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Use of Ball Lightning for THz Stand-off Detection of Bio-chemical Agents

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1. Introduction to Ball Lightning (BL)

- BL is a rare atmospheric electrical phenomenon, about 5% saw it ...
- BL is like a ball of plasma, usually about a child's head in size, ranging from 2 inches to several meters in diameter; orange or white
- Other than a ball of plasma, BL does not flame upwards, is well confined, much colder than arch discharge; lasts seconds to minutes
- BL most often occurs right after a lightning flash, towards the end of a thunderstorm, but also during, before, or after it ...
- BL may come down from a cloud, suddenly appear outside, in closed rooms or in airplanes, may enter through a chimney, through an open or closed window (30% damage rate), door, or even thin walls
- BL preferentially moves horizontally but may jump occasionally to a different altitude; it frustrates AE scientists, never appearing at peaks
- Outdoor BL often ends with a violent explosion, indoors silently

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INTRODUCTION to BALL LIGHTNING



This 1886 drawing of a "globe of fire descending into a room" by G. Hartwig is believed to be an early depiction of ball lightning.

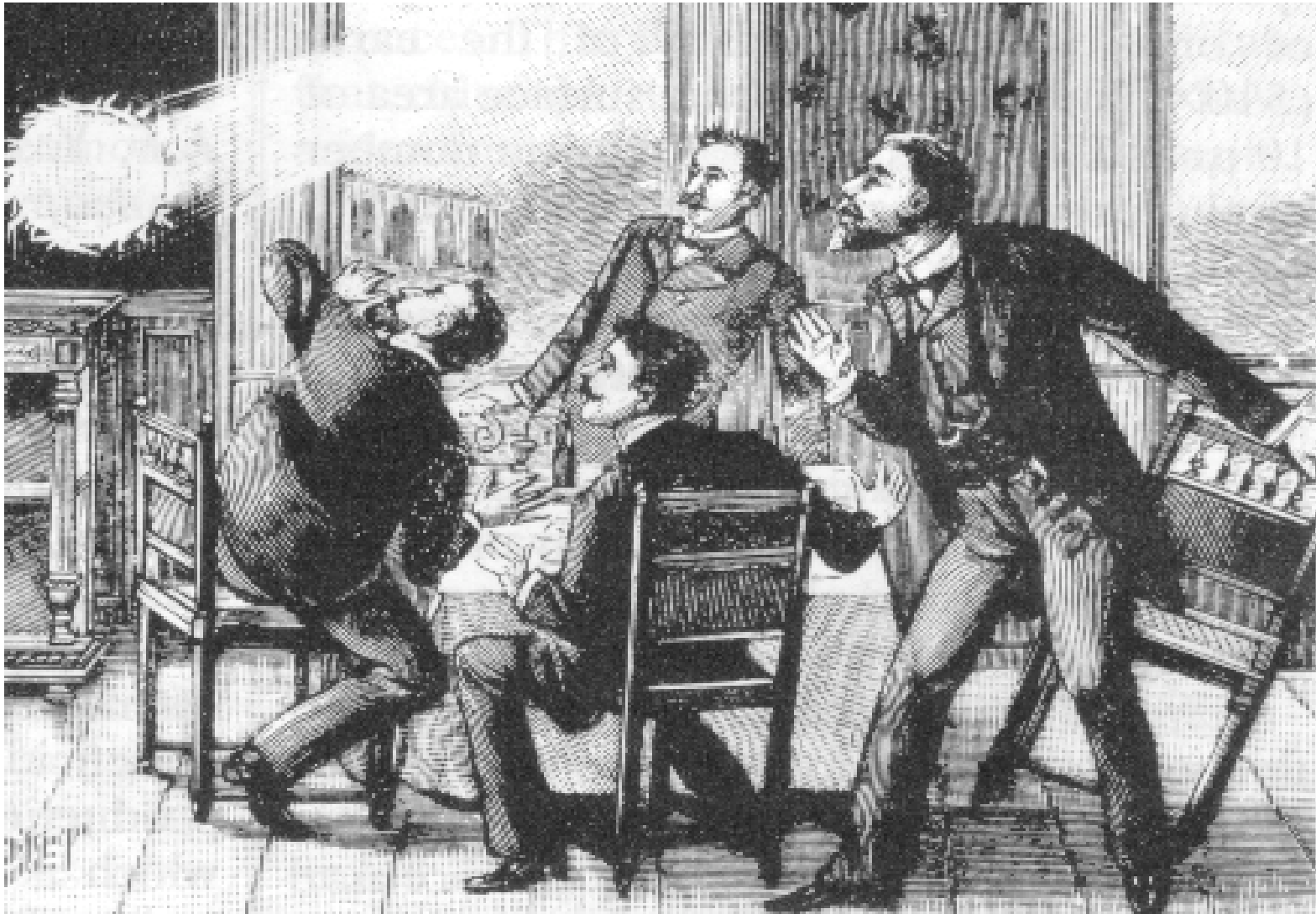
Image courtesy NOAA

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INTRODUCTION to BALL LIGHTNING



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INTRODUCTION to BALL LIGHTNING



Death of Prof. G. W. Richmann, St. Petersburg 7-26-1753. By Sokolov, Engraver, Imperial Academy. **University of Missouri-St. Louis**

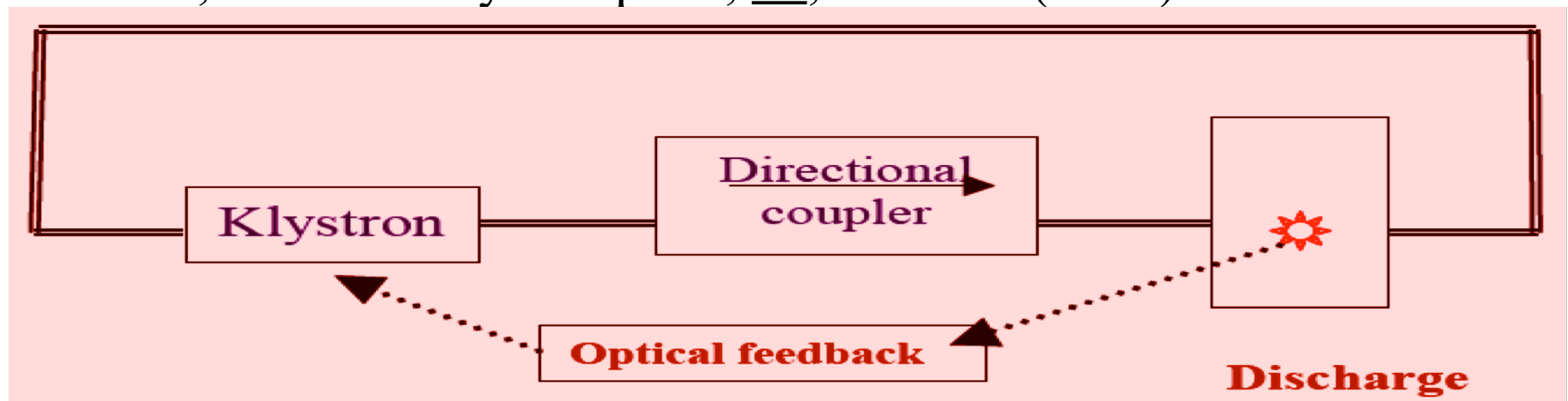


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- Our maser-soliton theory of ball lightning (BL) explains BL as a localized nonlinear vibrating plasma caviton, locally trapping the electromagnetic field generated by a large spiking atmospheric maser created by the electric field pulse of lightning in several cubic miles of moist air over flat areas. This is a new type of discharge.
- The quasi-stationary state of the coupled nonlinear system of ball lightning (BL) fireball and atmospheric maser feeding the fireball, is studied on the basis of our Maser-Soliton (or -Caviton) BL theory.
- Combining the energy balance equation of the fireball with the expression describing the exponential temperature and electric field dependence of the plasma conductivity, we obtain a power/temperature characteristic with two stable branches, separated by a branch which is unstable when driven with the usual RF or UHF sources.

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- One of the usually stable branches and part of the usually unstable branch represents the hotter, white, BL.
- Part of the other usually stable branch and an adjacent part of the usually unstable branch corresponds to the colder, orange BL. **The BL temperature is much lower when cold emission is included in the spiking regime:** A.V. Zvonkov, A.B. Timofeev and P.H. Handel: “On the Stability of Low Temperature States of the VHF discharge at High Pressure,” Plasma Phys. Reports, **26**, 801-808 (2000).



**Position stabilization at low T by spiking and feedback**

At these low temperatures, there are no electrons that could sustain the discharge. However, right when the discharge is dying, a powerful klystron spike is automatically caused by the sudden decrease of the load. This extracts electrons through cold (Fowler) emission, also known as field ionization, and rekindles the discharge. The optical feedback is responsible in part for the fast reaction. Then the spiking cycle repeats itself, causing the BL to vibrate with a continuous sequence of death and re-birth cycles. This stabilizes the unstable line:

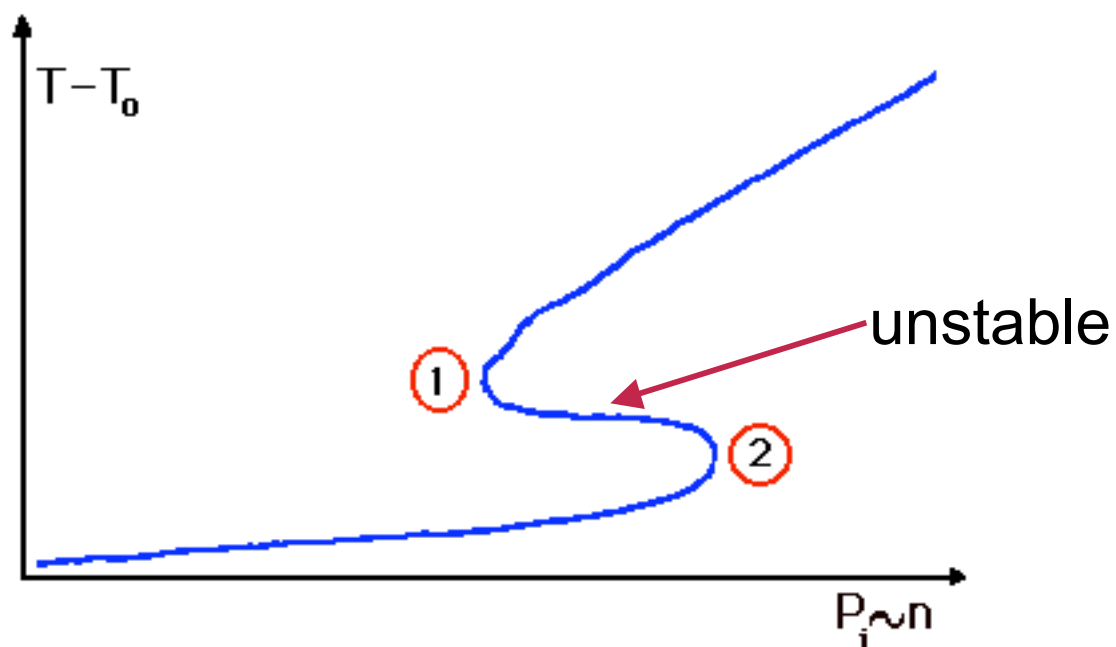


Fig. 2: Relative temperature of BL discharge as a function of incident power P_i or maser photon number n .



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- BL was not understood by AE experts, until it was explained by us as a localized soliton/caviton, instantly fed by an atmospheric maser of many cubic miles in volume:

Handel, P.H. and J.F. Leitner (1994) “Development of the Maser-Caviton Ball Lightning Theory”, J. of Geophys. Research, **99**, 10689.

Handel, P.H. (1985), *Polarization catastrophe theory of cloud electricity*, J. Geophys, Res. **90**, 5857-5863.

