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14. ABSTRACT
Several comprehensive studies of rf breakdown and rf heating are reported. They are of general interest to magnetic confinement fusion, rf linacs, and high power microwave source development. The major results include: (1) ground-breaking theory of multipactor on dielectric, including a successful proof-of-principle experiment that verified the newly developed scaling laws, (2) in depth investigation of the failure mechanisms of diamond windows and ceramic windows, of the roles of graphitization, thin films of coatings and contaminants, and (3) a most comprehensive theory, to date, on the heating of particulates by an electromagnetic pulse, on the separate roles of rf magnetic field heating and of rf electric field heating, including the construction of new scaling laws that govern them. The above form a valuable knowledge base for the general problem of heating phenomenology.

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Final Technical Report

Analysis of Multipactor Discharge

DoE Grant *DE-FG02-98ER54475*
[University of Michigan Contract No.: C036858]

Submitted to

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Summary

Presented herein is the Final Technical Report on the multi-year DoE grant, DE-FG02-98ER54475, “Analysis of Multipactor Discharge”. Several comprehensive studies of rf breakdown and rf heating have emerged. They are of general interest to magnetic confinement fusion, rf linacs, and high power microwave source development. The major results of this research include: (1) ground-breaking theory of multipactor on dielectric, including a successful proof-of-principle experiment that verify the newly developed scaling laws, (2) in depth investigation of the failure mechanisms of diamond windows and ceramic windows, of the roles of graphitization, thin films of coatings and contaminants, and (3) a most comprehensive theory, to date, on the heating of particulates by an electromagnetic pulse, on the separate roles of rf magnetic field heating and of rf electric field heating, including the construction of new scaling laws that govern them. The above form a valuable knowledge base for the general problem of heating phenomenology.

The research has been highly interactive. The DoE-sponsored workshops, the feedback from the presentations at conferences, tele-conferences, and industrial site-visits enabled the Investigator to address major concerns of the rf community. As an example, CPI performed an experiment on a broken diamond window to test the Investigator’s theory even before the theory’s publication. This in turn has led to new areas of research. There have also been collaborations, to various degrees, with UC Berkeley, Argonne National Lab, and L-3 (formerly Litton) throughout the course of this research.

It should be stressed that this DoE Grant has been used primarily to support and to train graduate students. Four (4) completed PhD theses have been supported by this Grant, either fully or predominantly. The fifth PhD student has been supported up to the termination of this Grant. The research findings have been fully documented and disseminated, quite a few with acknowledgment of this DoE Grant as primary or sole support. The pdf files of the refereed, archival publications supported by this DoE Grant are attached separately.

Table of Contents

I. Introduction

Multipactor discharge may occur whenever an AC electric field exists on a surface that is under some vacuum condition. Its presence is known to threaten space communication systems, accelerator structures, antennas, various microwave components and even solar panels (through a closely related process). While the basic phenomenon is well-known, there have been remarkably few supporting theories on the subject. For example, prior to the submittal of this DoE proposal (DE-FG02-98ER54475), there was only one theory paper on multipactor on a dielectric surface and that paper was published in 1961.

Subsequent to the submission of the proposal, the Investigator and his students provided the definitive theory of multipactor on dielectric. These include the construction of the susceptibility diagram that determines the necessary conditions (in terms of rf frequency, rf power, secondary electron yields, and the degree of dielectric charging) under which the multipactor could occur on a dielectric [1]. This is followed by a first attempt on the dynamical evolution and saturation mechanism [2]. The susceptibility conditions predicted by the theory was subsequently verified by the students in a series of elegant experiments that were exclusively supported by this DoE grant [3]. The significance of these works was recognized in the form of Invited Papers, from the beginning [4] to the recent past [5].

As multipactor is a prime candidate that seeds all kinds of rf breakdown whenever a dielectric is involved, its importance is gaining considerable attention in recent years. Air-side window breakdown in high power microwave source development [6], wakefield studies in dielectric accelerators [7, 8], and development of magnicon sources, etc., all recently experienced multipactor-related failure mechanisms. In all of these latest developments, the Investigator's works were extensively used.

