

PLASMA PHYSICS GROUP

N72-29117

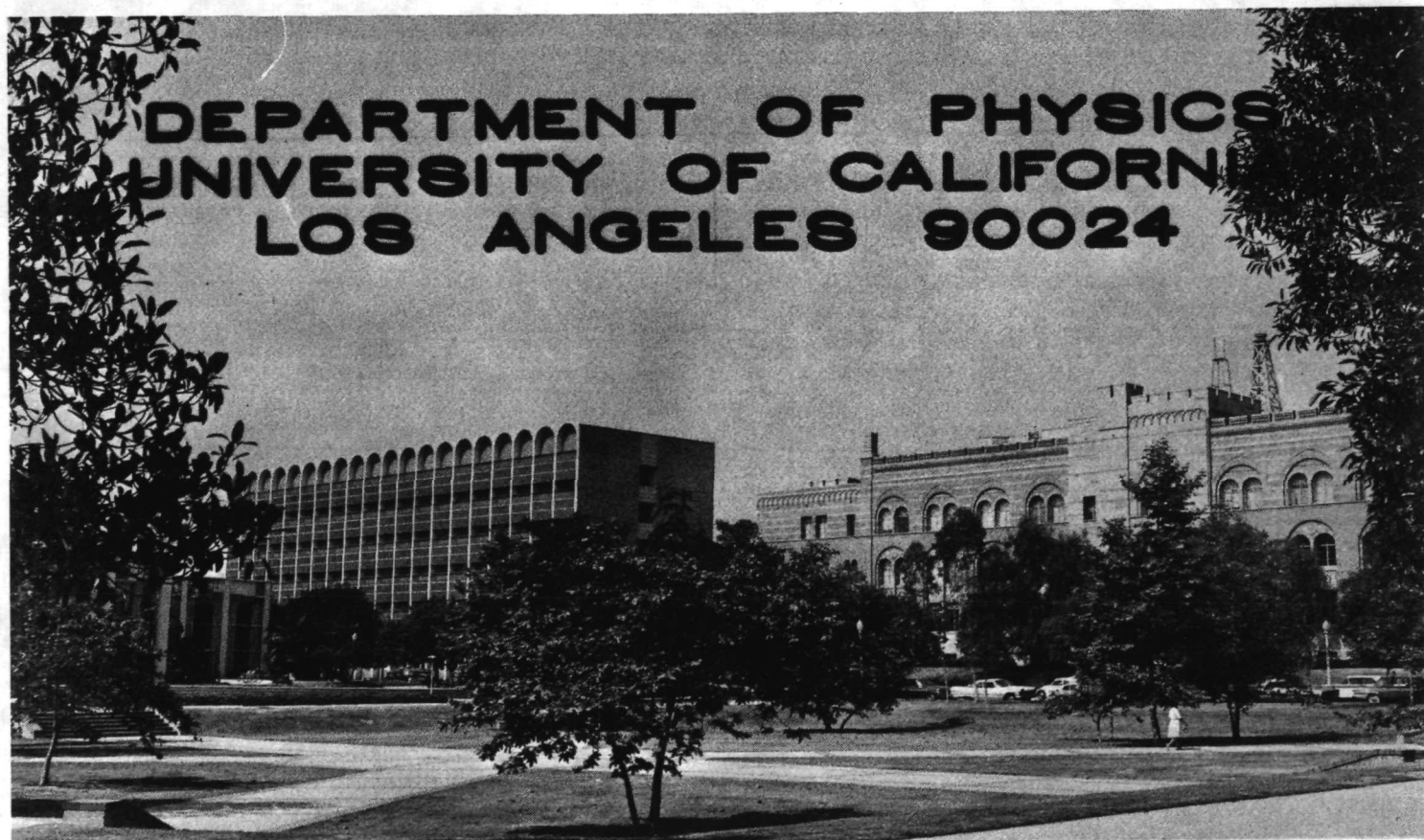
Remote Double Resonance Coupling of Radar Energy
to Ionospheric Irregularities

Charles F. Kennel

**CASE FILE
COPY**

January 1971

R-85



Remote Double Resonance Coupling of Radar Energy
to Ionospheric Irregularities

Charles F. Kennel

**CASE FILE
COPY**

January 1971

R-85

Plasma Physics Group
Department of Physics
University of California
Los Angeles, California 90024

This work was partially supported by the Office of Naval Research, Grant #N00014-69-A-0200-4023; The National Science Foundation, Grant #GP-22817; the Atomic Energy Commission, Contract AT(04-3)-34, Project #157; and the National Aeronautics and Space Administration, Contract #NGL-05-007-190.