Handel, P.H. (1975), *Maser theory of ball lightning*, Bul. Amer. Phys. Soc. Ser. II, **20**, 26.

Handel, P.H. and Schneider, R.T. (1985), *Nature of resonances leading to high-pressure cavitons*, Fusion Technolgy, **7**, 320-324.

Handel, P.H. (1988), *Maser-caviton ball lightning mechanism*, Proc. 8 Int. Conf. on Atmosph. Electr, Uppsala, Sweden, pp. 177-182.

Handel, P.H. (1989), *New approach to ball lightning*, in Science of ball lightning, Y-H Ohtsuki Ed World Scient, pp. 254-259.

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EMULATION of BALL LIGHTNING

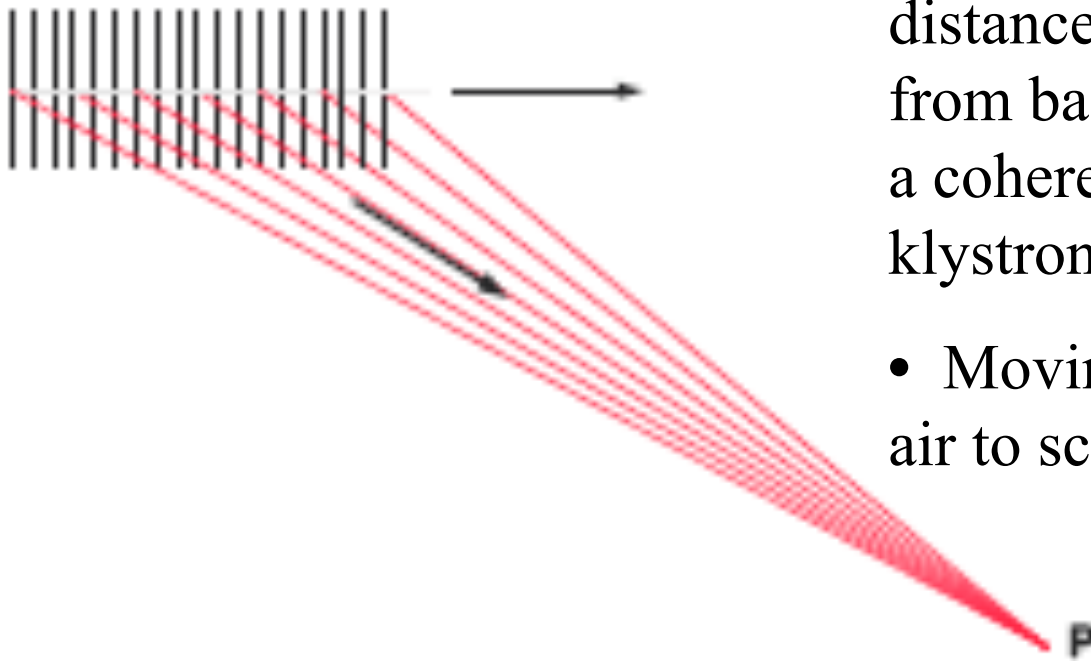


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To create a BL soliton at P at a stand-off distance of the order of 1 km, a coherent superposition of klystron-generated waves is needed, with well defined phase differences, as shown below. By changing the phase differences, the sharp pencil beam can be quickly scanned through space. The needed antennas: parabolic.

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- BL is different from other microwave discharges because it is stable, much colder, well defined, and does not flame upwards due to buoyancy forces. Its motion is always opposed to the gradient of the population inversion in moist air and is not influenced by wind, static electric field, or gravity.

Antenna Array

- Creating an oscillant/vibrating BL (or BL system) artificially at a distance of the order of a mile from base in the atmosphere, with a coherent system of oscillating klystrons close to spiking and
- Moving it quickly through the air to scan a certain volume.

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2. THz Stand-off Bio-chemical Agent Detection

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- At any moment, it would produce the mid-air system of BL-like plasma points where an 800 nm infrared "pump" femtosecond pulsed laser-beam and its second harmonic (SH), [both coherently emitted along with a "probe" beam from the base to track the BL], generate **BL plasma-enhanced*** strong broadband "THz waves" locally, nonlinearly, through four-wave mixing and ponderomotive forces, as shown by X.-C. Zhang's group [PRL **97**, 103903 (2006)].
- These "THz waves" will in turn be finally detected by measuring with a photomultiplier the time-resolved SH' signal (about 400 nm).
- The latter is generated by mixing the "probe" field with the "THz waves" incident on the closely adjacent probing BL points of the moving BL ensemble and locally generated THz (LO). The detection of the time-resolved SH signal that carries the THz waveform is done at the base. It relies on back-scattering and/or re-action from the adjacent close BL/plasma.

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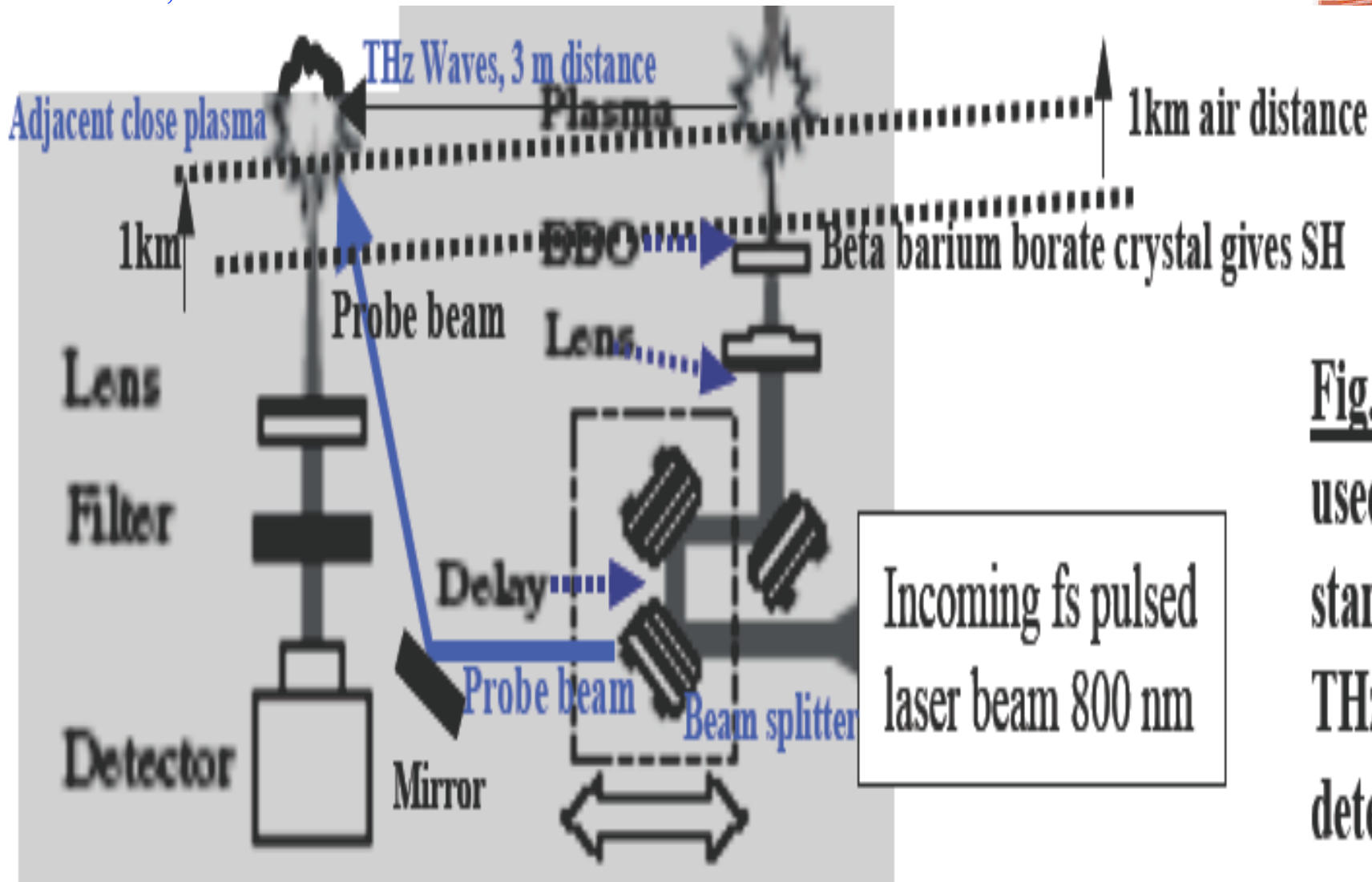


Fig. 1: BL
used for
stand-off
THz agent
detection

*X.Xie, J. Xu, J. Dai, X.-C. Zhang Appl Phys Lett 90, 141104 (2007):

Enhancement of THz generation by preexisting plasma **University of Missouri-St. Louis**

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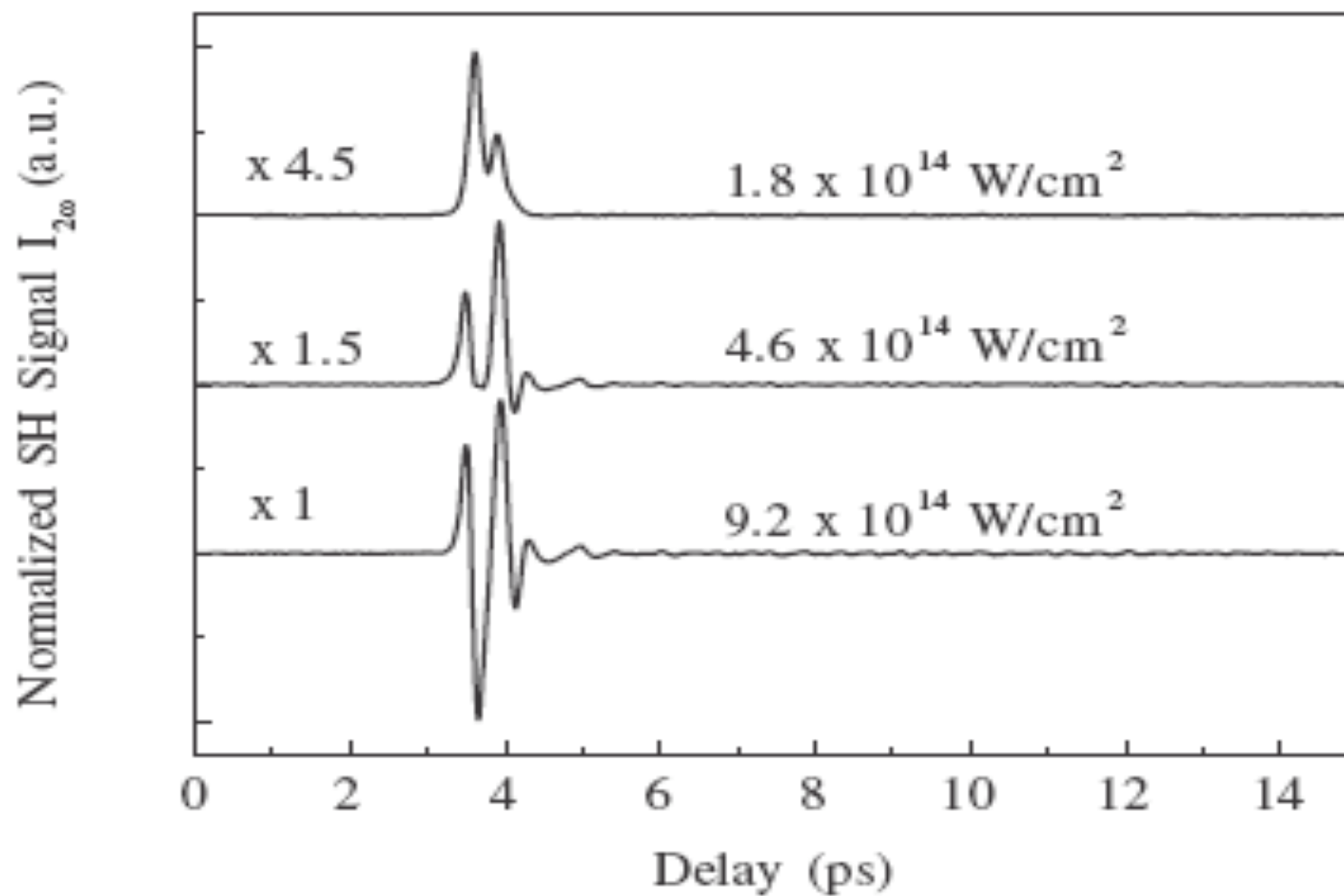
- Detection in the second BL (or sBL system) is **coherent with the help of a strong 800 nm "probe" field(s)**, or incoherent with a weaker "probe" field(s).
- In the first case the larger amplitude of the probe field is essential in order to locally generate in the probing BL a **BL-enhanced** "THz-field-induced second-harmonic" (TFISH) component from the probe field. **That TFISH could act as a local oscillator (LO) field and would thus allow for the coherent detection process*.**
- In its short travel between the BL points, the broadband THz waves acquire the absorption lines/bands of biological and/or chemical agents. These modulate the returned SH' intensity, and will permit agent identification after a discrete Fourier transform of the detected THz waveform, through computer comparison with digitized spectral signatures. [*X.-C. Zhang's group PRL **97, 103903 (2006)**].