In addition to the multipactor discharge, the Investigator has also contributed to a significant understanding of the heating mechanisms of diamond windows. Again, this work was supported this DoE grant.

Dr. T. V. George, a program manager of this DoE grant, requested the Investigator's service as a member of the DoE Peer Review of the Electron Cyclotron Heating Technology Program [November 8, 2000, La Jolla, CA]. During the informal "brain storm" session at the conclusion of this Review, an important problem was identified: diamond window failure in long pulse, high power gyrotrons. The Investigator then engaged a new graduate student, Mr. Herman Bosman, who has been exclusively supported by this DoE grant, to examine this important issue. A number of interesting results emerged from this study, such as the conclusions that graphitization is not the cause for diamond window failure, that a thin film of contaminant on a window may locally absorb 50 percent of the incident rf energy, and that the rf magnetic field may lead to much more severe heating of an isolated contaminant than the rf electric field. These results, and others, will be described in more detail below. As we shall see, they are of considerable current interest to the rf, accelerator, and material processing communities.

II. Original Works Supported by the DoE Grant (1998-2005)

In its duration of seven (7) years, this DoE Grant has supported five (5) very able graduate students, the first four having received PhD degrees:

Dr. L. K. Ang (Director's Postdoctoral Fellow, Los Alamos National Laboratory; now Assistant Professor in Singapore)

Dr. Agust Valfells (Postdoc at University of Maryland; now Assistant Professor in Iceland)

Dr. Rex Anderson (now with Applied Materials)

Dr. Herman Bosman (now a postdoc at U of New Mexico)

Mr. Wilkin Tang (currently beginning his third year of graduate study)

Their original works follow.

A. Suppression of 2-surface multipactor by an auxiliary signal

Two-surface multipactor between two metallic plates (the geometry customarily analyzed in the literature) depends sensitively on the resonant condition on the electron's time-of-flight between the plates. If a low level auxiliary signal at a neighboring frequency is injected, this resonant condition may be upset, thereby suppressing the multipactor. In his thesis [9], Valfells provided a theoretical analysis of the feasibility of this concept, for various powers and frequencies in the auxiliary signal. He also spent considerable time designing an experiment to test this method of multipactor suppression, with the help of Professors Ronald Gilgenbach and Ward Getty. This experimental effort was not pursued further, after an extensive search of the parameter space, mainly because we did not have a convenient microwave source for an in-house experiment.

B. Effects of an oblique rf electric field

In the analysis of multipactor on a dielectric, it is usually assumed that the rf electric field is parallel to the dielectric surface. The role of an oblique rf electric field is of considerable interest because of its occurrence on rf windows. Valfells studied this issue extensively and concluded that the dielectric is most susceptible to multipactor if the rf electric field is parallel to the dielectric surface. This susceptibility is dramatically reduced if the angle of obliqueness exceeds 5 - 10 degress [9, 10].

C. Space Charge Shielding of Multipactor Discharge

Our simple transmission line model for multipactor [2] attracted the interest of the PIC simulation experts at UC Berkeley. Dr. John Verboncoeur (one of the writers of PDP and OOPIC Codes with Professor C. K. Birdsall) modified his PIC codes, including the emission alogrithms, to simulate the multipactor problem on dielectric. An outgrowth of this collaboration was Valfells' construction of an elegant analytic solution [9, 11] of the multipactoring electrons' energy distribution that is consistent with the space charge force. This work is very useful because it lays the foundation in the next step, which is to predict the x-ray yield by the multipactoring electrons on a dielectric, to estimate the effects of outgassing, and to study the transition of multipactor to catastrophic failure on a dielectric.

D. Effects of External Magnetic Field

Since dynamically, multipactor is more likely to occur on a dielectric (than a 2-surface multipactor between a metallic gap) because the former does not require a resonance condition, it is of fundamental interest to examine whether an external magnetic field will suppress multipactor on a dielectric. Mr. Ang examined this problem in great detail and found that the answer is no in general [10], for reasonable values of magnetic field (e.g., up to the value whose cyclotron frequency is on the order of the rf frequency), regardless of the orientation of the magnetic field.