Remote Double Resonance Coupling of Radar Energy
to Ionospheric Irregularities

The purpose of this note is to communicate to the readers of Comments on Astrophysics and Space Physics a suggestion for an interesting ionospheric modification experiment by A. Y. Wong, D. Arnush, B. D. Fried, C. F. Kennel, R. J. Taylor, and N. Booth of the TRW Systems Group, Redondo Beach, California. This idea stems from the laboratory work of A. Y. Wong, D. Baker, and N. Booth at UCLA. Earlier related proposals involving nonlinear interactions of a radar beam with the ionosphere have been made by Wong⁽¹⁾ and by Gurevich and Schvartzburg.⁽²⁾

Recent laboratory experiments⁽³⁾ indicate that collisionless nonlinear interactions between a high frequency carrier beam and low frequency ion modes occurs at sufficiently low power levels that remote production of ionospheric irregularities may be feasible. A microwave carrier tuned to a critical (electronic) frequency for one radial position in a laboratory Q-device and modulated at low (ionic) frequencies produces a large amplitude response within the plasma whenever the modulation frequency equals one of the natural ionic eigenfrequencies, corresponding to electrostatic drift waves and ion cyclotron harmonic waves. An unmodulated beam also excites similar oscillations, but only at higher power. As applied to the ionosphere, a high power radar would beam a carrier signal, typically with frequencies $f < 10$ MHz, at the ionosphere. For a given frequency and polarization, the carrier will encounter either a propagation cutoff or resonance, where the interaction with low frequency waves peaks. This interaction region would be localized in altitude. The carrier would then be modulated at a low frequency, corresponding to one of the resonant eigenfrequencies of the ionosphere. By tuning the carrier frequency, one could select the altitude region where irregularities would be produced; by tuning the modulation frequency, one could select the low frequency irregularity to be produced. Because both the interaction region and low frequency modulation are resonant, this technique has been called "Double Resonance Modulation."

Radiation of the ionosphere with an unmodulated 2 MW 5-10 MHz radar beam may have already produced such nonlinear interactions.⁽⁴⁾ The Boulder radar appeared to trigger spread-F, which was observed on a

separate low power ionosonde probe, some tens of seconds after the high power heating pulse was turned on, at altitudes near the reflection points for the heater beam. In addition, density and temperature changes in the background ionospheric plasma were observed, as well as enhanced absorption of a probing ionosonde signal, when the high power beam was illuminating the plasma. A possible interpretation of the induced spread-F might be that low frequency waves, such as the drift or ion cyclotron waves produced in the laboratory, may have been created. These would lead to field aligned density irregularities. If so, laboratory experience indicates that modulation of the carrier should produce an even more clearcut result.

The laboratory Q-machine and ionospheric F layer have similar temperatures, $T_i \sim T_e \sim 0.1-0.2\text{ev}$. The electrons may be considered collisionless in both cases. While typical laboratory power densities used ($10-50 \mu\text{w}/\text{cm}^2$) are 10^5 higher than those available in the Boulder experiments ($50 \mu\text{w}/\text{m}^2$), this may not be serious since the time during which an electron is exposed to coherent radiation is much longer in the ionosphere than in the laboratory. Since the radar beam illuminates a large region of the ionosphere, its interaction with electrons is not limited by transit time, but by the electron-ion collision time, $\approx 10^{-3}$ seconds; in the laboratory, the electron transit time across the waveguide (10^{-7} seconds) limits the interaction. Thus the ratio of these interaction times ($\tau_{\text{ionosphere}}/\tau_{\text{lab}} \approx 10^4$) exceeds the ratio of the electric fields in the two cases ($E_{\text{lab}}/E_{\text{ionosphere}} \approx 10^2$).

A.) Discussion of Carrier Interaction Regions

The polarization of the carrier may be either in the ordinary (O) or extraordinary (X) mode, according to whether the oscillating carrier electric field is parallel to (O) or perpendicular to (X) the ionospheric magnetic field. The ray paths for the two polarizations will differ, but more importantly, the cutoffs and resonances differ. When the O-mode carrier encounters its plasma cutoff--that region in the ionosphere where its frequency matches the local plasma frequency--the index of refraction goes to zero, and the wave is reflected back to Earth. However, near the reflection point, its electric field is enhanced, due to the fact that its group velocity goes to zero, and its energy piles up near the reflection point. Clearly, this region will be a preferred one for nonlinear interactions.