- Coherent detection, simultaneously measuring amplitude and phase of a THz wave, has become the basis of time-domain spectroscopy (TDS); e.g. by photocond. dipole antennas or electro-optic crystals.
- In the four wave mixing in the second BL the TFISH $\mathcal{E}_{2\omega}$ is LO, added to the third order nonlinearity term $E_{2\omega} \propto \chi^{(3)} E_{\omega} E_{\omega} E_{\text{THz}} \propto I_{\omega}$, yielding $I_{2\omega} \propto (E_{2\omega})^2 = (E_{2\omega} + \mathcal{E}_{2\omega})^2 = (E_{2\omega})^2 + (\mathcal{E}_{2\omega})^2 + 2E_{2\omega}\mathcal{E}_{2\omega}\cos\phi$, where ϕ is the phase difference between $E_{2\omega}$ and $\mathcal{E}_{2\omega}$. The latter is contributed from the white light generated from the laser-induced plasma through self-phase modulation and self-steepening; it increases with the plasma density, so a BL-generated plasma (Fig.1) background helps. The first term, big for weak LO, gives incoh. det..
- Thus, $I_{2\omega} \propto (\chi^{(3)} I_{\omega})^2 I_{\text{THz}} + (\mathcal{E}_{2\omega})^2 + 2\chi^{(3)} I_{\omega} \mathcal{E}_{2\omega} E_{\text{THz}} \cos\phi$, in which the last term permits coherent detection of the THz wave info obtained between the two BL plasmas. The first term is small for strong LO.

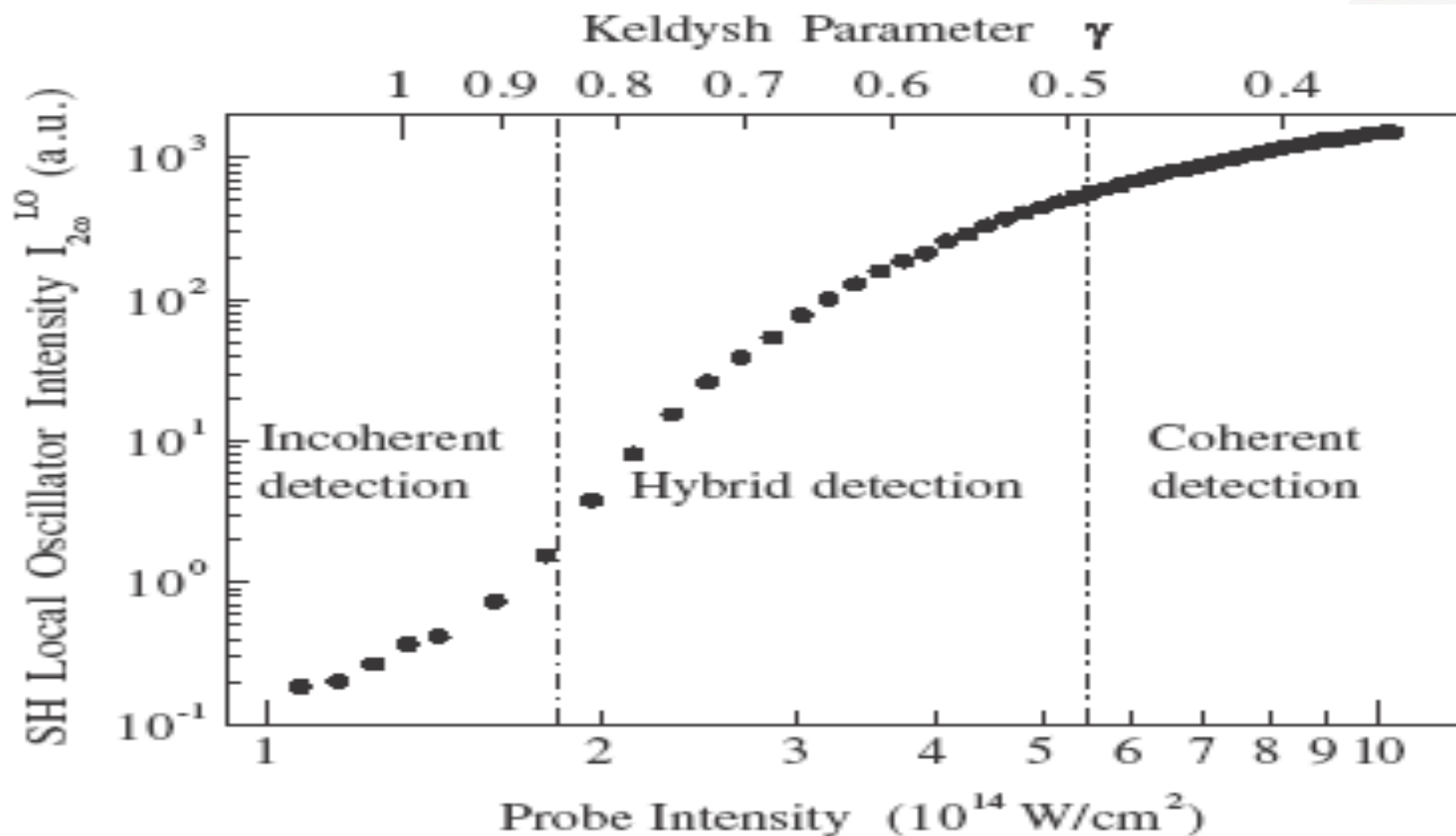
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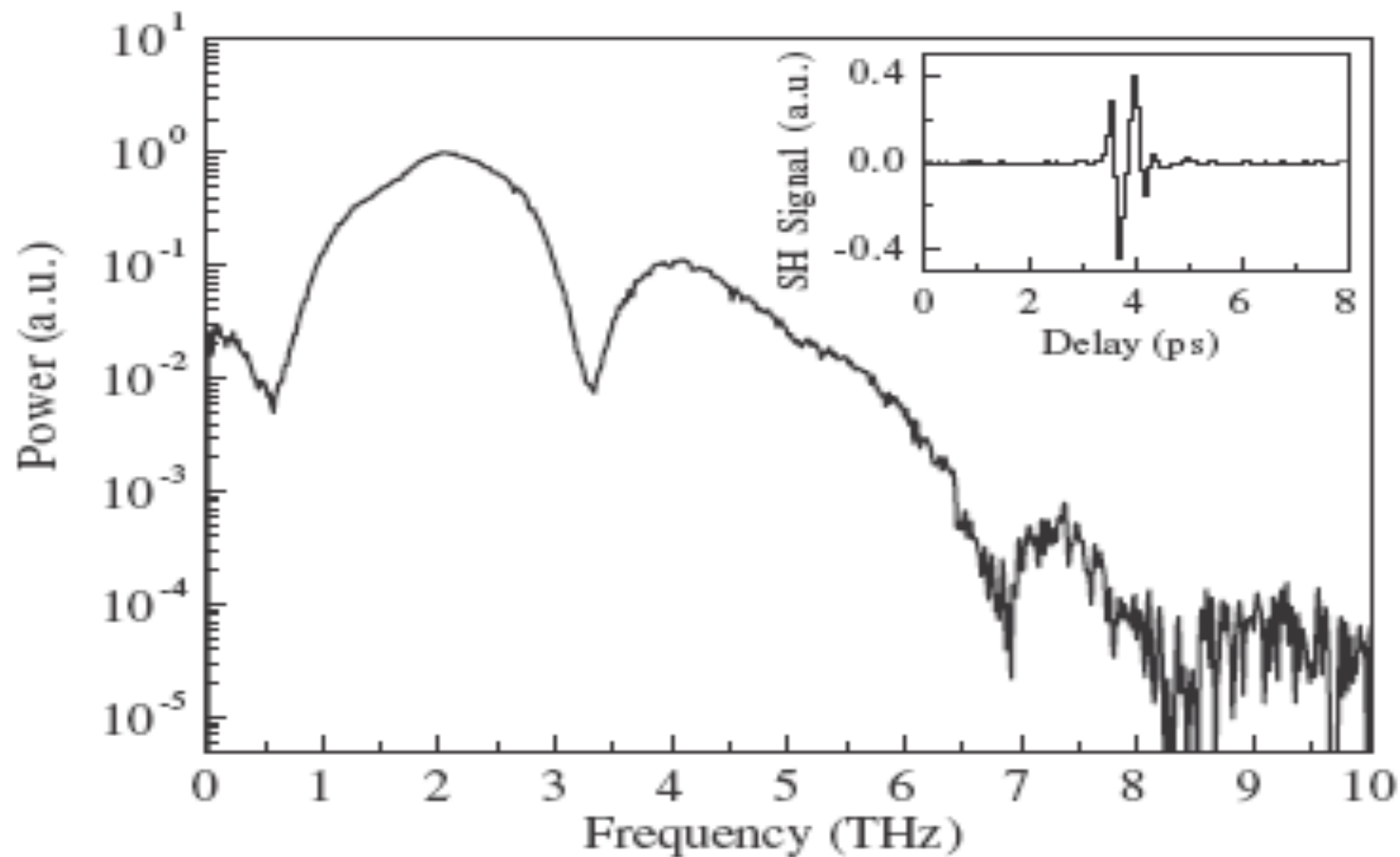
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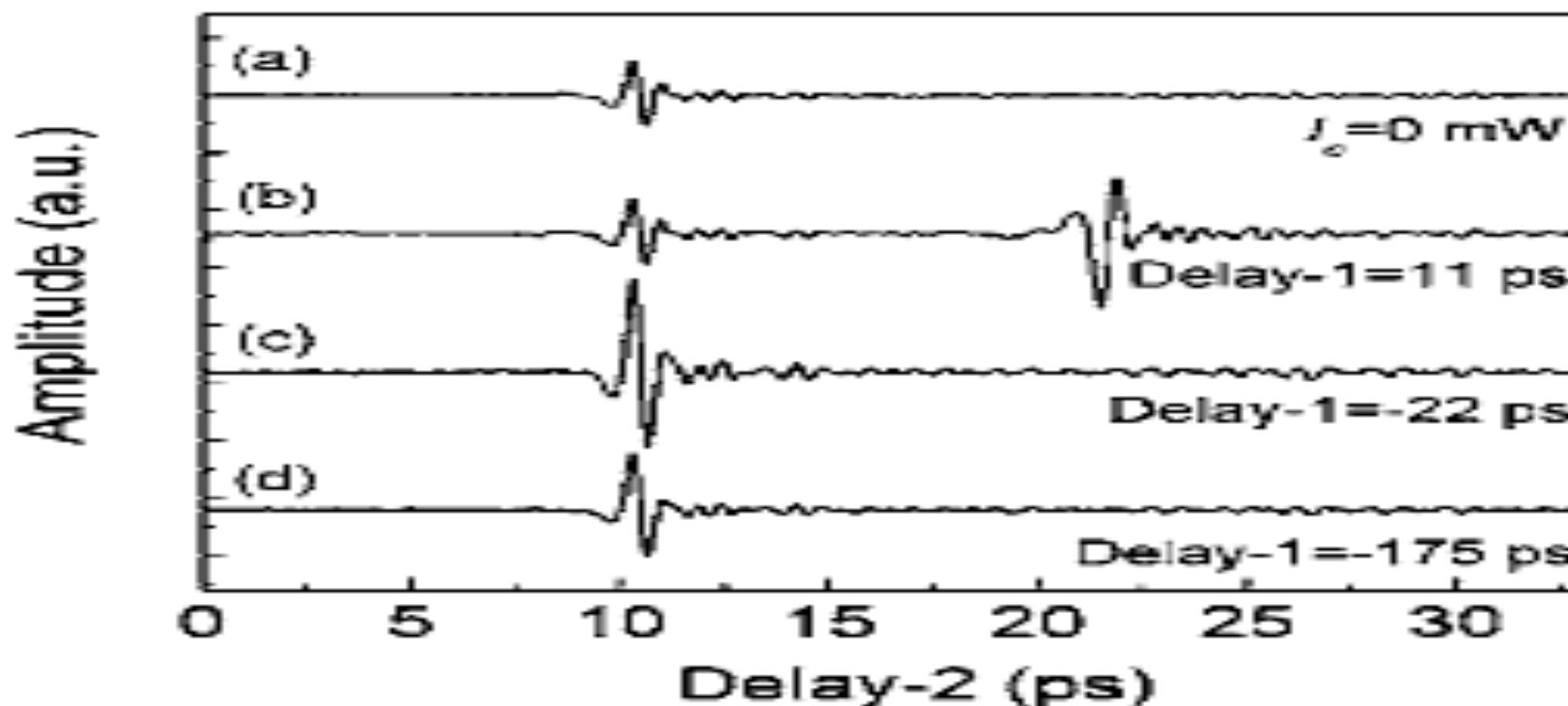
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Xie et al.



