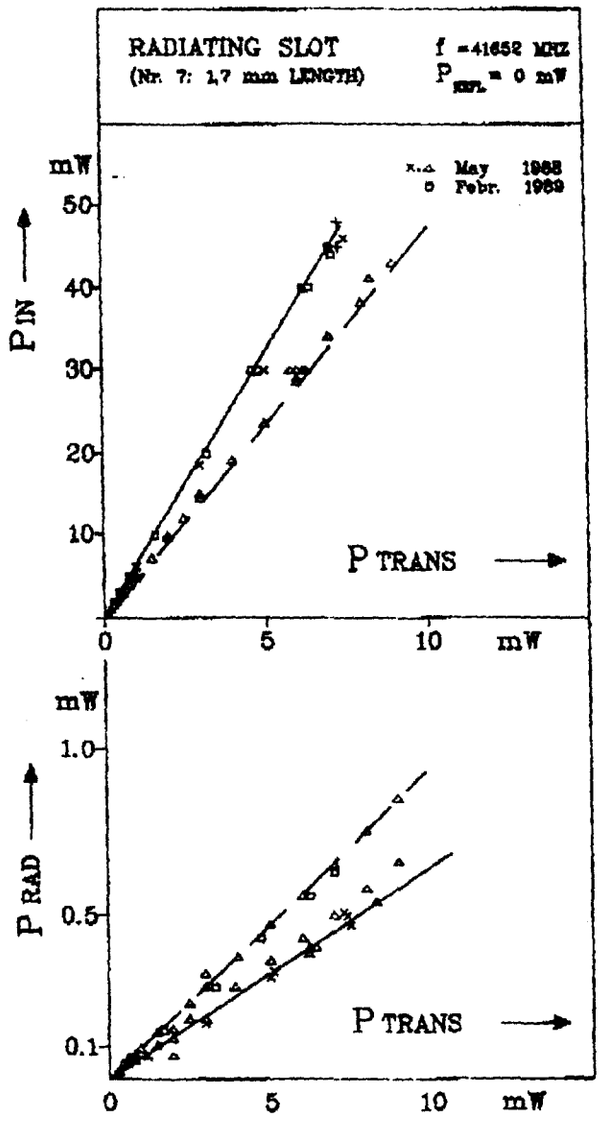

FIGURE 5. Power emitted by radiating slot dependent on the incident and transmitted power of the irradiation chamber.

After switching on c.w. radiation, the pictures of the selected cell ensemble are recorded by a CCD camera every 7·5 min over a time period of 10 h corresponding the lag phase and two cell cycle times.

The cells can easily be discerned by pattern-recognizing programs. The appearance of budding can be determined with high resolution. This budding coincides with the transition of the cell from the G_1 to the S phase. Therefore, by defining the cell cycle time as the time between consecutive budding our method allows us to determine the cell cycles for each of the cells individually (Figure 6).

The evaluation of experimental data for all cells observed thus yields the distribution of cell cycle times, either separately for the first generation (= first-to-second budding), for the second generation or for all generations together.

