Electrohydrodynamically Driven, Large-Area Liquid Metal Ion Source for Inertial Confinement Fusion

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Abstract

Analysis of the electrohydrodynamic (EHD) equations of motion of a planar liquid-lithium surface in the presence of a normal electric field suggest that liquid lithium may provide a large-area ion source for intense ion-beam diodes. Such sources are being developed for the Particle Beam Fusion Accelerator II at Sandia National Laboratories. In this paper, theoretical and experimental studies of the planar EHD ion source will be reviewed.

When a planar liquid surface is subjected to an electric field of sufficient magnitude, EHD instabilities produce an array of cusps on the surface. The electric field enhancement at the apex of each cusp is sufficient to permit field evaporation of ions. The time delay between application of the electric field and ion emission depends on the magnitude and rate of increase of the applied electric field, and on the initial amplitude of the surface perturbation. Above 10 MV/cm, theory indicates that field

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emission will occur on a nanosecond time scale and that the characteristic spacing of emitters will be less than one micrometer. At these fields, the source should have an intrinsic divergence of less than 6 mrad and the effects of space charge from neighboring emitters should not inhibit emission significantly. Experimental measurements of wavelengths and cusp-formation-times for water and ethanol at electric fields near the critical field for instability have agreed well with theory.

I. Introduction

At Sandia National Laboratories, there is a major effort underway to develop a lithium ion source for Inertial Confinement Fusion (ICF) research on the Particle Beam Fusion Accelerator II (PBFA II).[1] One of the most promising ion sources under investigation is a two-dimensional electrohydrodynamically driven liquid ion source. This approach utilizes the fact that electrohydrodynamic (EHD) instabilities occur on a liquid surface which is subjected to a sufficiently high normal electric field. The instability results in an array of cusps on the surface. The enhanced electric field at the apex of the cusps can be sufficient to cause field evaporation of ions from the liquid.

The electrohydrodynamic instability has been studied by many investigators; for example, see Refs. 2-5. When an electric field is applied normal to the surface of a conducting liquid, the surface acquires a charge. The electric field interacts with this charge, pulling the surface out. Surface tension and possibly gravity oppose the electrostatic stress and pull in the surface. As the electric field increases, there is a critical value E_c at which the the effect of electrostatic stress balances the effects of surface tension and gravity for the surface perturbation of wavelength λ_c. This wavelength becomes unstable, and its amplitude grows exponentially in time.

The surface of the liquid will distort into an array of cusp-like structures separated by a distance λ_c. For perturbations with wavelength less (or greater) than λ_c, the effect of surface tension (or gravity) dominates and the wave is stable. When the applied electric field is above the critical field for instability, there is a spectrum of unstable wavelengths. In this case, the behavior of the surface will be dominated by the wavelength which has the largest growth rate, referred to as the dominant mode. Both the wavelength and the growth time of the dominant mode are very rapidly decreasing functions of the applied electric field [6].

Two important applications of the EHD instability are point and linear liquid metal ion sources (LMIS)[7,8]. The single LMIS operates by the application of an electric field to a liquid held in a small-diameter (typically 20 - 100 μm) capillary, or to a liquid-wetted needle of similar dimensions. The liquid at the tip is drawn up into a cusp by the EHD interaction previously described. At the tip of the cusp, the electric field is greatly enhanced due to the nanometer-scale dimensions of the cusp apex, and field evaporation of ions occurs. The emitting LMIS is stable: the space charge from the emitted ions balances the effects of the electric field. This prevents the liquid from being torn from the supporting structure. Currents in the range from one to hundreds of microamps are obtained from these

single LMIS. These currents persist stably until the reservoir of liquid is depleted.

At the European Space Agency in Nordwijk, Netherlands, a linear EHD emitter is being developed as a thruster for use in satellites [8]. For this application, a voltage is applied to a liquid held in a slit that is 1.0 μm wide and up to 5 cm long. Thus, a small cylinder (about 1.0 μm diameter) of liquid is exposed to the electric field. The EHD instability causes the liquid to erupt into a linear array of cusps along the liquid in the slit. Each cusp acts like a single LMIS. The distance between emitting cusps corresponds to the wavelength of the dominant instability and agrees reasonably well with that predicted by theory. The linear emitter is also a steady-state ion source. For typical operating conditions, each cusp provides a current of about 10 microamps until the reservoir of liquid is depleted.