Xu Xie, Jingzhou Xu, Jianming Dai, and X.-C. Zhang:
“Enhancement of terahertz wave generation from laser induced
plasma” **APPLIED PHYSICS LETTERS** **90**, 141104 (2007)

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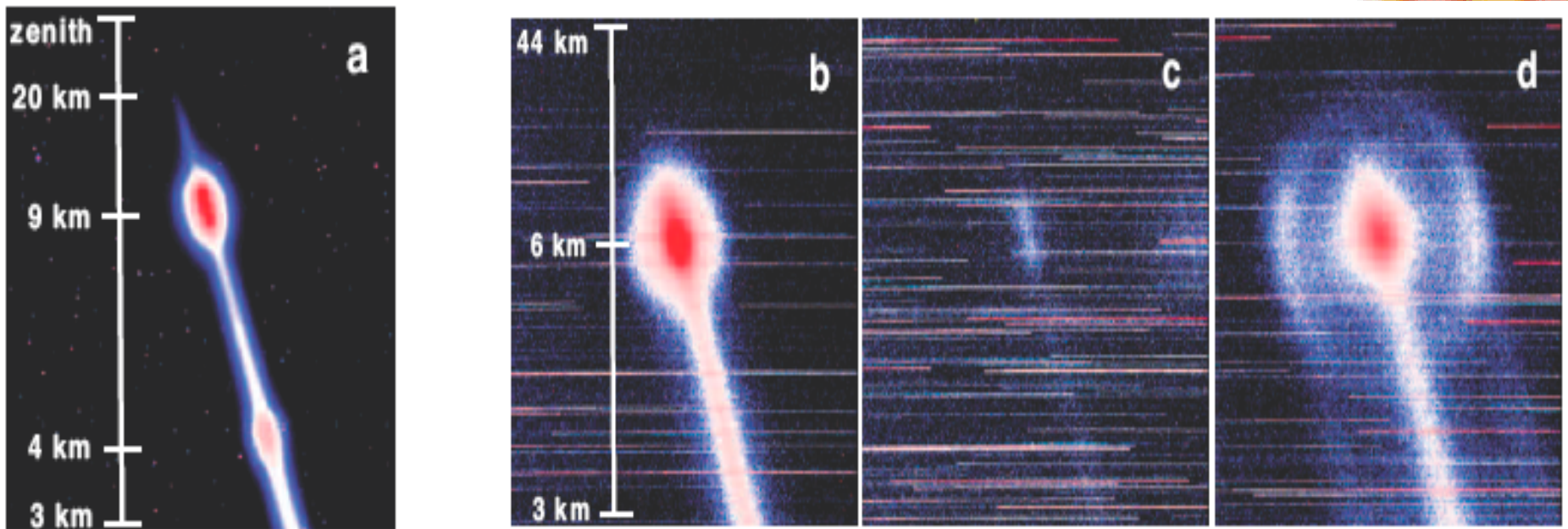
Implementation with fs pulsed lasers

- The initial generation of the BL soliton by the original spike of the atmospheric maser of many cubic km volume is described in the classical paper of Handel and Schneider [4].
- It starts with a double resonance effect, both electrostatic and acoustic, leading to an elimination of ions from the growing solitonic volume, and self-trapping of the electromagnetic field in the generated langmuir soliton, based on the nonlinear ponderomotive forces and Vlasov's "nonlinear Schrödinger equation".
- A similar process of atmospheric radiation self-trapping happens in high power laser beam. [4] P.H. Handel R.T. Schneider: Fusion Technology 7 320 (1985).



FILAMENTATION

- In high power laser beams in the atmosphere, the index of refraction $n=n_0+n_2I$ increases with the local intensity I due to Kerr effect with $n_2>0$. This causes self-focusing of the beam and beam collapse until multi-photon ionization MPI of N_2 and O_2 sets in at intensities of 10^{13} - 10^{14} W/cm².
- This generates plasma, which defocalizes the beam, thereby compensating the positive Kerr effect. The result is a quasi-solitonic self-contained propagation, with the formation of stable filaments, several hundreds of meters long and only 100-200m wide, in violation of the expected diffraction-caused spreading.
- Delivery of high energy 800nm laser beams to large distances and high altitude is thus possible:



Pictures a-d [5] were taken with the 2 m diameter telescope of the Thuringian Landessternwarte Tautenburg. The Teramobile laser truck was parked right next to it, with the powerful 800nm laser. Picture a is in the initial wavelength of 800nm, while b-c are in shorter wavelengths, in the visible. This shows why in particular the THz generation and four-wave mixing are going to be strong. The pulses, except in c, were anti-chirped in order to shorten to the fs durations farther away, with increased intensity.



1. Introduction.

The quasi-stationary state of the coupled nonlinear system of ball lightning (BL) fireball and atmospheric maser feeding the fireball, is studied on the basis of our Maser-Soliton (or -Caviton) BL theory. Combining the energy balance equation of the fireball with the expression describing the exponential temperature and electric field dependence of the plasma conductivity, we obtain a power/temperature characteristic with two stable branches, separated by a branch which is unstable when driven with the usual RF or UHF sources. One of the usually stable branches and part of the usually unstable branch represents the hotter, white, BL. Part of the other usually stable branch and an adjacent part of the usually unstable branch corresponds to the colder, orange BL. The BL temperature is much lower when cold emission is included in the spiking regime.



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The maser load line is different from that of all RF and VHF power sources used so far in the laboratory, and allows nature to stabilize a discharge at much lower temperatures T than the minimal temperatures needed to stabilize a discharge in the laboratory. Specifically, an avalanche of identical photons, created by stimulated emission, causes the maser-generated local electric field at the fireball site to increase instantly when the discharge tries to end due to a drop in temperature and a corresponding drop in the electron concentration. The instantaneous field increase is thus caused by the increase in the maser quality factor when the discharge tries to extinguish and by the corresponding increase in photon life time, which leads to an avalanche of RF or VHF photons generated by stimulated emission. This avalanche instantly compensates the initial temperature drop, thereby reigniting and stabilizing the discharge even at temperatures below the usual stability limits.



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Field emission processes in the bulk of the plasma, solitonic effects, Rydberg matter surface tension, and quantum resonance effects such as the Ramsauer effect are important in this new low-temperature, low-dissipation discharge, characteristic only for the BL fire ball.

The rate equations describe instantaneous explosive field growth caused by the large maser volume. The stationary rate equations of the maser and the power balance equation of the fireball give us both an independent expression for the number of photons n present in the maser modes. Equating these two expressions yields the fundamental nonlinear stationary BL equation. This relation connects the power dissipation rate of the stationary fireball with the required pumping rate renewing the population inversion in the maser. The energy spectrum of H_2O is honeycombed with almost coincident pairs of levels connected by forbidden transition, weakly allowed for $E \neq 0$.



3. General Description of the BL Mechanism

The rotational energy levels of the water molecule include many closely spaced pairs linked by forbidden transitions in the VHF domain. **A sudden, very strong and short electric field pulse, caused by lightning, can induce a population inversion on some of these closely spaced pairs of energy levels.** In the absence of very high pointed conductors, the equipotential surfaces are planes, and the population inversion can develop over volumes of many cubic kilometers. When the electric field increases to values of the order of 10^4 V/m, some of the forbidden transitions will become weakly allowed and will feed a large atmospheric maser which exceeds the critical volume. The latter is defined large enough to yield more photons per time unit through stimulated emission than the loss rate which is mainly caused by the absence of a cavity.



Due to this maser action, **a standing electromagnetic wave will be present below the cloud in the vicinity of the earth**, as in Kapitsa's model. If in a certain point the local plasma frequency of ions coincides with the maser frequency, a resonance process will lead to local enhancement of the electric field, to ponderomotive forces which pump out the ions from the high field region, creating a resonant cavity in the plasma, finally leading to the formation of a plasma soliton known as high-pressure caviton (Handel and Schneider, 1985). The caviton is an eigenfunction-solution of the non-linear Schrödinger equation describing the field-plasma interaction with the ponderomotive force included, physically represented by an almost empty sphere containing the resonant high electric field and ions mode. These cavitons were first introduced by Zaharov in 1972, and were thought to be unstable with respect to collapse until Laedke and Spatschek (1984) proved them to be stable for sizes exceeding a certain minimum. A detailed study of the initial resonance igniting the caviton was presented elsewhere (Handel and Schneider, *Nature of resonances* Fusion Technol, 7, 320-324 (1995))

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General Description of the Mechanism



The caviton is thus a stable quasi-spherical configuration of trapped electromagnetic field, surrounded by plasma and moving horizontally at the level of a standing field antinode, being noticed as ball lightning. The sudden demise of the caviton fed by a large atmospheric maser in open air will lead to spiking of the maser, observed as an instantaneous large release of energy like a giant spark, and interpreted as a powerful explosion. On the other hand, the sudden demise of the caviton in closed spaces (inside a house, airplane, etc.) will not lead to noticeable energy releases or explosions, because the volume of the maser equals the volume of the closed space which is relatively small in this case, and the total energy associated with the population inversion in the water vapor contained in it is limited usually to a few hundred Joules. Finally we mention that due to the unfavorable geometry of the high-field cone above a mountaintop lightning research station, the inverted air mass will never become critical, no maser action will be possible, and ball lightning will never be observed. This explains the notorious frustration and skepticism of famous lightning researchers who never get to see ball lightning, while non-specialists in the flatlands report it frequently.