E. Resonant absorption by dielectric impurities

Since heating of dielectric is an issue, out of curiosity, we investigated the effects of impurities in a dielectric on the radiation absorption, having in mind dielectric failure in the microwave regime. To make this work to be as widely applicable as possible, we constructed dimensionless scales [24]. This work turns out to be quite relevant to present and future developments of photoresists in the semiconductor industry. The scaled parameters we constructed would allow optimization of the chemical concentrations, required resonant linewidths, laser pulselength, dielectric thickness, etc., when various lithography wavelengths are used. They were part of the PhD thesis of L. K. Ang [23]. Both Refs. [23] and [24] acknowledged DoE support.

F. Experiment of Multipactor on a Dielectric

Our modeling works [1, 2, 4, 9-11] have generated significant interest in multipactor among experimentalists (students and faculty), and with the support of this DoE grant, graduate student Mr. Rex Anderson designed, constructed, and completed a PhD thesis on an experiment of multipactor on a dielectric, under the close supervision of Profs. Ward Getty, Mary Brake, and Ron Gilgenbach [3, 12]. This was what they came up with, given our very limited resources: The experiment consists of a small brass microwave cavity in a high vacuum chamber. The dielectric is cut into a thin disc with a diameter slightly less than the inner diameter of the cavity [Fig. 1]. It is slid into place inside the cavity where the electric field is greatest in

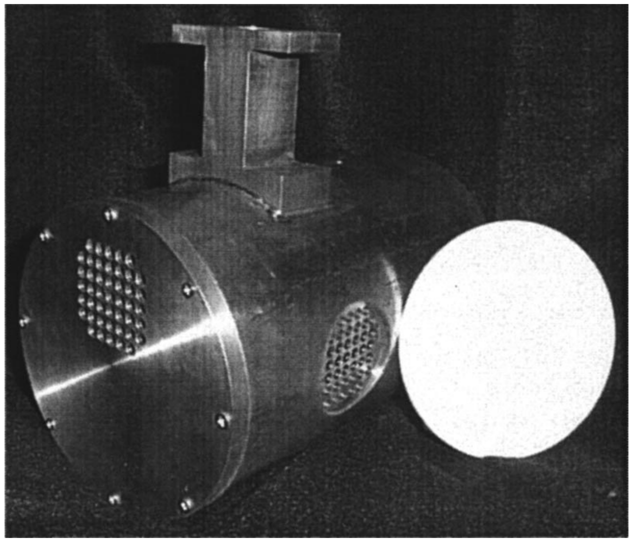


Fig. 1: Resonant cavity and dielectric: External view of cavity and the alumina disk. The external dimensions of the cavity are ~15 cm in length and ~10 cm in diameter. The alumina disk is ~8.5 cm in diameter. The arrays of holes in the cavity walls are used for visual and probe access. [From Ref. 3]

magnitude. The mode in the cavity is TE_{111}, which provides the desired RF electric field that is parallel to the dielectric surface. The charging field on the surface of the dielectric is seeded by the bombardment of electrons from a thermionic cathode located on the opposite end of the cavity. (It was later found that this thermionic cathode was not necessary.) The vacuum system is capable of base pressures in the 10^{-7} Torr region. The microwave source is pulsed at 2.45 GHz with 4.5 kW of power. Areas of study include operating parameters that multipactor occurs on different dielectric materials, outgassing of the dielectric surface, detuning of the cavity, and ways to prevent, or extinguish multipactor. Diagnostics include various probes to measure current and electric fields, and phosphor painted on the dielectric surface to allow visual detection of multipactoring. Figure 2 shows that multipactor is turned on only if the microwave power is beyond the threshold value that is consistent with theoretical prediction. Figure 3 shows phospher illumination when multipactor occurs.