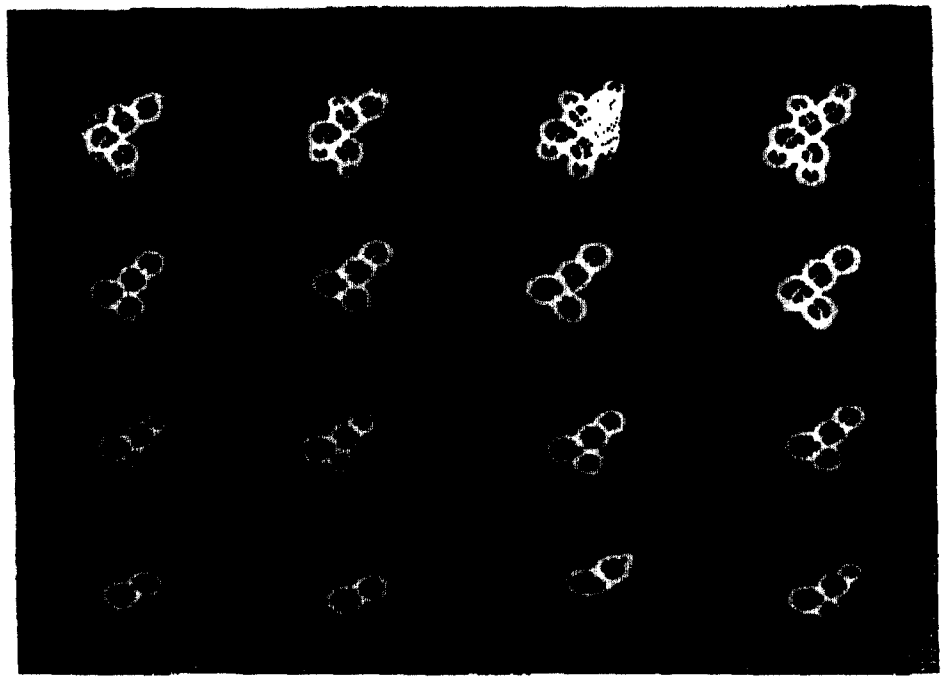

FIGURE 6. The second half of a processed set of 32 pictures describing a single cell kinetic from a double cell to an eight cell colony. (Numbers correspond to registration intervals; generations are indicated by colours, the degree of relationship by bars.)

EXPERIMENTAL RESULTS

Microwave radiation responses of cells stirred in suspension suggest both a short radiation time or an intensity much lower than some mW per cm^2 sufficient for causing growth effects (Keilmann, 1983). In addition, the theoretically proposed trigger function of microwaves can be performed by very low intensities (Kaiser, 1988). Finally, biological effects caused by frequencies lower than 100 Hz have been shown to be induced by extremely low electrical field strengths (Nair *et al.*, 1989). These suggestions have brought us to the application of very low mean intensities ($P = 1$ nW cm^{-2}) as the mean of the slot $\sin^2$ distribution, corresponding to a mean specific absorption rate of $\overline{SAR} = 0{\cdot}04\ \mu W\ g^{-1}$) when reproducing the most pronounced resonance around 41 696 MHz (Figure 1) measured on cells in suspension.

We conducted a series of 37 growth experiments, 27 with and 10 without microwave radiation. Figure 7 gives several examples of the resulting distribution of cell cycle times as computed by the image processing programs.

In these runs the control experiments resulted in the narrowest distributions. The effect of irradiation can be seen in Figure 7 to be an asymmetric deformation of the distribution. Any broadening must mean that not all cells respond in the same way. In particular, radiation induced reduction of growth velocity is significantly pronounced. Partly, a doubling of cell cycle time can be observed (Figure 7), a 100% effect for a single cell.

For further evaluations we disregard this effect and concentrate on the shift of the distribution by calculating the average cycle time t_{av} in each distribution. By taking the inverse of t_{av} we obtain the average growth rate t_{av}^{-1}, which we further normalize to the mean value obtained in the control runs. Figure 8 shows the resulting normalized growth rate for different frequencies.

The data obtained from the new experimental set-up (determining absolutely the intensity within a factor of ± 5 for a single cell), again prove the existence of a microwave effect on the growth of yeast cells. Significant growth rate values are found well outside the scatter of