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4. Nonlinear System of Maser and HF Soliton

When lightning strikes on flat terrain, a strong homogeneous electric field pulse is present simultaneously in a large volume of moist air, of the order of cubic miles. As shown earlier [*Handel* 1988, 1989], this pulse can lead to homogeneous population inversion in the rotational energy levels of the H₂O molecule. Close to mountain tops, the electric field and the ensuing population inversion is limited to a cone-shaped volume, so this pulse does not lead to maser action without cavity walls. On flat terrain this field pulse will sometimes lead to maser action for a period of the order of seconds, due to the low rate of forbidden transitions between closely spaced pairs of rotational energy levels of the water molecule. The condition for this maser action to take place is that the gain G exceeds the loss L in the number of photons per time unit

$$dn/dt = G - L > 0,$$



resulting in a net increase in the number of photons n first in a certain, well defined standing wave mode of oscillation of the decimetric electromagnetic spectrum, or in small number of modes of the same frequency. The loss term can always be represented in terms of an effective cavity lifetime τ_c , and in terms of an effective load lifetime τ_b , the load being represented by the caviton, i.e., by the visible ball lightning (BL). In the open air case there are no cavity walls, at best some reflecting objects, such as the trees lining an opening in the forest. In the absence of any cavity walls and reflecting objects or boundaries, τ_c assumes the lowest value, of the order of L/c , where L is the diameter or characteristic size of the inverted volume which can be of the order of several miles. With $L = 3 \text{ km}$ we get $\tau_c = 3 \text{ km} / (3 \cdot 10^5 \text{ km/s}) = 10^{-5} \text{ s}$, better than for resonant cavities with copper walls.



On the other hand, on a high peak, such as K. Berger's observatory on Mount San Salvatore in Lugano (Switzerland) we have $l \approx 10\text{m}$ and $\tau_c \approx 3 \cdot 10^{-8} \text{ s}$, which precludes maser action. This explains why Berger never saw ball lightning.

Collisional deexcitation of molecules is in competition with stimulated emission. The latter wins sometimes because it is faster when it happens to go into a high-gain field mode.

The gain G is from stimulated emission, being proportional to the number N_2 of molecules present in the upper maser level E_2 , and to $n+1$, i.e., roughly to the number of photons already present in the mode under consideration

$$dn/dt = K(n+1)N_2 - n/\tau_c - n/\tau_b \quad (2)$$

$$dN_2/dt = -KnN_2 - N_2/\tau_2 + R_e, \quad (3)$$



where we added also the rate equation for the upper maser level population N_2 in terms of the relaxation time τ_2 ($\gg \tau_c$) of the upper maser level, a time which can be as long as a second or a minute, because the transition is, in fact, one of the many well-known strongly forbidden transitions between pairs of nearly coincident rotational energy levels of the H_2O molecule and is becoming only weakly allowed under the influence of perturbing fields. We also included an effective pumping rate R_e describing the rate by which in some cases the population inversion is replenished by various processes (such as, e.g., a circulation of inverted air through a barn, or recuperation of a hole burned into an inhomogeneously widened gain profile in the frequency domain).



In the quasi-stationary regime the time-derivatives are zero in equations (2)-(3). We can then eliminate N_2 and solve the resulting quadratic equation for n , with the result

$$n = (p/2) \{ r-1 + [(r-1)^2 + 4r/p]^{1/2} \} \approx p|r-1| \{ \theta(r-1) + r/p(r-1)^2 \}, \quad (4)$$

where $p = 1/K\tau_2$, $r = R_e/R_t$ is the reduced pump rate close to 1, $R_t = 1/\tau_2 K\tau$ is the threshold pump rate, and $\tau^{-1} = \tau_c^{-1} + \tau_b^{-1}$. We have introduced $\theta(x)$ which is 1 for $x > 0$ and 0 for $x < 0$. Here p is close to the number of field modes within the width of the maser line. This width is very large in our case. Therefore, p is a very large number of the order of 10^{20} and equation (4) describes an explosive growth of the number of photons n as a function of r , whenever r exceeds unity even by very little. Indeed, from the last form of Eq. (4) obtained for $p \gg 4r/(r-1)^2$, we see that for $r > 1$ but close to 1, we get $n \approx p(r-1)$ which is an enormously large number of the order of 10^{20} , for $r < 1$ we get $n \approx r/1-r$ which may be a number from 1 to 1,000 for example, and for $r=1$ we have $n=p^{1/2}$.



Precisely this explosive growth as a function of r (and also in time) is what happens at the start and also at the demise of a BL discharge. The demise causes τ_b to become suddenly infinite and therefore r to exceed unity considerably. A similar spike exists also at the creation of the BL discharge when the original population inversion is established by the initial field pulse.

To Eqs. (2)-(3) an effective heat diffusion equation describing the BL must be added. The simplest form considered is

$$P = \alpha(T - T_0), \quad (5)$$

where α is a heat exchange coefficient and T_0 is the ambient temperature of about 300K. Here we have introduced the power P absorbed by the BL from the standing wave of the main maser mode.



This power is assumed to be in part ohmic as in previous experiments of Ohtsuki & Ofuruton (1991) as well as Zhil'tsov et al. (1995), although other forms of absorption such as multiphoton field-ionization of neutral atoms in the BL will also be present. The field ionization of atoms caused by the large spike of the maser's electric field is generating carriers (mainly electrons), at a rate that is proportional to the squared electric field times the $\exp[-bI^{3/2}/E]$, (Fowler-Nordheim)

$$dv/dt = avE^2 \exp[-b(I^{3/2}/E)] = av(n\hbar\omega/V) \exp[-b(VI^3/n\hbar\omega)^{1/2}]$$

which yields with Eq. (5)

$$\begin{aligned} P &= v\sigma_{(T,E)} n\hbar\omega/V = v\sigma_o(n/V)\hbar\omega e^{-I/2kT} \\ &\quad + v(n/V^2)\hbar^2\omega^2 \int a n\sigma_o' \exp[-b(VI^3/n\hbar\omega)^{1/2}] dt \\ &= v\sigma_o(n/V)\hbar\omega e^{-I/2k(P/\alpha + T_o)} + av\sigma_o'(n/V^2)\hbar^2\omega^2 \int n \exp[-b(VI^3/n\hbar\omega)^{1/2}] dt. \end{aligned} \quad (6)$$

$$b = 4(2m)^{1/2}/3\hbar e; \quad c = b(VI^3/\hbar\omega)$$



Here a and b are constants describing the field emission rate for electrons, and we have used the relation $E^2 = 8\pi n\hbar\omega/V$ connecting the squared electric field amplitude with the photon concentration n/V , where V is the volume of the atmospheric maser of many cubic miles, divided by a factor slightly larger than 1 describing the solitonic localized electric field enhancement in the BL, and v is the BL volume. I is the ionization energy and k is Boltzmann's constant. We have assumed thermal ionization equilibrium at the temperature T in calculating the conductivity, in the first term, which contains the dissipation allowed by the thermally generated conductivity σ_T . The coefficient σ_0 in the expression of σ_T is proportional to the number of electrons v sustaining the discharge. In the second term, this number of electrons is replaced by the time integral of the generation rate of electrons by field ionization of neutral, mostly excited atoms, perhaps also Rydberg matter left from the previous cycle in the oscillating (humming) process.



Therefore we have introduced in the second term the conductivity per electron $\sigma_o' = \sigma_o / v$, which is the mobility times the elementary charge, and is a constant. Neglecting the field ionization term, will already allow for a crude stationary BL theory. The actual oscillating (humming) BL theory will be provided for the first time below subsequently. From Eq.(6), the stationary approximation that neglects the field emission from atoms is described by the function

$$n = [VP/v\sigma_o\hbar\omega]e^{I/2k(P/\alpha + T_o)}, \quad (7)$$

which has a maximum, a minimum and a linear asymptote as shown in Fig 1. Indeed, setting $dn/dP=0$ we obtain

$$kP^2 + (2kT_o - I/2)\alpha P + k(\alpha T_o)^2 = 0 \quad (8)$$

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with the discriminant

$$\Delta = I(I/4 - 2kT_o) > 0. \quad (9)$$

This inequality is applicable, since I is of the order of 10 eV, much larger than kT_o which is 0.025 eV. Therefore we get the roots

$$P_1 \approx \alpha I/2k \quad \text{and} \quad P_2 \approx (\alpha T_o)^2/[\alpha I/2k] = 2k\alpha T_o^2/I. \quad (10)$$

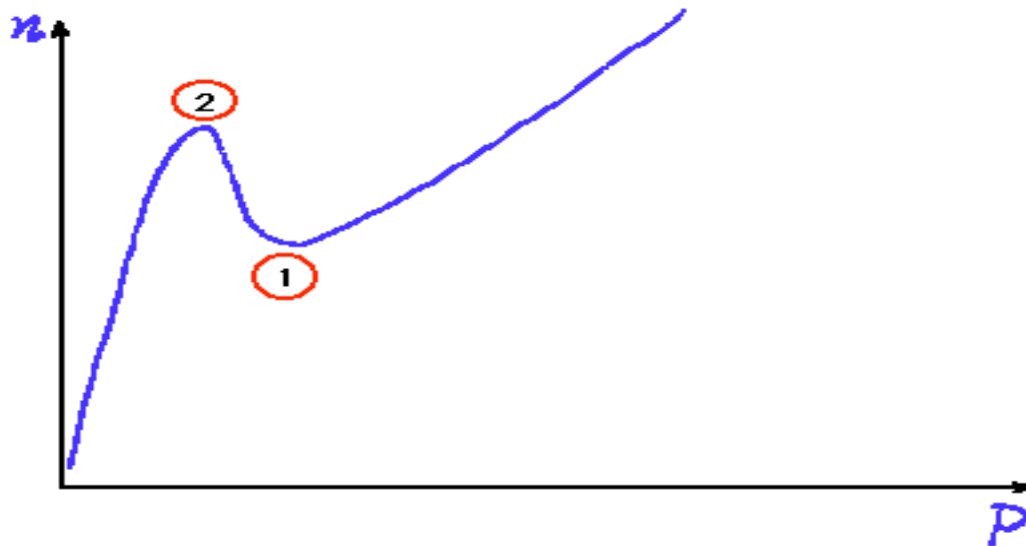


Fig. 1: Photon number n of the maser as a function of the power P absorbed in the BL.

These roots define two branches of the curve in Fig. 1, corresponding to the two forms of BL.

Note that in our model, P is related to T through a simple linear transformation and can be considered an equivalent variable with T . On the other hand, n is equivalent to the external power incident on the BL, P_i . Switching the axes, we obtain the T versus P_i diagram shown in Fig. 2.

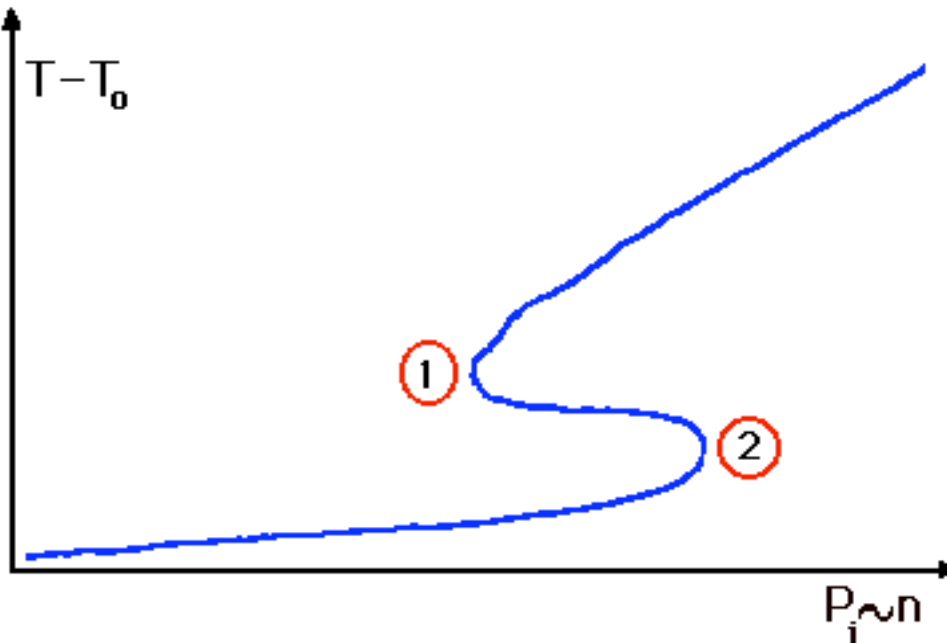


Fig. 2: Relative temperature of BL discharge as a function of incident power or maser photon #



Note also that replacing Eq. (5) with the other extreme case, energy transfer by radiation with $\beta(T^4 - T_0^4)$, does not change the situation qualitatively, although the maximum and minimum are less pronounced and less separated.