An X-mode carrier also encounters a propagation cutoff at that ionospheric layer where its frequency matches the right hand cutoff frequency, $f_{RHC} = f_c/2 + \sqrt{f_c^2/4 + f_p^2}$. Amplitude enhancement also occurs at X-mode cutoff, so that the RHC layer is a preferred region for nonlinear excitation. Both X and O mode cutoffs are accessible to a ground-based radar. However, the X-mode can have another preferred coupling region at the upper hybrid resonance (UHR), where the carrier frequency matches $f_{UHR} = (f_p^2 + f_c^2)^{1/2}$. Cold plasma wave propagation theory predicts that the index of refraction goes to infinity, and consequently, that the wavelength goes to zero. In this situation, the driving electric field of the carrier can produce oscillating electron orbits whose spatial excursions are comparable to the carrier wavelength at upper hybrid resonance, thereby leading to another nonlinearity in the plasma response.

In both the Q-machine and F-region, the UHR layer is separated from

Figure 1. Experimental Arrangement. The stimulating wave is generated by the generator G1, modulated, and then radiated on the plasma. The ion waves are detected by monitoring the transmission of S-band waves from the generator G2, through the plasma, to the detector D2.

Figure 2. Amplitude response of the plasma monitored by D2 vs. the modulation frequency on the incident wave; $n \approx 10^9 \text{ cm}^{-3}$, $B = 1.25 \text{ KG}$. Density gradient waves of azimuthal number $m = 1, 2$ and electrostatic ion cyclotron waves near ω_{ci} and $2 \omega_{ci}$ are shown.

the RHC reflection point by an evanescent layer in which the wave amplitude decays exponentially. UHR excitation requires tunnelling through this evanescent region; therefore UHR couplings will be particularly strong when the RHC and UHR layers are close together. In the laboratory, these layers are separated by a freespace wavelength, whereas in the unperturbed ionosphere, the separation distance is of order 10^2 wavelengths, based upon a 40 km density scalelength. However, the ionospheric density profile could be sharper than this for a variety of reasons. For example, sharp density irregularities do occur naturally. Moreover, ionospheric heating by the carrier may alter the density profile. Such profile sharpening has been observed in the laboratory⁽³⁾, and may have been observed in the ionosphere.⁽⁴⁾

In summary then, 0-mode couplings are strongest at the plasma cutoff, whereas X-mode couplings can occur at both the right hand cutoff and upper hybrid resonance layers.

B.) Nonlinear Production of Low Frequency Modes

Given a nonlinear coupling to low frequency waves, one must distinguish between two general methods of excitation.

1. Excitation by unmodulated carrier.

In parametric excitation, one large amplitude high frequency carrier drives a low frequency "signal" wave and an "idler" wave, whose frequency matches the difference of the driver and signal frequencies. A low frequency wave initially present at low amplitude as part of the noise spectrum will be amplified. Amplification occurs, however, only if the carrier power exceeds an absolute threshold which depends upon the wave damping rate and upon the convection of the signal or idler waves out of the illuminated region of the ionosphere. Moreover, this threshold depends upon the initial noise amplitude of

the signal. Parametric excitation takes advantage only of the propagation resonance. Moreover, the low frequency waves generated depend upon the state of the ionosphere, will therefore vary from day to day, and are not under the control of a ground-based radar.

Kaw and Dawson⁽⁵⁾, and the references therein, discuss the excitation of a low frequency waves by a high power carrier, via the so-called "oscillating two-stream" instability. While directed towards the problem of laser heating of dense unmagnetized plasmas, these calculations could presumably be easily extended to the magnetized ionospheric plasma. When collisions are included, there is a carrier power threshold for instability.

2. Mode coupling or double resonance excitation.

Here, two large amplitude high frequency waves drive a low frequency wave at the difference frequency of the high frequency waves. The difference frequency is just the modulation frequency imposed upon the carrier. This, of course, will amplify fluctuations. More importantly, it will produce waves even if they are not favored in the natural spectrum. The response is large when the modulation frequency equals one of the natural eigenfrequencies of the plasma. Because mode-coupling is independent of the initial spectrum, there is no real threshold for this effect, although loss mechanisms play a role in determining at what carrier power desirable or detectable effects occur.

Mode-coupling takes advantage of the second resonance in the plasma response. By choosing the modulation frequency, one can choose which low frequency mode to produce (impossible with parametric couplings); by varying the modulation amplitude, one can control the strength of the nonlinear coupling rate -- again impossible with

single resonance. These advantages make a compelling argument for modulating the radar carrier.