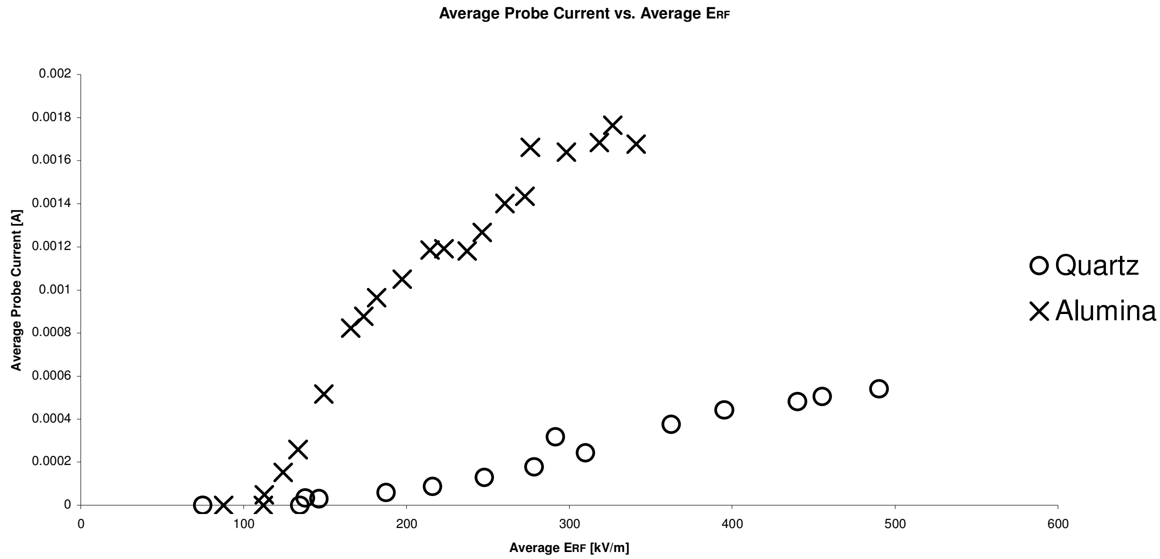


Figure 2: Average probe current vs. average E_{RF} for alumina and quartz. [From Ref. 12].

G. Generation of X-ray by Multipactor Discharge

Our multipactor models attracted the interest of the PIC simulation experts at UC Berkeley, as indicated in Part C of this section. An outgrowth of this collaboration [11] was Valfells' construction [9] of an elegant analytic solution of the multipactoring electrons' energy distribution that is consistent with the space charge force. This work is very useful because it lays the foundation in the next step, which is to predict the x-ray yield by the multipactoring electrons on a dielectric, to estimate the effects of outgassing, and to study the transition of multipactor to catastrophic failure on a dielectric. This work was not completed because attention was shifted to the more urgent problem of diamond window failure.

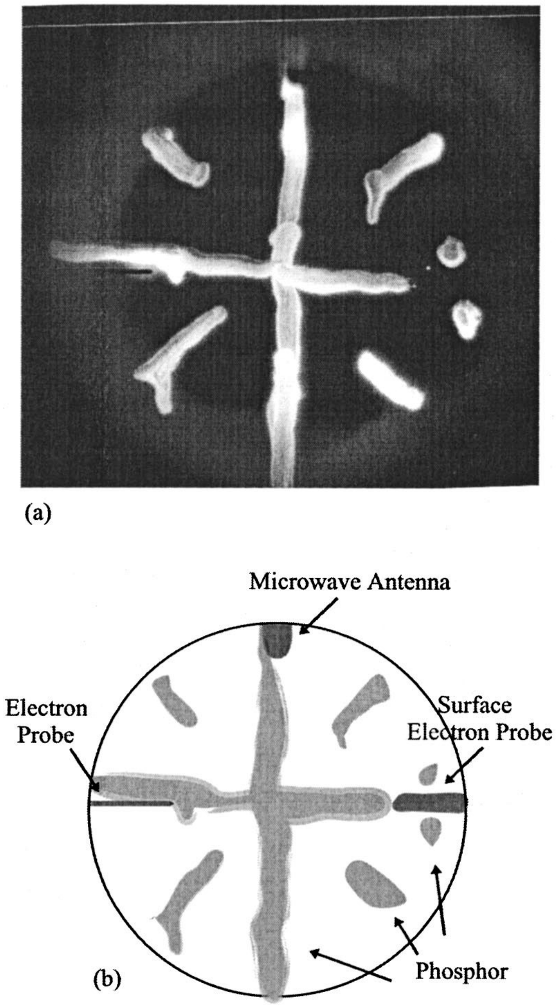


Figure 3: Phosphor photos: (a) Photograph of phosphor diagnostic. (b) Schematic of the phosphor picture. The multipactoring electrons cause the phosphor to emit light. The two electron probes and the microwave antenna are also labeled and can be seen in the photograph. [From Ref. 3]

