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TRIGGERING THE HF BREAKDOWN OF THE ATMOSPHERE BY BARIUM RELEASE

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Abstract. RF ionization rates for mixtures of air with barium are computed using a Fokker-Planck code. It is shown that there is an optimum mixing ratio of barium to air, significantly lower than unity, which maximizes the ionization rate for a given value of incident RF power density and frequency. Rocket injection of barium at a selected height reduces significantly the RF breakdown threshold for the mixture, and allows atmospheric and ionospheric breakdown at the selected heights using the radiation from the powerful HF radio facilities. The possibility of field experiments using currently available or projected HF heaters is discussed.

Introduction

To assess the technological requirements for creating artificial ionospheric layers [Borisov et al., 1986] using ground based radio frequency (RF) transmitters, the ionization rate of the air as a function of the RF frequency and the incident power density is a required input. A comprehensive study of the subject using numerical solution of a Fokker-Planck (FP) code was published recently [Tsang et al., 1991]. The results of the study are summarized in a convenient form in Figure 1, which shows the effective ionization rate per ambient neutral ν_i/N as a function of the quiver energy, defined as

$$\tilde{\epsilon} = \frac{1}{2}m\frac{e^2E_o^2}{m^2\left[(\omega \pm \omega_c)^2 + \nu_o^2\right]} \qquad (1)$$

where m is the mass of the electron, e is its charge and ω and E_0 are the frequency and amplitude of the radio wave. Also ω_c is the electron cyclotron frequency, and the $\pm$ signs refer to "O" and "X" polarization. In practical units the quiver energy is expressed as

$$\tilde{\epsilon} = 1.68\frac{P}{\left[(f \pm f_c)^2 + \left(\frac{\nu_o}{2\pi}\right)^2\right]}\ \mathrm{eV} \qquad (2)$$

where P is the power density of the RF field in W/m^2, and the frequencies are in MHz. The results shown by the curve 1 in Figure 1 apply for $\omega >> \nu_o$, where ν_o is the maximum electron-neutral collision frequency which for a neutral density N(#/cm^3) is given by

$$\nu_o = 1.7 \times 10^{-7}\mathrm{N\ sec}^{-1} \qquad (3)$$

The purpose of this paper is to determine whether the ionization rates for RF breakdown can be increased using an admixture of a low ionization potential gas. For concreteness this study is confined to use of Ba.

Superficially one would expect that under the same irradiation conditions the RF ionization rate for a low ionization potential species such as Ba, would be larger than air. It is shown here that this is not the case. The results of Section 2, indicate that the ionization rate for pure Ba is lower than that of air, due to high inelastic losses at low energies. However, by judiciously choosing the proportions of the air/Ba mixture, ionization rates in excess of those of air can be achieved under the same irradiation conditions. The plan of the paper is as following. The next section uses the FP code of Tsang et al. [1991], modified to include the atomic physics of Ba, to determine the ionization rate of air/Ba mixtures as a function of the incident quiver energy. Section 3 uses a one dimensional code to demonstrate that a proof of principle experiment is possible using the NIIR HF facility located in the vicinity of Moscow or the HAARP heater currently under construction. The final section summarizes the results and speculates on the possibility for maintaining the ionized cloud after the Ba admixture has been diluted.

Ionization Rates for Air/Ba Mixtures

The FP code used in this study has been described in Tsang et al. [1991] and Short et al. [1990]. It is based on the numerical solution of the Boltzmann equation in the Fokker-Planck approximation and includes energy transfer due to both elastic and inelastic collisions of electrons with molecular nitrogen and oxygen. For the present study it has been generalized to include the effects of collisions of electrons with Ba atoms. The ionization and momentum transfer cross sections were taken from Detman and Kartensen [1982] and Romanyuk et al. [1980] and Jensen et al. [1978] respectively. The important cross section for the allowed $6s^1S_o \rightarrow 6p^1\,P_1^o$ transition was taken from the latter paper, while the excitation rate of the electronic levels $6p'^1P_1^o$, $7p^1\,P_1^o$ was estimated using the Rigemorter formula [Van Rigemorter, 1962]. The oscillator strengths for these levels were adapted from Radzig and Smirnov [1985]. Finally, the cross section for the $5d\,^1D_2$ level was adapted from Sobelman et al. [1981].