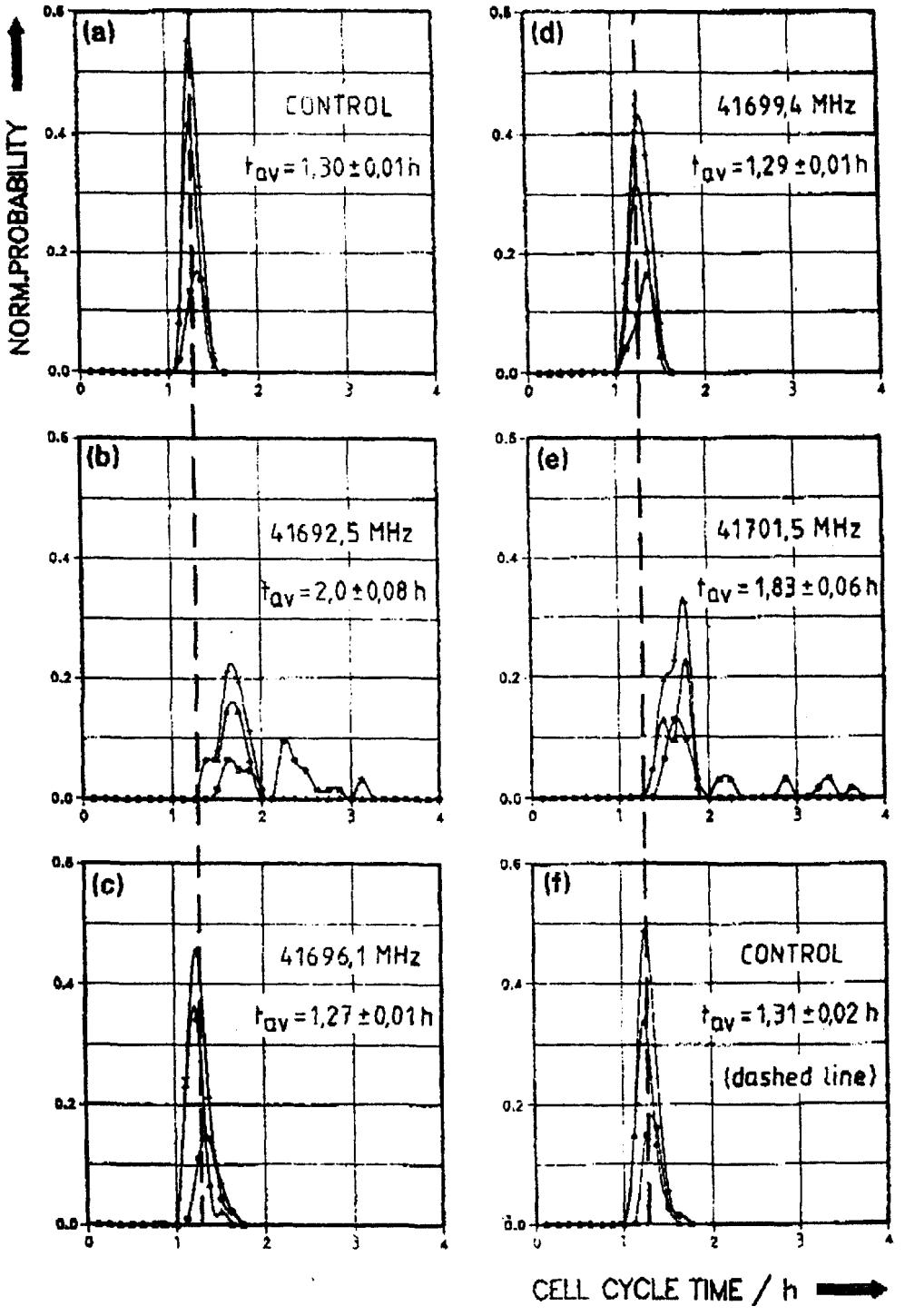

FIGURE 7. Normalized distribution of cell cycle times of growing single yeast cells for two generations (○, first; ▲ second) and for all together (×). (a) and (f) Results for cells without irradiation. (b)–(e) Irradiated with different frequencies. Intensity: 1 nW cm^{-2} (0.04 μW g^{-1}). Modulation: 8 kHz, square wave. Dashed line: mean value of all control distributions.