H. Studies of Diamond Window Failure Mechanisms

Diamond window failure in gyrotrons was identified as one of the most critical problems in magnetic fusion confinement experiments which employ the high power gyrotrons for current drive, profile modification, and electron cyclotron resonance heating. Thus, attention was shifted from multipactor to the broader problem of rf window failure. The awareness and urgency of the latter topic was highlighted in a November, 2000 DoE Program Review in which the Investigator was invited to participate. Given in this section are the results of our research, in response to the general consensus reached in this Program Review. [See also p. 5 of this Final Technical Report].

H1. *Graphitization*

Since diamond windows usually perform adequately for some time before rapid, destructive failure occurs, this would suggest a failure mechanism that is cumulative for each successive microwave pulse, with the individual contributions being small and non-destructive. Herman Bosman conjectured and tested a failure mechanism based on a chemical transformation at the grain boundaries: Graphitization is initiated preferentially at discrete nucleation sites on the diamond surface or internal microcracks, and grows outward from these sites. Each successive microwave pulse will then contribute to the graphitization of the grain boundary regions through heating. Since graphite has a lower density than diamond, the resultant increase in volume due to graphitization will produce tensile forces across the grain boundaries, which could ultimately lead to window failure. We constructed a simple model to analyze this failure mechanism by estimating the temperature rise in the graphite. We find that the temperature rise is too small to cause diamond window failure by graphitization.

This result was presented by Herman Bosman in 2002 in a teleconference that was attended by many experts. The response was enthusiastic from the emails Mr. Bosman received from the audience:

"Thank you very much for your excellent talk! Everyone here was very impressed. I hope that you can benefit from the many questions and comments. Please note that your talk did attract many questions and a great deal of interest because you have chosen a very important topic for your research, namely, failure mechanisms of diamond windows for high power microwave devices …. We will be glad to help knowing that your research will help us with a major problem. … Thank you again for a very interesting and stimulating talk and good luck on your research projects!"

Dr. Richard Temkin, MIT (Feb. 5, 2002)

"I really enjoyed the student talk yesterday and learned a lot. Would you please let Herman know he did a great job! It was really clear and stimulated much thinking and many comments. As a bonus, if it turns out that a major reduction in the cost of diamond windows is the end result from the talk and the subsequent comments, well, that's something to feel pretty good about!"

Dr. Dick True, Litton, in a letter to the Investigator (Feb. 6, 2002)

Upon hearing these results, Dr. T. V. George among others directed our attention to the role of contaminants that is deposited on the window, which is described next. Our research has been truly interactive in the community.

H2. *Heating of Surface Contaminats*

We next constructed a simple model to assess the degree of microwave absorption by a thin layer of contaminant attached to the window surface. We found the surprising result that this thin layer may absorb up to 50 percent of the incident RF power, even if the layer thickness is much less than its resistive skin depth [Fig. 4]. This large absorption took us by surprise because such a thin film might be expected to appear "transparent" to the incident wave, leading to little absorption. Ours, however, is a general result, and has a simple explanation [13].