Let us assume now that we have r just slightly larger than 1 with a BL present as a load. Then $n = (r-1)p$. Since $\hbar\omega n / \tau_b$ is the load $P = v\sigma_0(n/V)\hbar\omega e^{-I/2k(P/\alpha + T_0)}$, we can identify τ_b as

$$1/\tau_b = \sigma_0(v/V)e^{-I/2k(P/\alpha + T_0)}. \quad (11)$$



This result is substituted into the expression of R_t present in the definition of r , yielding

$$n = (r-1)p = p[r_o/(1+v\tau_c\sigma_T/V) - 1], \quad (12)$$

where we introduced $r_o = R_e K \tau_2 \tau_c$ as the reduced rate corresponding to a given pumping rate R_e in the absence of the BL load (for $\tau_b = \infty$).

Equating the two expressions of n in Eqs. (7) and (12), we obtain the fundamental stationary BL equation

$$p[r_o/(1+v\tau_c\sigma_T/V) - 1] = VP/v\sigma_T\hbar\omega, \quad (13)$$

or, for the linear heat diffusion case,



$$p[r_o/(1+vV^{-1}\tau_c\sigma_o e^{-I/2k(P/\alpha + T_o)}) - 1] = [VP/v\sigma_o\hbar\omega]e^{I/2k(P/\alpha + T_o)}. \quad (14)$$

This equation determines the reduced equivalent pumping rate $r_o = R_e K \tau_2 \tau_c$ that an atmospheric maser must have in order to sustain a stationary BL discharge with power dissipation P , heat convection coefficient α and volume v at an ambient temperature T_o . Substituting the roots defined in Eq. (10), we obtain two limiting values of r_o , one for white and one for orange BL. These are the values corresponding to the end points of the hot (white or "1"-type) and cold (orange or "2"-type) BL state-branches, present in both Figs. 1 and 2. Numerical calculus is in A.V. Zvonkov, A.B. Timofeev and P.H. Handel: "On the Stability of Low temperature States of the VHF discharge at High Pressure" Plasma Phys. Reports **26**, 801-808 (2000), proving for the first time that the "forbidden" branch can be stabilized with feedback, as from masers.



5.The Humming of Ball Lightning

By linearizing Eqs. (2)-(3) and solving the resulting system of linear differential equations, we obtain oscillatory solutions describing the low amplitude limit of the spiking behavior of the maser-soliton system with the neglect of the internal soliton dynamics. These oscillatory solutions will lead to the emission of sound waves that could be perceived as the often observed "humming" of the BL. Indeed, a linearized approximate form of Eqs. (2)-(3) for the limit of small spiking oscillations is

$$d\Delta n/dt = (r-1)\Delta N/\tau_2; \quad d\Delta N/dt = -\Delta n/\tau_c - r\Delta N/\tau_2. \quad (15)$$

The solution is an exponential function of time:



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$$\Delta n = \Delta n(t=0)e^{st}; \quad \Delta N = \Delta N(t=0)e^{st}. \quad (16)$$

Here,

$$s = -r/2\tau_2 \pm i[(r-1)/\tau_2\tau_c - (r/2\tau_2)^2]^{1/2} = -\gamma_s \pm i\omega_s. \quad (17)$$

This determines both the attenuation of the spikes γ_s and their repetition (humming) frequency ω_s as a function of the reduced pumping rate $r = R_e/R_t$ defined above. The relaxation time τ_2 of the upper maser level ($\tau_2 \gg \tau_c$), can be as long as a second or a minute, because the transition is in fact one of the many well-known strongly forbidden transitions between pairs of nearly coincident rotational energy levels of the H_2O molecule. It is becoming only weakly allowed under the influence of the large foul weather field.

The humming frequency is thus determined in first approximation by $(r-1)$, τ_2 and τ_c through Eq. (17).



Returning now to Eq. (6), we re-write it in the form

$$P/n = \sigma_o(v/V)\hbar\omega e^{-I/2k(P/\alpha + T_o)} + a\sigma_o'(v/V^2)\hbar^2\omega^2 \int n \exp[-b(VI^3/n\hbar\omega)^{1/2}] dt. \quad (18)$$

The first term on the r.h.s. leads to the stationary behavior shown in figs. 1 and 2. The second term describes the field ionization or cold emission contribution, lowering the BL temperature strongly. Neglecting now in turn the first term, and taking the time derivative, we obtain

$$\exp[b(VI^3/n\hbar\omega)^{1/2}] dn/n^3 = -(\hbar\omega/V)^2 (\sigma_o'\sigma_o/P) a dt. \quad (19)$$

Setting $n=1/x^2$ and integrating, we obtain with $c=b(VI^3/n\hbar\omega)^{1/2}$ and $b=4(2m)^{1/2}/3e\hbar$:

$$2e^{cx} [6/c^4 - 6x/c^3 + 3x^2/c^2 - x^3/c] = (\hbar\omega/V)^2 (\sigma_o'\sigma_o/P) at + \text{const.} \quad (20)$$



$$2e^{cx}f(x)=(\hbar\omega/V)^2(\sigma_o'\sigma_o/P)at+const; f'=-3x^2/c+6x/c^2-6/c^3<0; x=(1\pm i)/c$$

$$2e^{cx}[6/c^4-6x/c^3+3x^2/c^2-x^3/c] = (\hbar\omega/V)^2(\sigma_o'\sigma_o/P)at + const = \text{monoton}(x)$$

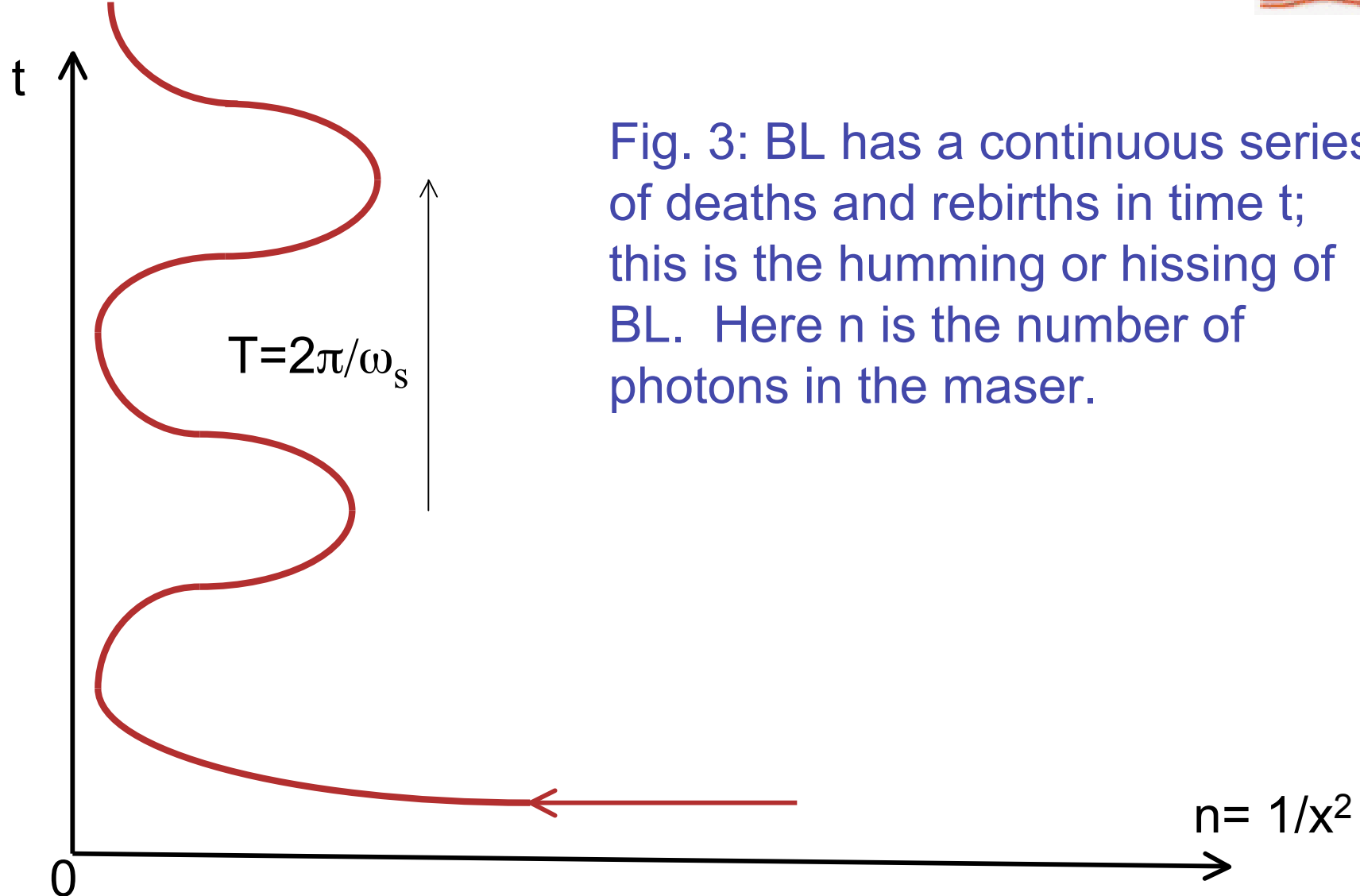
Since n is a quasi-periodic function in the humming BL, $x = 1/n^{1/2}$ is also quasi-periodic, and so is the whole left hand side. Therefore, the ratio σ_o/P must be quasi-periodic and attenuating like $1/t$. Note that σ_o is proportional with the number of electrons, or current carriers in general. However, since we neglected the thermal ionization term, this result should be valid primarily for the very cold BL cases, with low oscillating n values and large x . The general case that keeps both terms in Eq. (18) may be solved numerically.

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6. The Motion of BL, etc.

Phase Differences

- the waves originating in region #1 with $\mathbf{k}$ parallel to $\mathbf{g}$, will be superposed on those coming from region #2, forming a standing wave $\mathbf{E}$
- $\mathbf{E} = \mathbf{E}_0 \exp i[\mathbf{k} \cdot \mathbf{r} - (\omega + s)t] + \mathbf{E}_0 \exp i[-\mathbf{k} \cdot \mathbf{r} - (\omega - s)t]. \quad (1)$
- We can define the component parallel to $\mathbf{k}$ of a vector $\mathbf{v}_k$, such that
- $s = \mathbf{k} \cdot \mathbf{v}_k; \quad \text{or } \mathbf{v}_k = s\mathbf{k}/k^2, \quad (2)$
- k -independent Then, the elementary standing wave becomes
- $\mathbf{E} = \mathbf{E}_0 \exp i[\mathbf{k} \cdot (\mathbf{r} - \mathbf{v}_k t) - \omega t] + \mathbf{E}_0 \exp i[-\mathbf{k} \cdot (\mathbf{r} - \mathbf{v}_k t) - \omega t]$
 $= 2\mathbf{E}_0 \{\cos[\mathbf{k} \cdot (\mathbf{r} - \mathbf{v}_k t)]\} \exp i\omega t. \quad (3)$



- Choosing the origin of the coordinate system at the location of the BL, for $s=0$ we can express the total electromagnetic field of the standing wave, including the BL, in terms of a cosine- Fourier integral, or packet of standing waves

- $$E_{\text{tot}} = \int E(\mathbf{k}) \cos \mathbf{k} \cdot \mathbf{r} \, d^3x, \quad (4)$$

centered on the origin. This is possible due to the assumed symmetry. With a small s different from zero, considering Eq. (2), this will become

- $$E_{\text{tot}} = \int E(\mathbf{k}) \cos[\mathbf{k} \cdot (\mathbf{r} - \mathbf{v}_k t)] d^3x, \quad (5)$$

and the BL will start to move with velocity $\mathbf{v}$, as we have shown, in the opposite direction of the gradient of the population of levels, defined above.