control runs (±3%). In particular, at frequencies inducing a shortened cell cycle time the overall effect is established to the greatest degree. Between these minima the normalized growth rate values measured vary around one. Nevertheless, the maximum value can be observed at 41 696

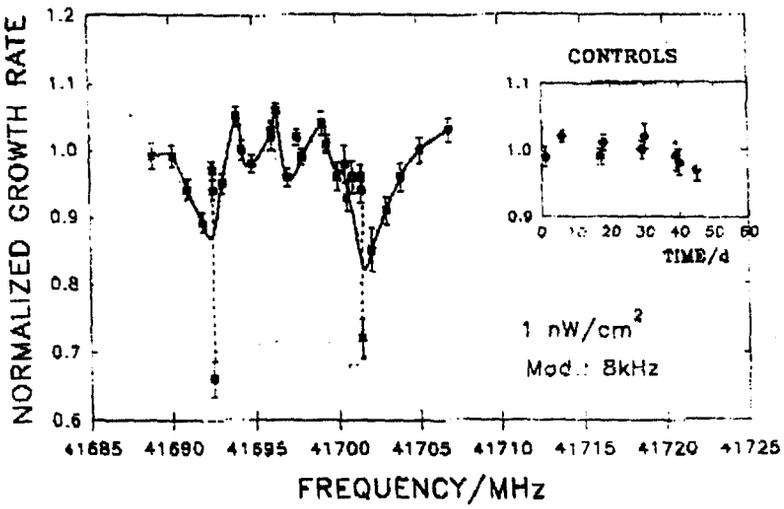

FIGURE 8. Normalized growth rate of population obtained by averaging over individually determined cell cycle times in dependence on frequencies around 41 696 MHz ($\bar{P}_{mod}$ = 1 nW cm^{-2}, f_{Mod} = 8 kHz, square wave).