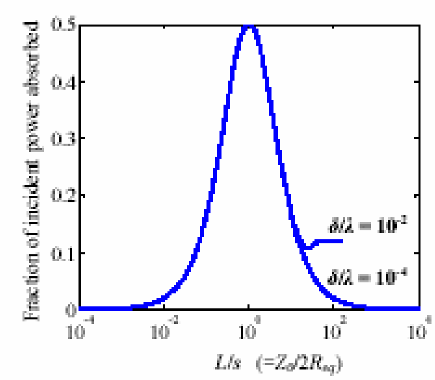


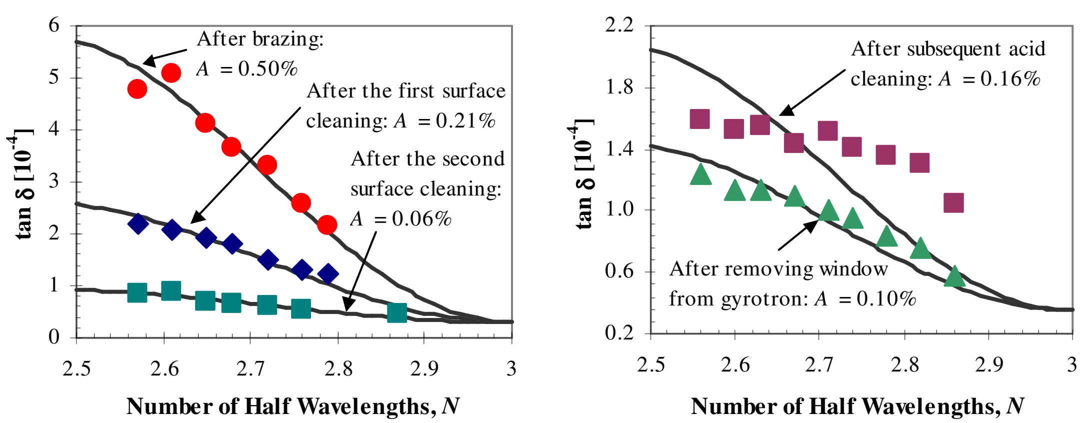
Fig. 4. The fraction of incident power absorbed by a thin surface film on an RF window as a function of L, the thin film thickness. [From Ref. 13].

We also constructed a scaling law for the temperature increase [13], in terms of the thickness of the thin film, its electrical conductivity, its thermal conductivity, and the frequency and power of the incident RF. Hundreds of degrees in temperature increase is possible, potentially linking the surface contaminants to severe local heating of the microwave window.

The above findings created a lot of excitements in the past year. Upon hearing these results while the Investigator visited Litton at San Carlos, CA, in August, 2002, the engineers there (Carter Armstrong, Al Theiss, Dick True, etc.) were very intrigued by the above results, and even suggested that our calculations might have explained their observed window failure which occurred (unexpectedly) at 1/4 of the rated RF power.

In addition, upon seeing our paper [13] in its preprint form, Dr. Howard Jory of CPI performed a measurement on the DC surface electrical conductivity on one of his broken diamond windows. His unpublished experiment [14] points to the difference between local and average heating on the window surface. This issue remains unsettled, however, but Jory's work suggests that typically a fraction of a percent of the incident rf power, on the average, is absorbed by the surface resistivity.

Earlier in 2002, the measurements performed by M. Thumm's group (Germany) on the changes of the "loss tangent" due to various surface treatments on diamond windows appeared in print [15]. This was an rf measurement, different from the DC measurements of Jory [14]. We tried to extend our theory on the contaminant-induced loss tangent and compared it against the Germany experiments. The results are shown in Fig. 5 [16]. The details of this study, together with a thermal-mechanical analysis, are given in Herman Bosman's PhD thesis [20].



(a) (b)

Fig. 5. (a) Comparison of the transmission line model (solid lines) with experimental data (points) for the W7-X #2 diamond window (growth face, from [15]), respectively after brazing (●) and two surface cleaning steps (♦,■). (b) Comparison of the transmission line model (solid lines) with experimental data (points) for the Maquette diamond window (growth face, from [15]), after being removed from the Maquette gyrotron (▲) and after a subsequent acid-cleaning step (■). [Taken from Ref. 16].

I. Heating by RF Magnetic Field vs Heating by RF Electric Field

During our study of heating of a small, isolated graphitic embedded in the diamond window [Item H1 above], our calculations showed the surprising result that the RF magnetic field component of the incident electromagnetic wave may provide significantly higher ohmic heating than the RF electric field component of the incident electromagnetic wave [17]. This result has been puzzling and troubling, as many issues can be raised – both computational and conceptual. These issues concern the legitimacy in separately and independently considering the heating by the electric and magnetic component of the electromagnetic fields; the dependence on the frequency, size, and electrical resistivity of the particulate; the constructions of the (complex) macroscopic permeability and permittivity by the presence of the particulates; and all of the above when the electromagnetic pulse is transient in nature. Note that a state-of-the-art eigenmode solver remains ill-equipped to simulate the minuscule perturbing effects of a small particulate, when the skin depth is small compared with the particulate size, which in turn is typically small compared with the size of the wavelength. Slater's perturbation techniques also fail in this case. In spite of these tremendous difficulties, we completely solved this problem with the use of a simple model [20-22].