Before presenting the results we should comment that the net ionization rate for air shown by curve 1 in Figure 1, is negative below a value of $\tilde{\epsilon}$ = .1 eV. This corresponds to the well known "idealized" threshold value for breakdown [Borisov et al., 1986; Short et al., 1990]. For lower values of the quiver energy the electron density is in fact decreasing because the electron loss rate due to the O_2 dissociative attachment exceeds the ionization rate. Curve 2 in Figure 1 shows the ionization rate per neutral for the pure Ba case. Notice that for values of $\tilde{\epsilon}$ in excess of the threshold the ionization rate is lower than the one corresponding to air.

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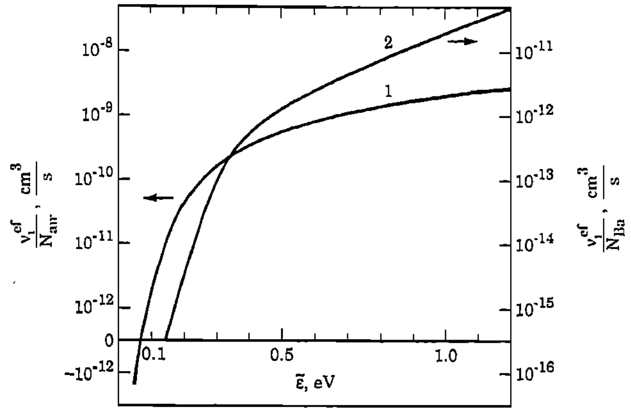

Fig. 1. The effective ionization rate per molecule of air (curve 1), and Ba (curve 2) depending on the electron quiver energy.

However, for pure Ba there are no losses and the value of the threshold is determined by the pulse length of the RF or the electron transport.

The results of Figure 1 should be contrasted to the results for mixtures shown in Figures 2 and 3. Figure 2 shows the ionization rate per neutral as a function of the mixing ratio for values of $\tilde{\epsilon}$ = 0.021, 0.042 and 0.084 eV. It can be seen that the rate maximizes for mixing ratios in the vicinity of 3 × 10^{-3}. The value of the rate at maximum exceeds that of the air by about an order of magnitude for the same value of $\tilde{\epsilon}$. Figure 3 shows the ionization rate as a function of $\tilde{\epsilon}$ for two mixing ratios at the height of 50 km. It demonstrates the presence of an effective threshold of the order of .05 eV, below which the ionization rate falls faster than exponentially. This threshold value is much lower than the corresponding for air.

The physics involved in the above results can be understood by examining the electron distribution function f(ϵ) under various conditions. Figure 4 shows f(ϵ) for a value of quiver energy .02 eV, for various mixing ratios. The top and bottom curves correspond to pure air and Ba. For pure Ba inelastic losses in the vicinity of 2 eV prevent significant electron energization to the Ba ionization energy of 5 eV. The

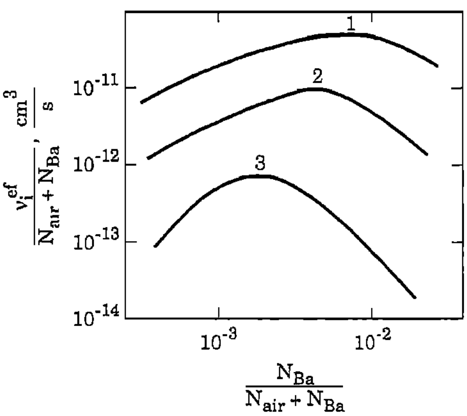

Fig. 2. The effective ionization rate per molecule of the Ba+air mixture depending on the Ba fraction. Curve 1 corresponds to the quiver energy $\tilde{\epsilon}$ = 0.084 eV, curve 2 - $\tilde{\epsilon}$ = 0.042 eV, curve 3 - $\tilde{\epsilon}$ = 0.021 eV.

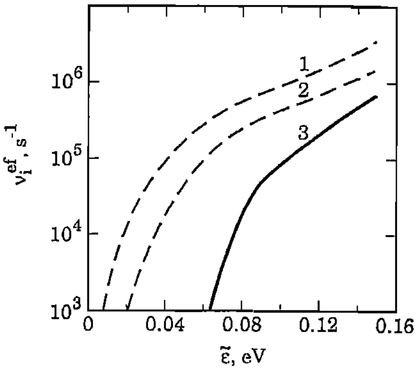

Fig. 3. The effective ionization rate of the Ba+air mixture depending on the quiver energy. Broken curve 1 corresponds to the Ba fraction of 10^{-3}, broken curve 2 to the fraction of 3×10^{-4}. Solid curve 3 shows the effective ionization rate in air for the density of 2.2×10^{16} cm^{-3}, which corresponds to the atmospheric height of 50 km.

pure air case shows the importance of the runaway properties of the elastic electron-neutral collision frequency [Tsang et al., 1991], which drive a strong non-Maxwellian tail. However, since the ionization energy of air is high it does not result in net ionization. By combining the runaway properties of the electron energization in air with the low ionization threshold of Ba, a high ionization rate can be achieved for appropriate mixtures.