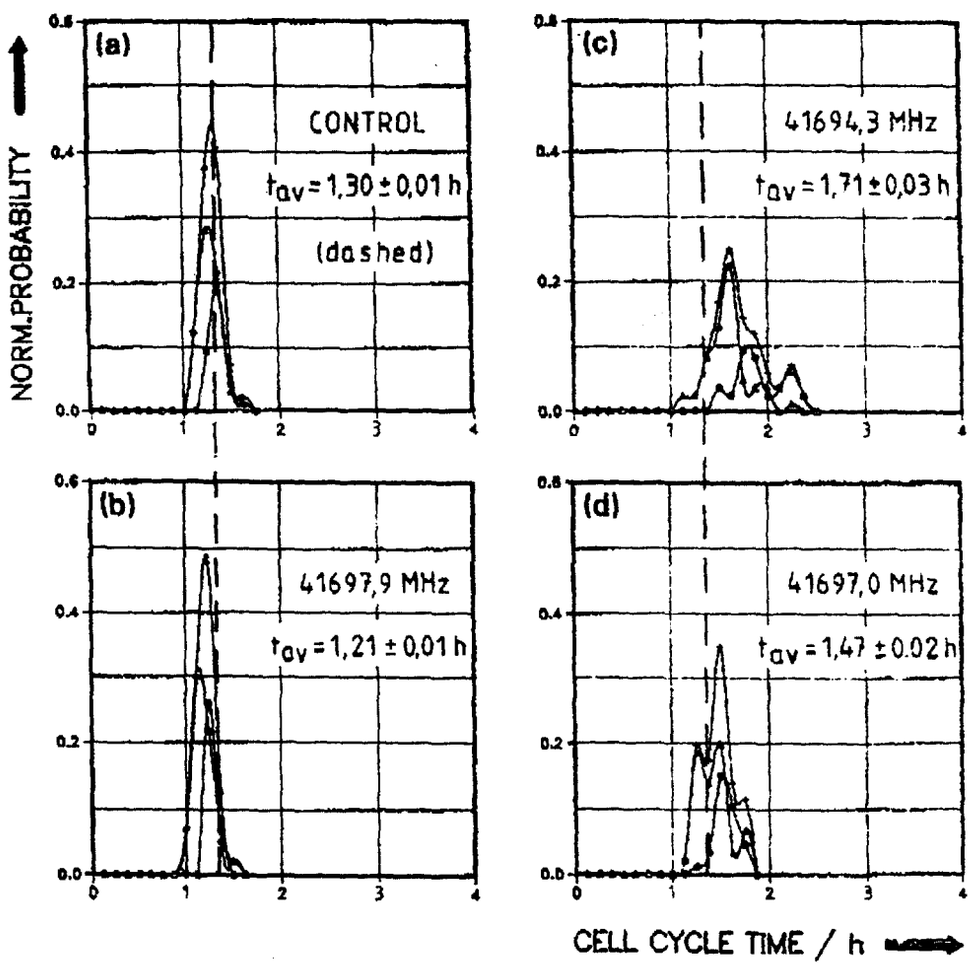

FIGURE 9. Normalized distribution of cell cycle times of growing yeast cells for two different generations (○, first; ▲, second) and for all together (×). (a) Results for cells without radiation, (b)–(d) irradiated with different frequencies. Intensity: 5 pW cm^{-2} (0.2 nW g^{-1}). Modulation: 8 kHz, square wave. Dashed line: mean value of all control distributions.

MHz. For testing the intensity dependence of the growth response on intensity of 5 pW cm^{-2} ($\overline{SAR}$=0.2 nW g^{-1}) was chosen for a further long series of 33 runs. In Figure 9 the rough experimental data indicate once again a frequency-dependent cell growth effect in spite of this extremely low intensity applied. Summarizing the results of this second series, the normalized growth rates of these three runs (Figure 9) together with the other ones demonstrate the dependence on frequency (Figure 10). Once again, a resonance like structure can be observed around 41 696 MHz, as already measured on cells in suspension (Figure 1). At the frequency position characterized by the most pronounced negative effects a special sensitivity can be observed, indicated by effects partly of different signs.

In comparing both resonance curves measured by the use of intensities, roughly distinct by a factor of 200, we can summarize our main experimental findings as follows.

(1) The resonance frequency remains at the same position when the external applied intensity is changed.
(2) There is a clear indication of strong negative effects at both sides of the resonance frequency, though extremely low intensities are active.
(3) A narrowing of the resonance is observed when radiation of lower intensity (some orders of magnitude) is applied.

DISCUSSION

With respect to the results of the irradiation experiments it is clearly demonstrated that a fast oscillating, very weak outer field is influencing biological reactions of cells by changing their growth velocity. In spite of our assumption of a cell to be a black box, due to the lack of knowledge about the biomolecular reaction involved, we have to take into account an 'internal' oscillator (the cell itself or parts of the cell or of its environment) coupling with