In Ref. [22], we have provided a general theory on the ohmic dissipation of electromagnetic energy by a spherical particulate that is embedded in a lossless medium. The particulate may possess an arbitrary electrical conductivity, and both the medium and the particulate may assume general values of permittivity and permeability. Under the assumption that the wavelength (λ) of the electromagnetic field in the medium is large compared with the particulate size, we provide an accurate account of the degree of ohmic heating by the radio frequency (rf) electric field and by the rf magnetic field of the electromagnetic field. It is found that, in general, heating by the rf magnetic field is dominant whenever $\delta < a$, where δ is the resistive skin depth and a is the radius of the particulate. Analytic scaling laws in the various regimes are derived, from the static case to very high frequency, and for ratios of δ/a ranging from zero to infinity. The calculation is extended to a transient electromagnetic pulse. Also constructed is the loss tangent of the medium, resulting from a distribution of particulates.

In Figs. 6 and 7, we show respectively the polarizability, α_E and α_H, for different ratios of λ/a with $\mu_1/\mu_2 = 100$, $\varepsilon_{1r}/\varepsilon_2 = 10$. The asymptotic expansions are also shown in these figures. Here the subscripts 1 and 2 refer to the particulate and its surrounding medium, respectively. α_E and α_H is, respectively, the polarizability of the rf electric field and rf magnetic field. Roughly, the polarizability is the fraction of rf energy that is dissipated in the particulate's volume in one rf cycle. Figures 6 and 7 demonstrate the applicability of the theory to arbitrary values of μ_1, μ_2, ε_{1r}, and ε_2, and over a total of 12 orders of magnitude between δ, a, and λ. It is clear that α_H dominates over α_E when $\delta/a << 1$ by examining the scales in Figs. 3 and 4, thus perhaps offering a plausible explanation for the puzzling results of Refs. [18] and [19].

These results are very important because the role of RF magnetic field heating has recently been shown experimentally, by Rustum Roy's group at Penn State University, to be CRUCIAL in industrial processes [18]. It was also recognized to be the KEY mechanism for rf failures in high gradient accelerators [19].

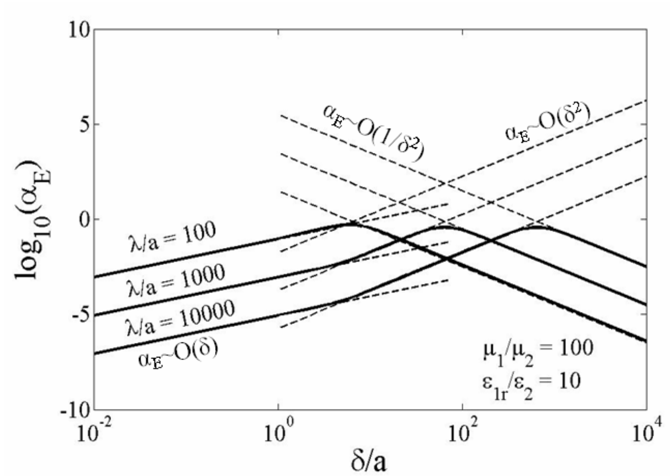


Fig. 6. The polarizability α_E as a function of δ/a for $\mu_1/\mu_2 = 100$, $\varepsilon_{1r}/\varepsilon_2 = 10$, and various values of λ/a. The dotted curves show the asymptotic formulas [From Ref. 22].