The liquid ion source that we are developing for PBFA II will be a large area (10^3 cm^2), barrel-shaped, vertical surface. This will be the first two-dimensional EHD driven ion source to be developed. The source will be located on the anode surface of the accelerator diode, where the high voltage power pulse from the accelerator is converted into a beam of energetic lithium ions. However, this ion source will not operate in a steady-state mode. The entire accelerator power pulse lasts less than 50 ns, and the source must begin producing ions within a few nanoseconds of

the time the accelerator pulse arrives at the diode. The work reviewed below suggests that a two-dimensional EHD source can produce a low divergent ion beam supplying a current density of 5 kA/cm^2 on the time scale of the accelerator pulse.

II. Theory

When a sufficiently high electric field is applied normal to the surface of a liquid, to first order, the amplitude ξ of an unstable perturbation of wavelength λ grows according to the relation

$$\xi = \xi_o e^{t/\tau_e - ik\cdot x} , \qquad (1)$$

where ξ_o is the initial amplitude, $k = 2\pi/\lambda$, and τ is the linear growth time of the instability. A dispersion relation between the growth time and the wavelength can be obtained from a linear analysis of the EHD equations of motion [4,9]. When the charge relaxation time is short compared to time scales of interest, i.e., $\varepsilon/\sigma \ll \tau$, where ε is the permittivity and σ the conductivity of the liquid, the dispersion relation can be written as:

$$gk\rho + Tk^3 - D\varepsilon_o E_o^2 k^2 + \rho n^2 + 4\mu k^2 n[M/(k+M)] = 0 , \qquad (2)$$

where E_o is the initial applied electric field, $n = 1/\tau$, g is the gravitational acceleration, ρ, T, and μ are the liquid density, surface tension, and viscosity, respectively; $D = (1 + 1/\kappa)/(1 + a/d\kappa)^2$, where a is the liquid depth, d is the equilibrium distance between the liquid surface and the upper electrode, and κ is the dielectric constant of the liquid; $M = (k^2 + \rho n/\mu)^{1/2}$. For $E_o > E_c$, τ is real. The value of E_c is obtained from Eq. (2) by setting both n and dn/dk equal to zero. Above E_c the surface dynamics should be determined by the dominant mode, whose wavelength and growth-time can be obtained from Eq. (2) by setting $dn/dk = 0$. Values of τ and λ for the dominant mode as a function of E_o are shown in Fig. 1 for lithium. Both are rapidly decreasing functions of E_o.

In the linear regime, the amplitude ξ of a perturbation of growth time τ grows according to Eq. (2). However, cusp formation is a nonlinear process and cannot be described by this formula. We can use Eq. (1) to determine how much time is needed to attain an amplitude ξ which is still in the linear regime: $t(\xi) = \tau \ln(\xi/\xi_o)$. Nonlinear analysis can then be used to determine how much additional time is needed to form cusps. This additional time, t', can be expressed as a multiple, α, of the linear growth time. The multiple α is a function of the normalized amplitude ξ/λ and the applied electric field E_o, that is, $t' = \alpha(E_o, \xi/\lambda)\,\tau$. The total time needed to form cusps, t_c, is then the sum of these two times:

$$t_c = [\ \ln(\xi/\xi_o) + \alpha(E_o,\ \xi/\lambda)\ ]\ \tau. \qquad (3)$$

It was shown in [10] that for $\xi/\lambda = 0.01$ and $E >> E_c$, $\alpha(\xi/\lambda, E_o) \simeq 2.6$ (see Fig. 2). For lithium, if $E_o > 10$ MV/cm, $\lambda \simeq 0.5$ μm and $\tau \simeq 1.0$ ns. If $\xi_o = 5$ nm, cusps should form in about 2.6 ns. It seems very reasonable to assume that the amplitude of an initial perturbation should be at least this large, and we therefore predict that for these conditions the EHD instability should produce an ion beam on a time scale that satisfies the requirements of ICF on PBFA II.

If $\lambda = 0.5$ μm, to achieve a current density of 5 kA/cm^2 (a requirement for ICF, [1]), each emitter must supply 12.5 μA of current. This is well within the regime of currents typically observed for single LMIS and should present no problems.