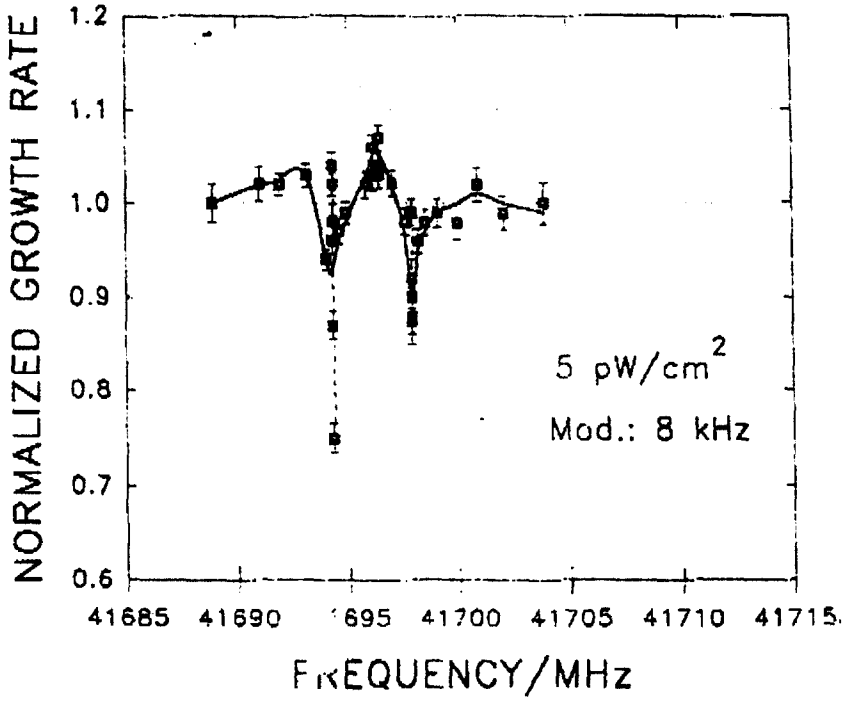

FIGURE 10. Normalized growth rate of population obtained by averaging over individually determined cell cycle times in dependence on frequencies around 41 696 MHz ($\bar{P}_{rad}$ = 5 pW cm^{-2}, $f_{Mod.}$ = 8 kHz, square wave).

the outer field. Models seeking to explain such a bioactive field–cell interaction mechanism must take into account the highly non-linear properties of living systems. Apart from non-linearity, such an oscillator must be dissipative. Consequently the question arises now as to whether the energy dissipation is internally compensated or not, i.e. whether we are dealing with a self-sustained or a non-self-sustained internal oscillatory system. This distinction can be clarified by the analysis of experimental results in comparison with theoretical considerations.

From a rather fundamental point of view, Fröhlich has promoted the ideas that coherent states can be established in active biological systems (Fröhlich, 1968, 1984). Possible types of coherent excitations are (1) highly polar metastable states and (2) coherent vibrations as a realization of self-sustained oscillators. The establishment of the latter type is possible if the rate of energy flux through the system is beyond a certain threshold ($S \gtrsim S_0$).

The possible excitation of coherent vibrations has been demonstrated with some simple physical model calculations (Fröhlich, 1968; Kaiser, 1979, 1988). The coherent vibrations include a very large frequency range from slow chemical or electrical oscillations to oscillations beyond the GHz range in membranes and proteins. The interaction of these non-linear coherent vibrations (for instance of limit-cycle type) with external fields creates a rich variety of non-linear responses (Kaiser, 1988). In particular, those processes or mechanism not explained by direct high intensity processes or by heating, e.g. non-thermal effects in irradiated biosystems, reveal a new interpretation.

In the realm of these theoretical considerations the sharp resonance peaks (Q value, $\Delta f/f \approx 10^{-4}$) in the frequency response relating to extremely frequency-sensitive processes, as found in our experiments, can be explained very consistently. The existence of sharp resonances is thus confirmed by both a very general theoretical concept and by the results of two different experimental methods (Grundler *et al.*, 1983). The biological responses found experimentally and their quantified dependence on different physical parameters may strongly increase the acceptance level of the validity of the theoretical concept. In this context, the evidence for the existence of self-sustained oscillators as specific coherent excitations is enhanced.

As a theoretical example of an internal system disturbed from outside and fitting the characteristic model behaviour, a limit-cycle oscillator (Van der Pol type) has been intensively studied (Kaiser, 1983, 1984). Its simplified resonance diagram (1/1 resonance, schematically) is demonstrated in Figure 11, indicating the system's response as a function of the external frequency and the external amplitude, with which the outer field entrains the internal oscillator. For a high external amplitude a broad response curve is to be expected; for a low external amplitude a smaller frequency region is relevant. It should be noticed that in this model even intensities near to zero can be active. This resonance curve is characteristic of a disturbed oscillator where a phase-locked or synchronized behaviour is displayed for certain λ and F_1 regions. Quantitatively we have observed the same behaviour by applying different external intensities to our yeast cells when registering their growth response.