A Proof of Principle Experiment

The potential for a proof of principle experiment using the NIIR heater located in the vicinity of Moscow [Shluyger, 1974] is examined next. The heater operates at a frequency of 1.35 MHz, near the electron gyrofrequency, and has an effective radiative power (ERP) of 90 dBW when operating on a pulse mode with .4 msec pulse width and 50 Hz repetition rate. A one-dimensional (1-D) kinetic calculation that includes effects of self-absorption has been performed to examine the possibility of a proof of principle experiment.

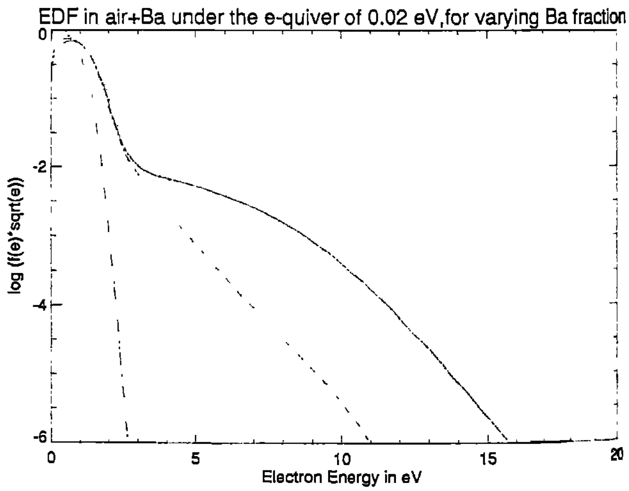

Fig. 4. The electron distribution function f(e) of the air+Ba mixture irradiated by the HF emission depending on the Ba fraction. The electron quiver energy is .02 eV. From top to bottom are: f(e) in air, in the mixture where Ba fraction is 10^{-3}, 10^{-2}, and in a pure Ba.

The relevant region of the ionosphere is modeled as a plane stratified medium divided into a series of thin slabs, each with thickness much less than an absorption length. The HF pulse is divided in a series of subpulses that propagate through the stratified medium. The interaction of the HF with the ionosphere in each thin slab is modeled by a fully kinetic Fokker-Planck code, whose output is the electron distribution function $f(\epsilon, t)$.

From the value of $f(\epsilon, z, t)$ and by integrating over the appropriate cross sections the ionization rate $\nu_i(z,t)$ and the elastic collision frequency $\nu_e(z,t)$ are computed. The density increase is found from

$$\frac{dn(z,t)}{dt} = \nu_i(z,t)n(z,t) \tag{4}$$

while the value of the electric field E will be given by

$$\frac{dE(z,t)}{dz} = -R(z)K(z,t)E(z,t) \tag{5}$$

In eq. (5) R(z) describes the geometric spreading of the wave, while the absorption index K(z, t) is given by

$$K(z,t) = \frac{\nu_e(z,t)\omega_e^2(z,t)}{c\left\{(\omega \pm \omega_c)^2 + \nu_e^2(z,t)\right\}} \tag{6}$$

ω_e is the plasma frequency.

The following computational procedure has been applied. The leading part of the HF pulse, which is represented by a subpulse of the duration Δt_1, propagates along the undisturbed media. The amplitude of this subpulse is obtained in each of consequent slabs using eqs. (5), (6), in which $\nu_e(z)$ and $\omega_e(z)$ correspond to the ambient ionosphere. Following F-P calculations provide the disturbed values of $\nu_e^1(z, \Delta t_1)$, $\nu_i^1(z, \Delta t_1)$ in each of the slabs. Then the increasing electron density $n^1(z)=n(z, \Delta t_1)$, is found in each of the slabs from eq. (4) when applying the value of $\nu_i^1(z, \Delta t_1)$. The propagation of the next subpulse is described by the eqs. (5), (6) where $\nu_e=\nu_e^1$, and $\omega_e=\omega_e^1(n^1)$. Then this procedure is continuing.