III. Description of Laboratory Results

The laboratory arrangement shown in figure 1 may be viewed as a scale model of the hypothetical interaction between an ionospheric plasma and a ground transmitter. The experiment was performed in a highly ionized potassium plasma beam produced in a Q-device with a magnetic field parallel B_0 parallel to the beam axis. Microwave power, at an S-band carrier frequency (2-4 GHz) corresponding to the range of plasma, right hand cutoff and upper hybrid frequencies in the column, is radiated by a waveguide located outside the chamber at G1; O and X mode excitations can be produced by proper orientation of the waveguide with respect to the magnetic field. The low frequency waves generated in the plasma can be measured by Langmuir probes within the plasma, or remotely by measuring the frequency modulation of a pure tone S-band wave transmitted through the plasma, produced at G2 and detected at D2.

Figure 2 shows the perturbed oscillating electron density $n^1(fm)$ normalized to the equilibrium density n_0 for X-mode upper hybrid resonance coupling. The modulation frequency f_m was swept through the range 0-1 MHz. An enhanced response was detected whenever f_m matched one of the eigenfrequencies of the Q-machine plasma. Drift waves, with $m=1$ and 2 azimuthal mode numbers, due to density gradients, were stimulated. Edge oscillations, a form of drift wave due to temperature gradients at the edge of the plasma column, were also produced. Finally, a spectrum of electrostatic ion cyclotron waves, with frequencies near but slightly above the ion cyclotron frequency ($1.2 f_{ci}$) and its

harmonics (up to 7th) were generated. All these modes are electrostatically polarized and propagate nearly perpendicular to the magnetic field and lead to field aligned density modulations. Preliminary experiments indicate that irregularities at the lower hybrid resonance frequency could be so produced as well.

Other features of this experiment may be summarized as follows:

(13) (1) An input microwave flux as low as 0.3 mw/cm^2 is sufficient to excite waves with $n^1/n_0 = 5\%$. Since the wave damping mechanisms are machine dependent, this efficiency should not be extrapolated to the ionosphere.

(2) The excitation occurs in frequency and density regions such that $f_{\text{UHR}} \lambda_{ee} = 10^4 \gg 1$ and $\frac{\omega}{\omega_{ci}} \lambda_{ei} > 1$, where λ_{ee} is the electron-electron collision time, $\frac{\omega}{\omega_{ci}}$ the ion cyclotron frequency, and λ_{ei} the electron ion energy exchange time. We believe that a collisionless nonlinearity, rather than a random collisional process, is responsible for the observed coupling.

(3) Excitation by a modulated carrier is a factor 3-10 more efficient than by an unmodulated carrier.

(4) Similar excitations have been observed at X-mode right hand cutoff and at O-mode plasma cutoff. In general, the coupling coefficients for the X-mode resonance, X-mode cutoff, and O-mode cutoff to low frequency modes are approximately in the ratios 20:10:1, where accessibility to X-mode upper hybrid resonance is no problem.

IV. Summary

Laboratory experiments suggest that low frequency modulation of a high power radar beam, tuned to one of the critical frequencies of the ionosphere, may produce field-aligned density irregularities

when the modulation frequency matches that of an ionospheric eigenfrequency. By choosing the radar carrier frequency and polarization, a number of interaction layers can be selected. In addition there are a large number of resonant eigenmodes of low frequencies which could be excited by nonlinear coupling. Each of the waves is different, and of course their properties may vary with the ionosphere from day to day; however, all the couplings may be investigated simply by sweeping the radar modulation frequency through the whole range of expected frequencies. The variety of possible excitations indicates that the double resonance technique may be adaptable to a number of different objectives.

communicated by C. F. Kennel

BIBLIOGRAPHY

- (1) A. Y. Wong, "Nonlinear Excitation in the Ionosphere"
UCLA plasma physics Group Report R-44, 1968.
- (2) A. V. Gurevich and A. B. Schvartzburg
Geomagnetism and Aeronomy (in English), 8, 893, 1968
- (3) A. Y. Wong, D. Arnush, B. D. Fried, C. F. Kennel, R. J. Taylor, and
N. Booth
Submitted to Physical Review letters, (1971)
- (4) "Radio Wave Modification of the Ionosphere", a series of papers in
Journal of Geophysical Research, 75, 6402-6446, 1970
- (5) P. K. Kaw and J. M. Dawson
Physics of Fluids, 12, 25B6, 1969.

Collisionless: $\omega_{UH} \tau_{ee} \gg 1$, $\omega_i \tau_{ei} \gg 1$