Figure 12 shows the most important experimental results on a frequency scale listing the resonance positions and the resonance width (due to the minima positions) for the different intensities used. The position of the resonance frequency is not changed for any of the intensities applied, indicating that in every case an oscillator with nearly the same resonance frequency has been disturbed. The intensity dependent resonance width is clearly demonstrated when comparing the frequency differences correlated to the minima positions caused by different intensities. Such an experimentally documented response indicates that an internal oscillator is involved as a coupling system between the external field and the biological response.

Finally, the experimental data should be analysed with respect to the fundamental question of whether a self-sustained or a non-self-sustained system is involved. As theoretical model representatives of a non-self-sustained system and of a self-sustained system, a physical pendulum with small deviations and a Van der Pol oscillator may be used (Kaiser, 1988). With respect to Fröhlich's coherence the latter selection may be adequate since Fröhlich's long-range coherent oscillation model is a self-sustained oscillator related to a generalized Van der Pol oscillator. The results of the theoretical treatment of these two oscillating systems with respect to their

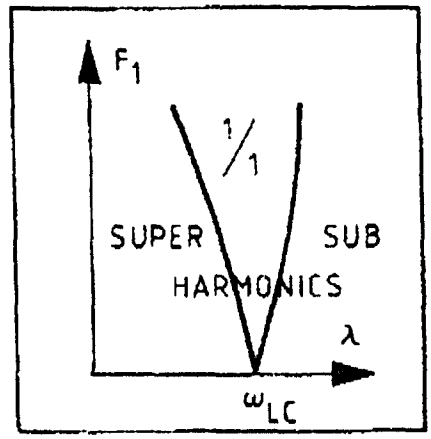

FIGURE 11. Schematic resonance diagram of a limit cycle oscillator. F_1, external field amplitude; λ, external field frequency.