The divergence of a 2-D EHD source has been examined [11] by applying results obtained in Ref. 7. It was found that for values of the applied voltage greater than 10 MV, and $E_o \geq 10$ MV/cm, the divergence should be less than 4 mrad. This meets the requirements of ICF [1]. In this same reference, it was shown that when operating at current densities of 5 kA/cm^2, space-charge effects should not significantly affect operating parameters.

III. Low Field Experiments

Experimental studies of the temporal and spatial characteristics of the EHD instability have been performed for values of the applied electric field slightly above the critical value[9]. Measurements were made of the wavelength and time-to-cusp formation of surface instabilities as a function of the applied electric field, E_o, for tap water, salt water, and ethanol. Using Eq. (2), the linear growth times for these liquids is between 1 ms and 100 ms for $E_o <$ 50 kV/cm.

Figure 3 shows theoretical and experimental values of the wavelength λ as a function of E_o. The experimental and theoretical values of the wavelength of the dominant mode are in good agreement.

The time-to-cusp formation was determined by the time needed to produce a uniform distribution of cusps on the liquid surface. The time-to-cusp formation was a decreasing function of the electric field, as seen in Fig. 4, consistent with theory.

VI. Conclusions

Theoretical studies indicate that a two-dimensional EHD source can provide an ion source for ICF on PBFA II. The success of theory in explaining and predicting behavior of liquids undergoing the EHD instability at electric fields

near the critical field lends confidence that the theory will correctly predict the behavior of liquid lithium and lithium nitrate at the much higher fields expected to be attained on PBFA II. Efforts are underway to field liquid lithium ion sources on PBFA II by summer 1989.

References

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Figure Captions

Figure 1. Linear growth time and wavelength of the dominant mode as a function of E_o for lithium.

Figure 2. Nonlinear analysis starting from an initial amplitude of $\lambda/100$, showing a cusp forms in 2.6 linear growth times.

Figure 3. Comparison of experimental and theoretical values of the wavelength of the dominant mode as a function of $E_o - E_c = \Delta E$ for ethanol and water. The critical fields are 17.5 kV/cm and 24.7 kV/cm for ethanol and water, respectively.

Figure 4. Time-to-cusp formation for water and ethanol as a function of $E_o - E_c$.