Molecular Formulation

The preceding formulation can be expressed also more explicitly in terms of the dielectric function and quantum mechanical matrix elements, in order to prove . The permittivity is

$$\varepsilon = \varepsilon_o[1 + \chi(\omega)] = \varepsilon_o[1 + \chi'(\omega) + i\chi''(\omega)] \quad (6)$$

The susceptibility introduced by a population inversion $N_n - N_m$ per unit volume on a molecular transition of frequency ω_{mn} and damping γ is

$$\bullet \chi(\omega) = -3[e^2 F_{nm}(N_n - N_m)] / \{m\varepsilon_o \omega_{mn} [2(\omega - \omega_{mn}) - i\gamma_{rad}]\}, \quad (7)$$

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where $\gamma_{\text{rad}} = 1/\tau_{\text{rad}}$ must be replaced by the total linewidth $\Delta\omega_{\text{mn}}$ to include all forms of broadening. The oscillator strength F_{nm} is related to the molecular quantum mechanical matrix element r_{nm} and to the real molecular damping rate τ_{mn}

$$F_{\text{mn}} = 4\pi m \omega_{\text{mn}} r_{\text{mn}}^2 / 3h = \tau_{\text{rad}} / \tau_{\text{mn}}. \quad (8)$$

- The phase velocity is $v = c/n = c/\epsilon_r^{1/2}$. Therefore, for $\chi'' \ll 1$ it can be written as

$$v = \text{Re}[c/(1 + \chi'/2 + i\chi''/2)] \approx c(1 + \chi'/2) / [(1 + \chi'/2)^2 + \chi''^2/4] \quad (9)$$

$$\approx [c/(1 + \chi'/2)] \{1 - \chi''^2/4(1 + \chi'/2)^2\};$$

$$s = \mathbf{k} \cdot \mathbf{v}_k \approx -ck\chi''^2/4(1 + \chi'/2)^3 - \langle -ck\chi''^2/4(1 + \chi'/2)^3 \rangle$$

The small difference present in $\omega = kv$ is given by the term χ'' . The average $\langle \rangle$ is over the whole maser volume of many cubic kilometers.



Thus, we obtain indeed $\mathbf{v}_k = s\mathbf{k}/k^2$, with

$$\chi'/2 = 3[F_{nm}e^2(N_n - N_m)(\omega - \omega_{mn})] / \{m\epsilon_0\omega_{mn}[(\Delta\omega_{mn})^2 + 4(\omega - \omega_{mn})^2]\}$$

$$\chi'' = 3[F_{nm}e^2(N_n - N_m)\gamma_{rad}] / \{m\epsilon_0\omega_{mn}[(\Delta\omega_{mn})^2 + 4(\omega - \omega_{mn})^2]\} \quad (10)$$

This is proportional to $(N_n - N_m)$. It proves the assertion made in Sec. (2) above, that the phase velocity contains a small term increasing with the population difference between the levels involved in the maser effect.

The linear absorption/amplification coefficient is $\alpha = \omega\chi''/2c$. For balanced maser conditions, the losses caused by the end reflection coefficient r must equal the maser gain: $r^2\exp(-2\alpha L) = 1$, or $\alpha L = \log r$.



Therefore, we get $\chi'' = (2c/\omega L)\log r$. Substituting into $\mathbf{v}_k$,

$$\begin{aligned}\mathbf{v}_k &= -c(\mathbf{k}/k) [\chi''^2/4(1+\chi'/2)^3] = -(\mathbf{k}/k) [c^3(\log r)/\omega^2 L^2(1+\chi'/2)^3] \\ &= -(1/2\rho L) 2[c(\log r)^2/(1+\chi'/2)^3].\end{aligned}\quad (11)$$

With $\lambda = 0.5$ m, $L = 1$ km, and $(1+\chi'/2)^3 = 2$, this yields $\mathbf{v}_k = 1$ m/s, in agreement with observations.



- This is proportional to $(N_n - N_m)$. It proves the assertion made in Sec. (2) above, that the phase velocity contains a small term increasing with the population difference between the levels involved in the maser effect. If no pair of levels is dominant, we use a sum over levels: $\sum'_{nm}$.
- -- An important cause of BL motion is the phase difference that can occur between the components of the standing wave feeding the BL. This has its cause in turn in small variations of the level population difference, or population inversion.
- -- Finally, electromagnetic boundary conditions place restrictions on the BL motion, and also generate a preference of horizontal motion along antinodal planes.



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Calculation of Population Inversions From a Field Pulse

Let E be the amplitude of a rectangular electric field pulse lasting from $t=0$ to $t=\tau$. Let E_2 and E_1 be the two closely spaced energy levels which are considered as possible upper and lower maser levels of H_2O responsible for maser action at the frequency $\omega_0 = (E_2 - E_1)/h$. Finally, let $W=W(E)$ be the perturbation term introduced by the electric field pulse into the Hamiltonian of the individual molecules considered (H_2O for instance). W is constant in time from zero to τ , and is zero outside this short interval. We assume that W can induce transitions between the states E_2 and E_1 , with nonzero matrix elements $W_{12}=W_{12}^*$.

If initially the molecules were in the state E_1 at $t=0$, considering transitions to other more remote states insignificant, we determine the state at a time $0 < t < \tau$ in the usual way as a superposition of the states E_1 and E_2 with amplitudes $a(t)$ and $b(t)$, from the Schrödinger equation:



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$$i\hbar \frac{da}{dt} = W_{11}a + W_{12}b \exp(-i\omega_0 t), \quad (5.1)$$

$$i\hbar \frac{db}{dt} = W_{12}^* a \exp(i\omega_0 t) + W_{22}b. \quad (5.2)$$

Denoting $\omega = \omega_0 + (W_{22} - W_{11})/\hbar = 2\pi f$ and $r = [\omega^2/4 + |W_{12}/\hbar|^2]^{1/2}$, with $a(0) = 1$ and $b(0) = 0$, we obtain the solution

$$a = \exp[-i(\omega/2 + W_{11}/\hbar)t] [\cos rt + (i\omega/2r)\sin rt] \quad (5.3)$$

$$b = -i(W_{12}/\hbar r) \exp[i(\omega/2 - W_{22}/\hbar)t] \sin rt. \quad (5.4)$$

After $t=\tau$ the amplitudes a and b will no longer vary, but will retain the value they will have reached at $t=\tau$. The resulting population ratio R of the two levels after the field pulse is therefore

$$R = |2W_{12}\sin r\tau|^2 / [(hf)^2 + |2W_{12}\cos r\tau|^2]. \quad (5.5)$$



We see that for $\tau = (2n+1)\pi/2$ (i.e., perhaps in 10% of the cases), we obtain a population inversion ($R>1$), provided the perturbation satisfies the criterion

$$2W_{12} \gg hf. \quad (5.6)$$

The matrix element must exceed $E_2 - E_1$. This is very likely if E_1 and E_2 are among the closely spaced pairs of rotational energy levels of the water molecule, and if the field amplitude E is large with abrupt onset and termination. The electric field pulse is assumed to be generated by the return stroke of a lightning flash, but we can not exclude all sudden polarization changes which do not result in a lightning flash as sources of effective field pulses (Handel, 1985).

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Cavitonic Eigenstates and Resonance Frequency

To analyze the developed caviton, we start from three equations:

$$\partial \mathbf{x} / \partial t + \nabla \cdot [(\mathbf{n} + \mathbf{n}') \mathbf{v}] = 0, \quad (6.1)$$

$$(\mathbf{n} + \mathbf{n}') \partial \mathbf{v} / \partial t + (\mathbf{n} + \mathbf{n}') e \mathbf{E} / m + (T / m) \nabla \mathbf{x} = 0, \quad (6.2)$$

$$\nabla \cdot \mathbf{E} = -4\pi e \mathbf{x}. \quad (6.3)$$

Here we have divided the electron concentration in three components: $\mathbf{n}$ is the average electron concentration, constant in space and time, balanced by the average ionic concentration; $\mathbf{n}'$ is a very slow fluctuation, neutralized by an identical fluctuation in the ionic concentration, also including a large time-independent part defining the caviton; the third part $\mathbf{x}$ is the fast fluctuation which can not be followed by the ions. We have considered both $\mathbf{x}$ and the average electron velocity $\mathbf{v}$ small, and neglected terms quadratic in them. The first equation is the equation of continuity for the fast (jitter) motion, the second is the equation of motion expressing the momentum balance, with electron temperature T in energy units. **University of Missouri-St. Louis**

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Eq. (3.3) is Poisson's equation. We neglect the time-derivatives of n' . m is the mass of the electron. Taking the divergence of Eq. (3.2), subtracting the time-derivative of Eq. (3.1), and eliminating x with Eq. (3.3), we obtain

$$\partial^2 \mathbf{E} / \partial t^2 + 4\pi e^2 (n + n') \mathbf{E} / m - T \nabla (\nabla \cdot \mathbf{E}) = 0. \quad (6.4)$$

The fast part of the variation in $\mathbf{E}(t)$ can be expressed through a time-dependent exponential

$$\mathbf{E}(t) = \mathbf{E}_0(t) \exp(-i\omega_p t) + \text{c.c.}, \quad (6.5)$$

where $\mathbf{E}_0$ is a slowly varying amplitude with a negligible second derivative, $\omega_p = 4\pi n e^2 / m$ and c.c. is the complex conjugate of the preceding term. The ponderomotive force of the electric field $\mathbf{E}(t)$ on the plasma of electrons and ions can be derived from an average potential energy

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$$U = |eE_0|^2/4m\omega^2 = e^2\langle E^2 \rangle/2m\omega^2, \quad (6.6)$$

where $\langle \rangle$ is a time average and $\omega \approx \omega_p$ is the actual "fast motion" frequency. Denoting by T_i and T_e the ionic and electronic temperatures in energy units, we expect a Boltzmann distribution of the plasma density

$$n + n' = n_0 \exp[-U/(T_i + T_e)]. \quad (6.7)$$

Introducing the dimensionless field amplitude $\mathbf{A} = e\mathbf{E}_0/\{2\omega[m(T_i + T_e)]^{1/2}\}$, we obtain

$$2i\omega_p \partial \mathbf{A} / \partial t + \omega_p^2 \mathbf{A} [\exp(-|\mathbf{A}|^2) - 1] - l_D^2 \omega_p^2 \nabla(\nabla \cdot \mathbf{A}) = 0. \quad (6.8)$$

Introducing the dimensionless variables $\tau = \omega_p t/2$ and $\mathbf{s} = \mathbf{r}/l_D$, where $l_D = (T_e/4\pi n e^2)^{1/2}$ is the Debye length, we get the fundamental nonlinear "Schrödinger" equation (Zaharov, 1972)

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$$i\partial\mathbf{A}/\partial\tau + \nabla_s(\nabla_s\cdot\mathbf{A}) + [1-\exp(-|\mathbf{A}|^2)]\mathbf{A} = 0, \quad (6.9)$$

which describes both the temporal evolution and the stationary states of the solitons (field structures trapped in the plasma) in terms of the normalized field amplitude $\mathbf{A}$. For stationary spherically symmetric solutions $\mathbf{A}(s, \tau) = (s/s)X(s)\exp(-i\Omega\tau)$, one obtains

$$s^{-2}(\partial/\partial s)[s^2(\partial X/\partial s)] - 2X/s^2 + [1 - \exp(-|X|^2)]X = \Omega X \quad (6.10)$$

with the boundary conditions $X = 0$ for $s = \infty$ and X bounded for $s=0$. Like the stationary Schrödinger equation, this is an eigenvalue equation for Ω . This equation admits stationary localized solutions which we will call cavitons and which are similar to the bound states of quantum mechanics: fundamental ($n=0$) and excited ($n=1, 2, 3, \dots$) modes. Two spherically symmetric solutions of Eq. (3.9) by Zitkova Wilcox and Wilcox (1975) are shown in Fig. 1. The stability of these solitons when they exceed a certain critical size was proven by Laedke and Spatschek (1984).