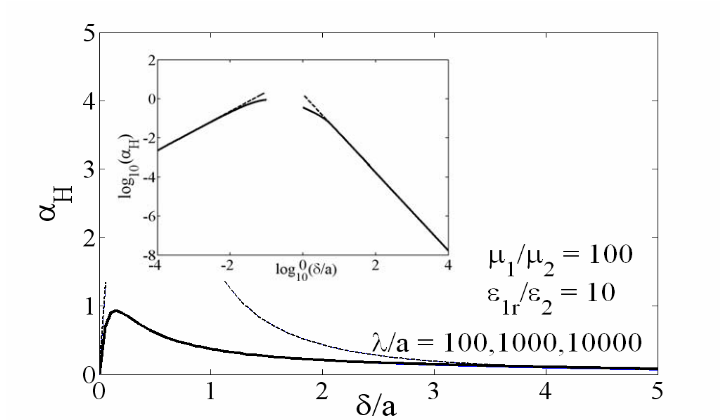


Fig. 7. The polarizability α_H as a function of δ/a for $\mu_1/\mu_2 = 100$, $\varepsilon_{1r}/\varepsilon_2 = 10$, and various values of λ/a. The dotted curves show the asymptotic formulas. The inset shows an expanded range of δ/a [From Ref. 22].

When the particulate is exposed to an electromagnetic pulse of a finite pulse length, the analytic expressions for α_E and α_H allow an immediate determination of the total electromagnetic energy $W = W_E + W_H$ that is deposited in the particulate, where [22],

$$W_E = \int d\omega \alpha_E(\omega) \frac{1}{2}\omega\varepsilon_2 |E(\omega)|^2 V_a, \;\; W_H = \int d\omega \alpha_H(\omega) \frac{1}{2}\omega\mu_2 |H(\omega)|^2 V_a. \qquad (1)$$

In Eq. (1), $E(\omega)$ and $H(\omega)$ is respectively the Fourier transform of the electric field and of the magnetic field that make up the finite pulse.

If the medium II is embedded with a population of the particulates, whose average inter-particulate distance is $\ell >> a$, the loss tangent in this composite medium is given by [22],

$$\tan\delta_{loss} = \left(\frac{\varepsilon_i}{\varepsilon_2} + \frac{\mu_i}{\mu_2}\right) = \frac{4\pi}{3}\left(\frac{a}{\ell}\right)^3 (\alpha_E + \alpha_H). \qquad (2)$$

These results not only has offered a plausible explanation for the puzzling results of Refs. [18] and [19]. They are also being applied to the heating of biological cells by an ultra-wideband electromagnetic pulse [25].

III. Recognitions

During the granting period, the following recognitions were accorded to the Investigator and his students who were supported by this DoE grant.

Y. Y. Lau received the 1999 IEEE Plasma Science and Application Award at the IEEE International Conference on Plasma Science (June 1999, Monterey, CA). Multipactor discharge was a major topic in his Plenary Award Lecture, entitled, "Simple models on some nasty problems in beams and plasmas."

Agust Valfells [9-11] received the Rackham Fellowship in 1999-2000, which was the highest honor that went to about ten (10) graduating PhD candidates at the University of Michigan in *all* engineering disciplines (Electrical Engineering and Computer Science, Mechanical, Materials, Civil, Aerospace, Nuclear, ...) and in *all* major science departments (Physics, Chemistry, Mathematics, ...).

L. K. Ang [2, 4, 23, 24] was appointed to the prestigious position of Director's Postdoctoral Fellow at the Los Alamos National Laboratory, upon completion of his PhD thesis in Summer, 1999. He is currently Assistant Professor at the Nanyang Technological University in Singapore.

Y. Y. Lau was invited by the Royal Swedish Academy of Science to submit nominations for the 2001 Nobel Prize in Physics.

Y. Y. Lau was invited to give a 1-hour tutorial paper on X-ray generation by nonlinear Thomson scattering in the 2002 APS-DPP Meeting (Orlando, FL).

Y. Y. Lau has been appointed as an Associate Editor of Physics of Plasmas, since the inception of that journal. He was also elected to 3-year term (2001-2003) on the Executive Committee in the IEEE Plasma Science and Application Committee; in that capacity, he served as the Chair for the IEEE ICOPS Students Travel Grant.

Y. Y. Lau was Chair of APS Plasma Physics Division’s 2003 Award Committee for Excellence in Plasma Physics Research.

IV. References

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