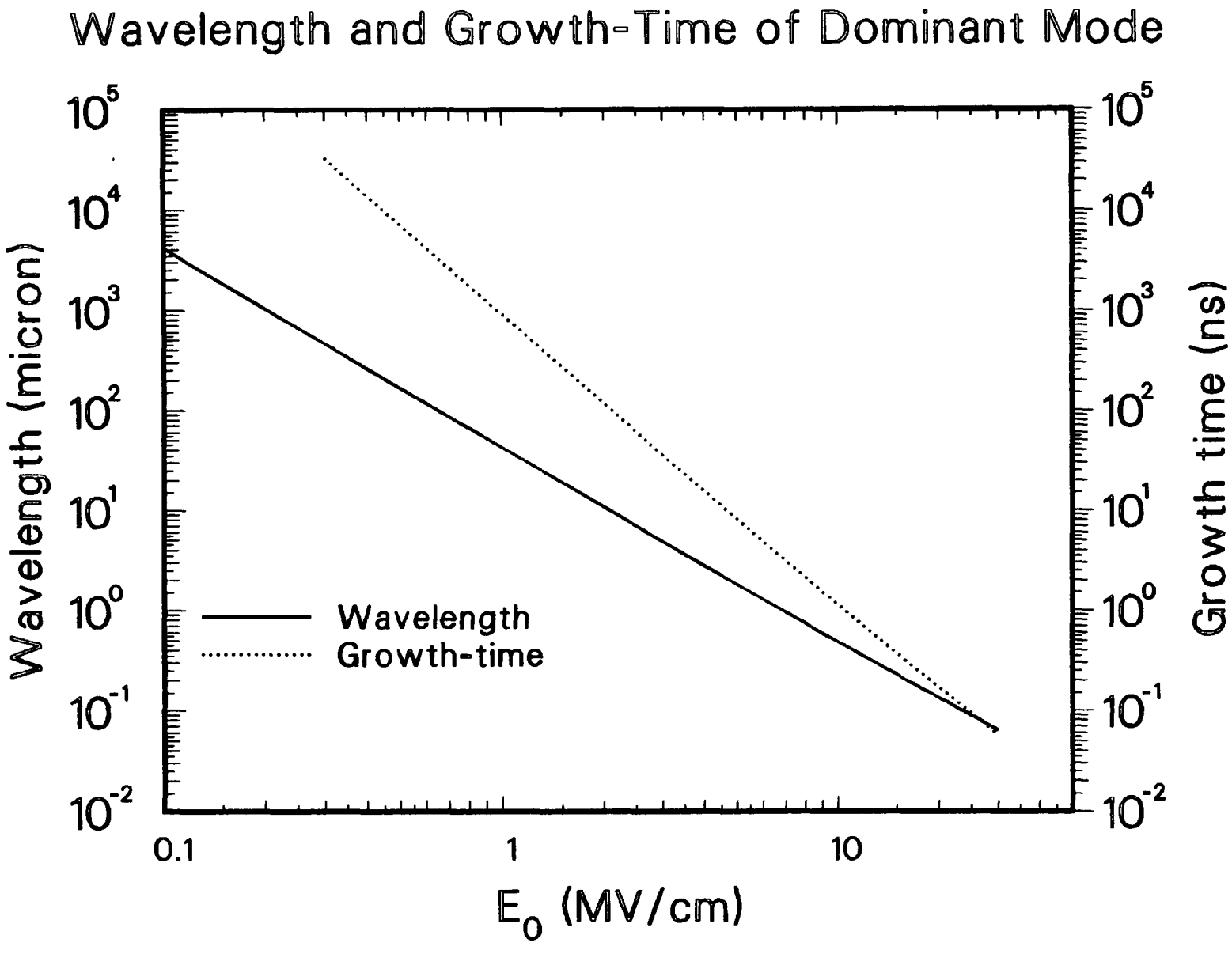
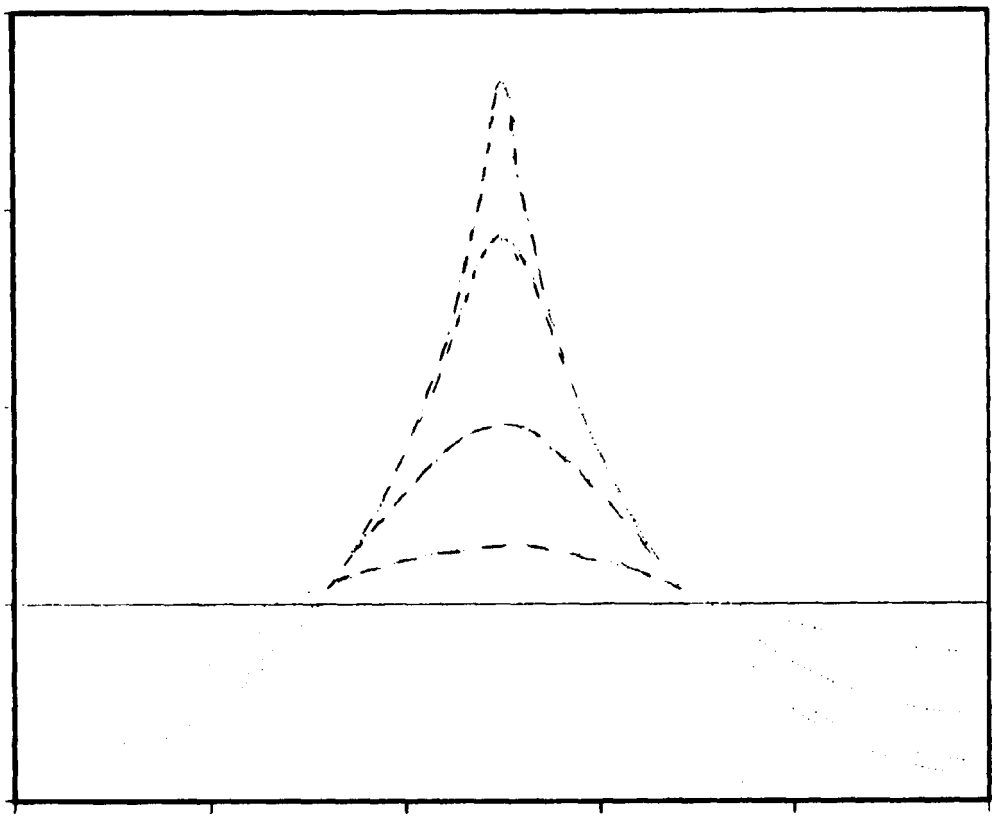

Wavelength and Growth-Time of Dominant Mode
Wavelength (micron)
Growth time (ns)
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
Wavelength
Growth-time
0.1
1
10
E_0 (MV/cm)

Fig 1

Nonlinear Results



Surface structure of liquid lithium at 1.0, 2.0, 2.5 and 2.6 times the linear growth time. For an initial amplitude $\xi_o = \lambda/100$, singular surface behavior occurs at about 2.6 τ.