The results of Figure 5, correspond to an injection of Ba cloud at an altitude of 90 km. The cloud was taken as Gaussian with a 1 km radius, a peak at 90 km and Ba to air mixing ratio at the peak of 0.5×10^{-2}. For a typical ambient neutral density of 6×10^{13}#/cm^3, such a cloud requires a release of about 20 kg of Ba. The temporal evolution of the electron density as a function of altitude and time for X-mode gyrofrequency heating, is shown in Figure 5. The electron density is limited by self-absorption to a peak value of 10^4#/cm^3. This density can be reached by using 700 pulses with pulse width of .4 ms and a repetition rate of 50 Hz, for a total irradiation of 14 s. Superimposed on the electron profile is the vertical profile of Ba. The calculation neglects electron losses over the 14 s time-scale. This is justified since the electron-ion recombination time for 10^4#/cm^3 is 350 s and the transport due to winds for a 1 km cloud at 90 km exceeds 100 s.

Ba assisted atmospheric breakdown can also be accomplished using the HAARP heater currently under construction. The heater is projected to operate on a continuous mode in the 3–10 MHz range with 87–95 dBW ERP. Our analysis shows that by injecting Ba with a mixing ratio of 2×10^{-3} breakdown times of the order of 1 minute can be achieved.

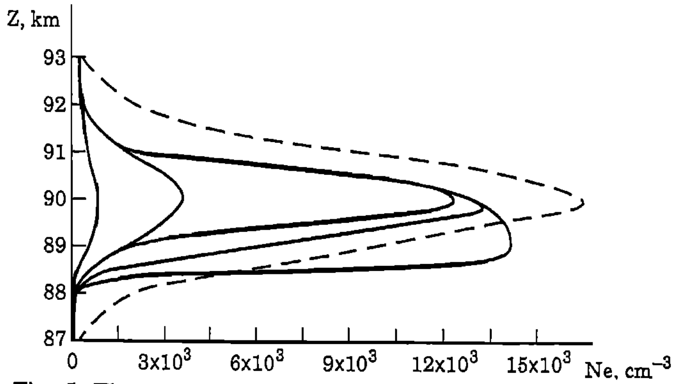

Fig. 5. The temporal evolution of the electron concentration profile. The subsequent solid curves from the left to right correspond to 55, 110, 165, 220, 275 ms of the HF heating. Broken curve shows the spatial distribution of the Ba cloud, where Ba density is reduced 5×10^7 times.

This is faster than losses due to wind driven plasma convection.

Summary and Conclusions

It was shown above that the presence of an admixture of .5% Ba in the D region can increase significantly the RF ionization rate of the mixture over that of the air. Following breakdown the majority of ions will be Ba^+. An important follow-up issue is to what extent the ionization can be maintained after the neutral Ba release has been convected away from the field of the heater. From Figure 1 and from analysis of Borisov et al. [1986], Short et al. [1990], and Tsang et al. [1991] the ionization will be maintained if the ionization rate balances the O_2 dissociative attachment. To achieve this we need a value of $\tilde{\epsilon}$ of the order of .1 eV which is in excess of the requirements for ionization of the mixture. At this point, however, we note that the existence of the ionized cloud offers the potential for amplification of the local electric field due to the swelling factor in the vicinity of resonance [Ginzburg, 1964]. The maximum amplification in the quiver energy is given by

$$\tilde{\epsilon}_{res} = \tilde{\epsilon} \times 3.6 \times \left(\frac{\omega L}{c}\right)^{1/3} \tag{7}$$

where L is the shorter of the density gradient or collisional absorption length. In practical units this can be written as

$$\tilde{\epsilon}_{res} = 10 \times \tilde{\epsilon} \times \left(\frac{L}{km}\right)^{1/3} \times \left(\frac{f}{MHz}\right)^{1/3} \tag{8}$$

A tenfold amplification of the local power density is more than adequate to maintain the ionization in the presence of even substantially greater losses than dissociative recombination.

In summary we have demonstrated that injection of small amounts of Ba in the atmosphere substantially reduces the effective radiative power required for atmospheric and ionospheric breakdown. We have, furthermore, shown, in an admittedly speculative fashion, that the Ba release can be used as the igniter of a long duration ionization patch. The enormous mesospheric diagnostic potential of artificial ionization through the detection of optical emissions [Papadopoulos, 1990], warrants that the concepts discussed here be assessed experimentally in the atmosphere and the laboratory. A detailed analysis of mesospheric diagnostics using Ba injection in conjunction with the HAARP ionospheric heater currently under development, will published elsewhere.

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