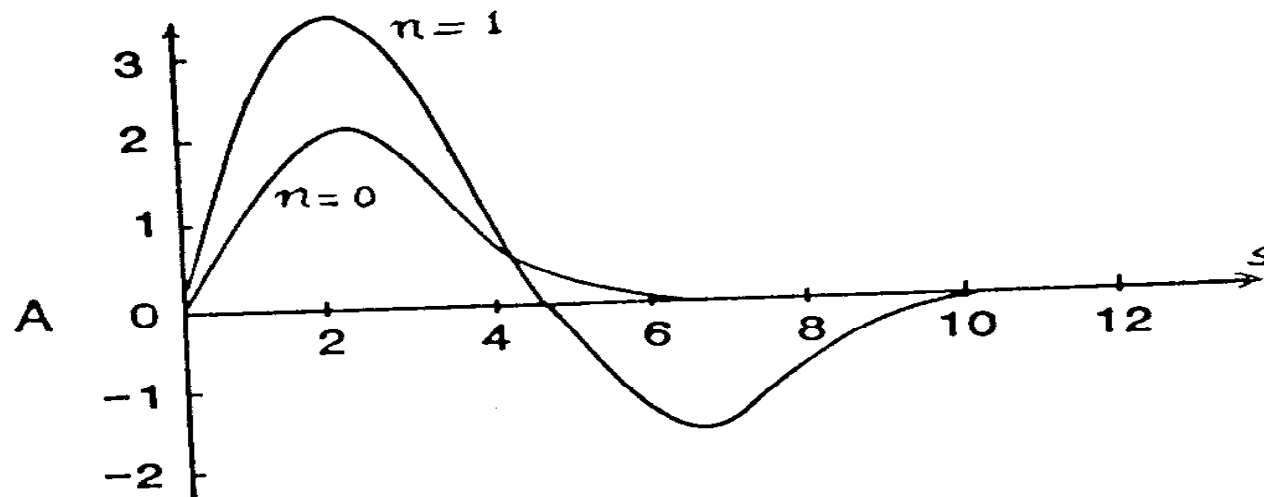


Fig. 1. Fundamental state ($n=0$) and first excited state of a spherical caviton, numerically calculated by Zitcova Wilcox and Wilcox (1975), and recently verified by R.T. Schneider and coworkers, Univ. of Florida - Gainesville (private communication).



7. Suggested Experiments

1. Outdoors Experiment. Both during a thunderstorm and in cloudy, humid, weather without thunderstorm, we will measure atmospheric absorption in the 300-1,000 MHz frequency interval, and determine the reduction caused by the thunderstorm as a function of frequency, as shown below in Fig. 1.

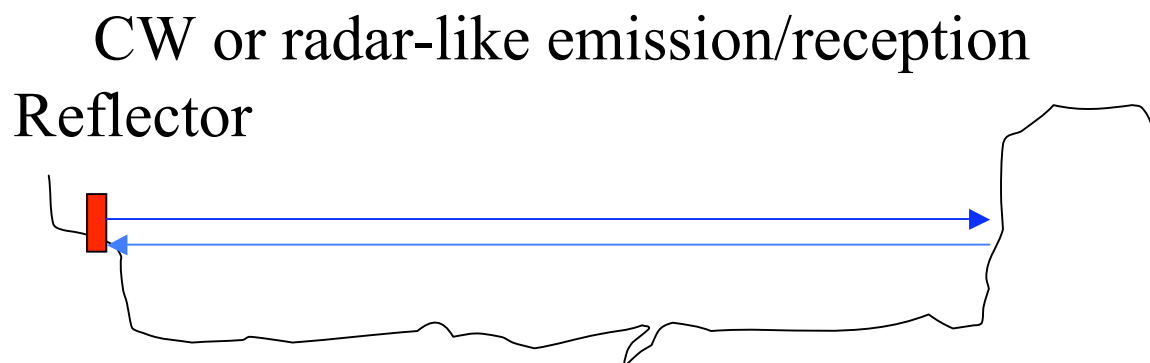
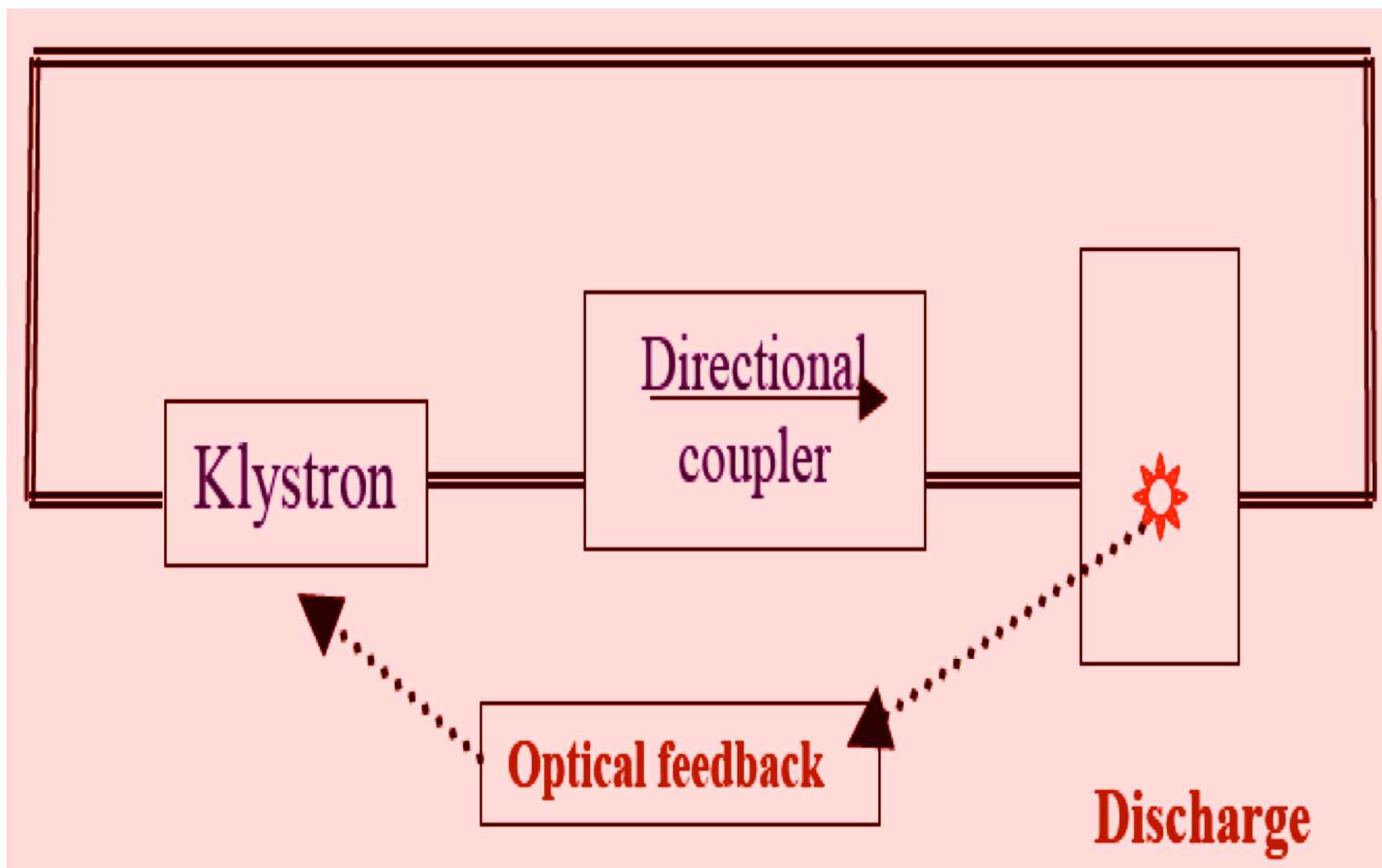


Fig. 4.: Atmospheric absorption spectrum measurements during thunderstorms, over a distance of 1 km, using a tunable VCO, or other generator.





8. CONCLUSIONS

1. BL appears in nature by maser action after a streak lightning-induced field pulse. This explains why it's misunderstood. BL motion and Humming are explained.
2. The universal BL equation determines the temperature of the BL generated by a given population inversion and cavity ringing time (or Q) correctly only if the Fowler-Nordheim cold emission and the spiking behavior are included properly in our BL maser-soliton theory; explains power, effects, nature, conditions of BL explosions.
3. BL can be reproduced artificially with klystron feedback; its origination can be studied in thunderstorm condition by atmospheric RF attenuation spectroscopy.
4. Artificial BL has many applications, can be used to facilitate stand-off coherent THz agent detection at miles from the base stations, with or without reflectors.
5. BL plasma localizes and greatly enhances THz generation and detection.
6. BL is similar to high power fs laser pulse self trapping and filamentation, with nonlinear ponderomotive force effects involved in both cases.



9. References

Arago, F. (1838), *Annuaire*, Bureau des Longitudes, Paris.

Arago, F. (1854), *Oeuvres completes*, Vol. 4, Claye, Paris.

Brand, (1923), *Der Kugelblitz*, Henri Grand, Hamburg.

Handel, P.H. (1975), *Maser theory of ball lightning*, Bul. Amer. Phys. Soc. Ser. II, 20, 26.

Handel, P.H. and Schneider, R.T. (1985), *Nature of resonances leading to high-pressure cavitons*, Fusion Technology, 7, 320-324.

Handel, P.H. (1988), *Maser-caviton ball lightning mechanism*, Proc. VIII Int. Conf. on Atmospheric Electricity, Uppsala University Press, Uppsala, Sweden, pp. 177-182.

Handel, P.H. (1989), *New approach to ball lightning*, in Science of ball lightning, Yoshi-Hiko Ohtsuki, Editor, World Scientific Publ. Co. 72 Lynton Mead, London N20 8DH, UK, pp. 254-259.



Handel, P.H. and J.F. Leitner (1994) “Development of the Maser-Caviton Ball Lightning Theory”, J. of Geoph. Research, 99, 10,689-10,691.

Handel, P.H. (1985), *Polarization catastrophe theory of cloud electricity*, J. Geophys. Res. 90, 5857-5863.

Kapitsa, P.L. (1955), Doklady Akademii Nauk SSSR, 101, 245.

Kapitsa, P.L. (1970), Soviet Physics JETP 30, 973.

Laedke, E.W., and K.H. Spatschek, (1984) *Stable three-dimensional envelope solitons*, Phys. Rev. Lett. 52, 279-282; *Stability properties of multidimensional finite-amplitude solitons*, Phys. Rev. A 30, 3279-3288.

Ohtsuki, Y.H., and H. Ofuruton (1991), Nature 350,139.

Singer, S. (1971) “The nature of ball lightning”, Plenum Press, NY.

Zaharov, V.E., (1972) Zh. Eksp. Teor. Fiz. 62, 1745,1972.

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Zitkova Wilcox, J., and T.J. Wilcox, (1975), Phys. Rev. Lett. 34, 1160.

A.V. Zvonkov, A.B. Timofeev and P.H. Handel: “On the Stability of Low Temperature States of the VHF discharge at High Pressure,” Plasma Physics Reports, v. 26, Issue 9, pp. 801-808, Sept. 2000.