Fig. 2

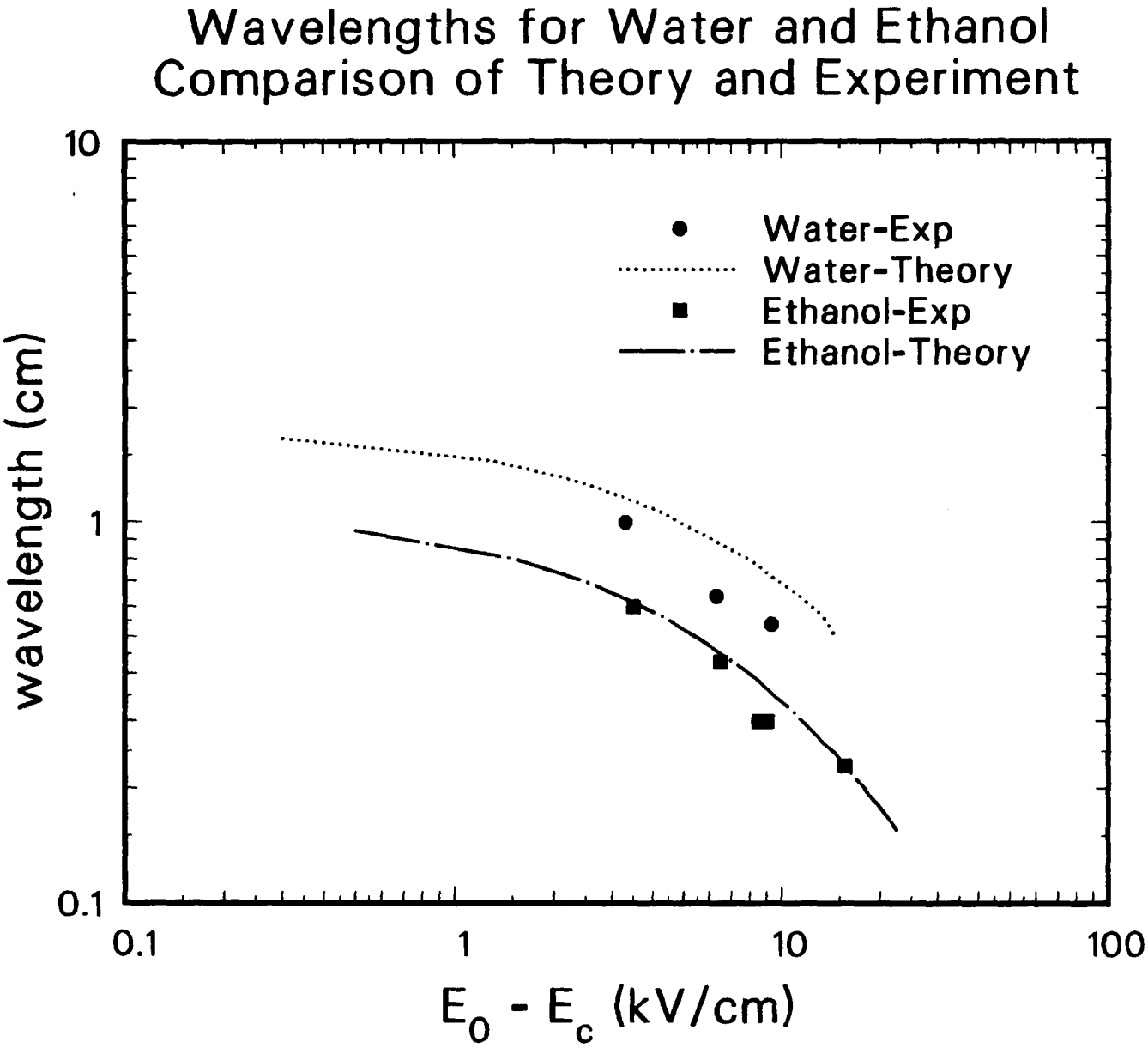

Wavelengths for Water and Ethanol
Comparison of Theory and Experiment
10
1
0.1
wavelength (cm)
0.1
1
10
100
$E_0 - E_c$ (kV/cm)
Water-Exp
Water-Theory
Ethanol-Exp
Ethanol-Theory