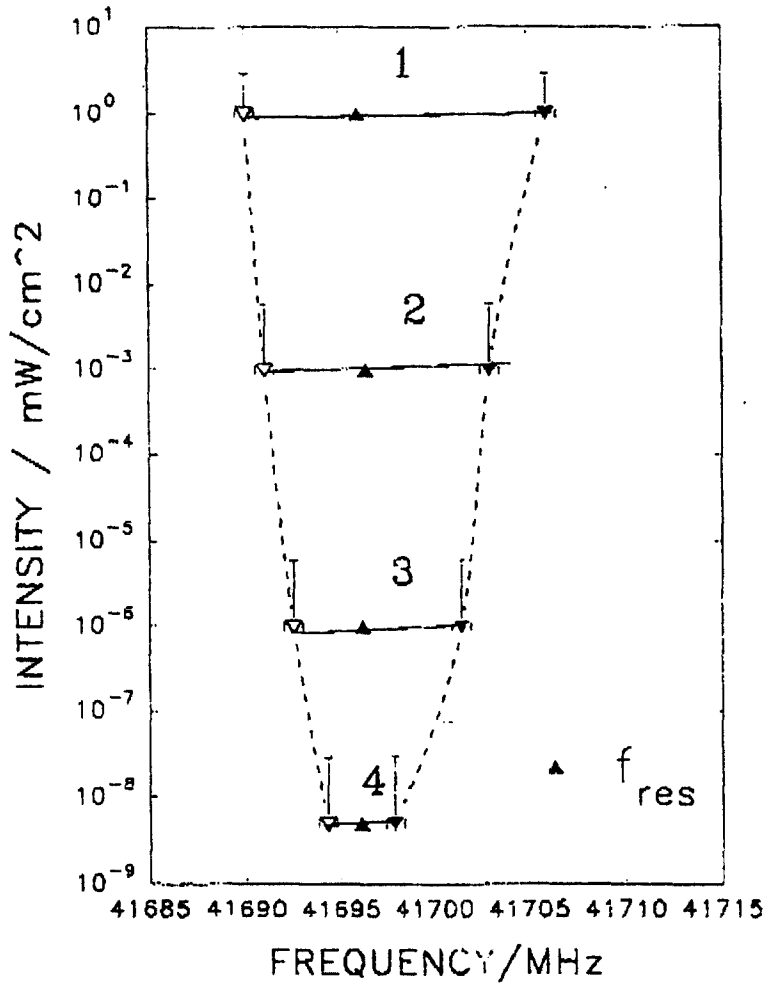

FIGURE 12. Experimental results: resonance frequency positions and resonance width for growth responses to microwave radiation of different intensities. (1) Cells in suspension, 10 mW cm^{-2} and lower. (2) Single cells in monolayer, around 1 μW cm^{-2}. (3) Single cells in monolayer, around 1 nW cm^{-2}. (4) Single cells in monolayer, around 5 pW cm^{-2}.

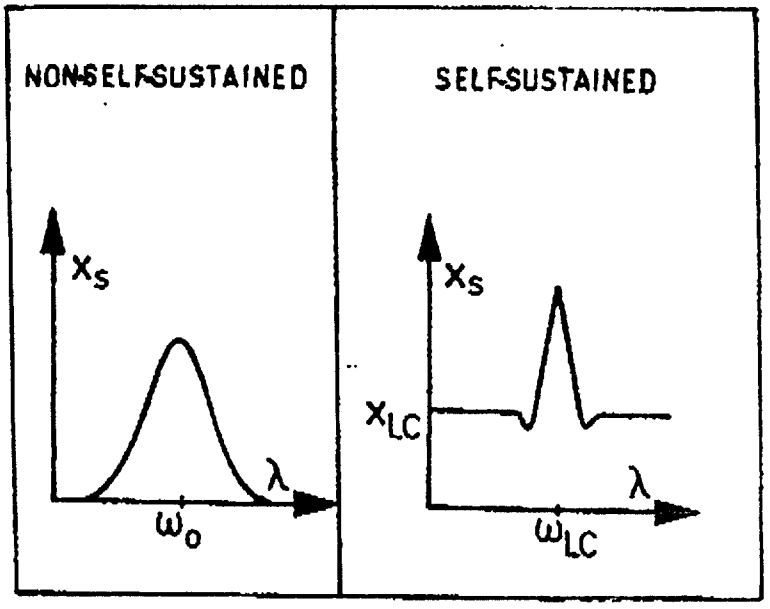

FIGURE 13. Schematic view of the steady state amplitude X_S of a non-self-sustained and a self-sustained oscillator. The oscillators are driven by $F_1 \cos\lambda t$ (subscript S = steady state, subscript LC = limit-cycle).

response to external disturbances are schematically summarized in Figure 13. For the non-self-sustained (passive) oscillator, the resulting internal frequency is always λ (i.e. the external frequency). The system oscillates with the driver frequency and with an amplitude that is directly proportional to the external field amplitude. The behaviour changes drastically in the self-sustained (active) case. Assuming a stable limit cycle with amplitude X_{LC} and frequency ω_{LC} for $F_1(t) = 0$, for a certain range of frequency the internal oscillation becomes entrained. One finds the following transitions: the internal frequency ω_{LC} with internal amplitude X_{LC} is synchronized to λ (sharp resonance peak). Then the reversed situation occurs. The important point is that the internal amplitude is reduced with respect to the undisturbed amplitude X_{LC}, just before the external frequency enters the entrainment region.

The biological response observed (Figures 8 and 10) has some similarity with the behaviour of the active, self-sustained system. Provided the amplitude of the unknown oscillator coupled to the external field is proportional to the biological response observed, the strong reduction of the normalized growth rate on both sides of the resonance curves provides strong evidence that the oscillator involved must be self-sustained.

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