Fig 3

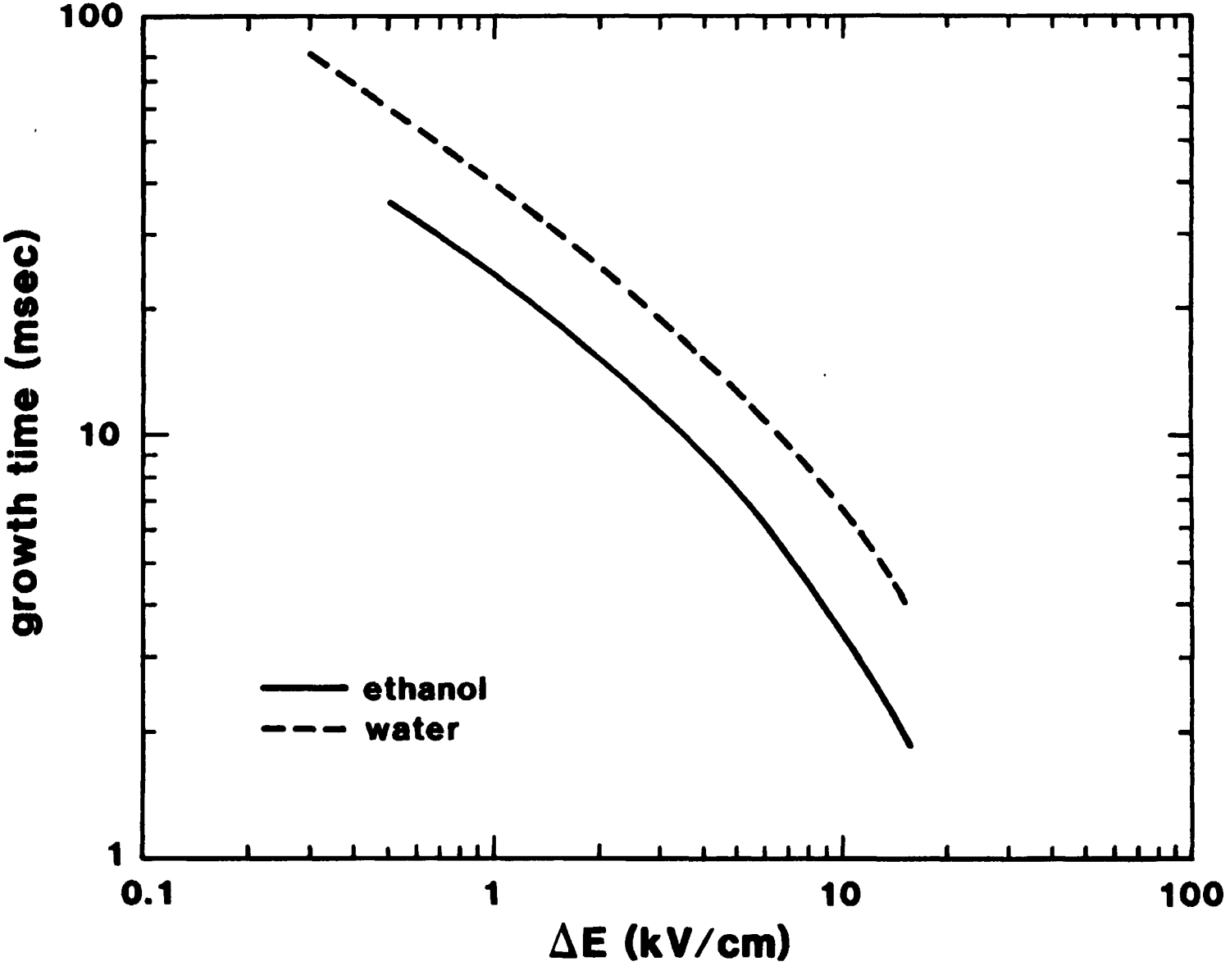


Fig. 4