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TECHNIQUES TO CONTROL AND POSITION LASER TARGETS

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P. O. 8962605 & 4475803

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TECHNIQUES TO CONTROL AND POSITION LASER TARGETS

Final Report

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by

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to

Target Research and Fabrication Group
Laser Fusion Program
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1. Introduction

This report summarizes research performed under Lawrence Livermore Laboratory subcontracts #8962605 and 4475803, from August, 1975, to January, 1978. The purpose of the work was to investigate the potential role of various electrohydrodynamic phenomena in the fabrication of small spherical particles and shells for laser target applications. A number of topics were considered. These included charged droplet levitation, specifically the combined effects of the Rayleigh limit and droplet elongation in the presence of electric fields. Two new levitation schemes for uncharged dielectric particles were studied. A dynamic dielectrophoretic levitation scheme was proposed and unsuccessful attempts were made to observe levitation with it. Another static dielectrophoretic levitation scheme was studied and used extensively. A theory was developed for this type of levitation, and a dielectric constant measurement scheme proposed. A charged droplet generator for the production of single droplets (< 1mm DIAM) of insulating liquids was developed. The synchronous DEP pumping of bubbles and spheres has been considered. Finally, some preliminary experiments with SiH_4/O_2 bubbles in Viscasil® silicone fluid were conducted to learn about the possibility of using silane to form SiO_2 microballons from bubbles.

The present emphasis on plasma chemistry and other vacuum techniques for the fabrication of laser targets has precluded the "wet chemistry" approaches to which most EHD processes are relevant. However, a few observations mentioned in the text of the report may still be useful during various target fabrication operations: These are summarized below:

(i) DEP levitation is by now well-understood and easily implemented for a large number of potential target particles including glass and acrylic microballoons.

(ii) DEP levitation in DC electric fields offers the possibility of extension of the class of particles levitated.

(iii) DEP levitation in DC electric fields offers the possibility of levitating particles which rotate due to the Quincke effect. In wet chemistry treatment, this rotation might be useful in promoting uniform coatings, etc.

(iv) DEP synchronous pumping of particles and bubbles, while not yet proven experimentally, may be useful in the handling of laser targets in ultrasonic cleaning baths, etc.

Summary of written work

T. B. Jones and G. W. Bliss, "Bubble dielectrophoresis", J. Appl. Phys., 48, 1977, pp. 1412-1417.

T. B. Jones and M. J. McCarthy, "Deformation of liquid droplets and gas bubbles in electric fields", research report #1 to Lawrence Livermore Laboratory, subcontract #8962605, May 1976.

T. B. Jones, G. A. Kallio and K. S. Robinson, "Polarized particle levitation in hexapole field," research report #2 to Lawrence Livermore Laboratory, subcontract #8962605, June 1976.

T. B. Jones and M. J. McCarthy, "Dynamic levitation of charged liquid droplets", research report #3 to Lawrence Livermore Laboratory, subcontract #8962605, July, 1976.

T. B. Jones, G. A. Kallio and K. S. Robinson, "Technique for levitation of a polar or polarizable particle in a hexapole electric field", ERDA Record of Invention #IL-6144, 1977.

G. A. Kallio and T. B. Jones, "Dielectrophoretic Levitation of Spheres and Shells", submitted to the Journal of Electrostatics.

G. A. Kallio and T. B. Jones, "Dielectric Constant Measurements using Dielectrophoretic Levitation", to be presented at IEEE-IAS Conference, Toronto, Ontario, Canada, October, 1978.

T. B. Jones, "Dielectrophoretic Force Calculation", submitted to the Journal of Electrostatics.

G. A. Kallio, "Dielectrophoretic levitation of spheres and shells", M.S. Thesis, Colorado State University, February, 1978.

2. Drop-Weight Surface Tension Measurements

Surface tension is an important liquid property for fluid particles in the size range of laser targets (< 1mm). In some possible applications of electrohydrodynamics, surface forces can compete with electrical forces. Thus, accurate surface tension values for various liquids are needed. Likewise, interfacial tension data for liquid/liquid combinations are valuable. Surface and interfacial tension measurement methods were examined and the so-called drop-weight method was used to measure a number of liquids and liquid/liquid systems.

Brief description

The drop-weight method is one of the most accurate and yet simple techniques for the determination of the surface and interfacial tensions of liquids. It is based on the fact that the weight of a drop of liquid that is formed extremely slowly and that detaches from the tip of a tube of known radius is directly proportional to the surface tension of that liquid with respect to its medium. The method entails using correction factors since not all of the drop departs from the tip. Consider the droplet hanging from the tip shown in Fig. 2.1. Ideally, at the instant of droplet departure,

$$\Sigma F_y = 0 = F_\gamma + F_b - mg$$

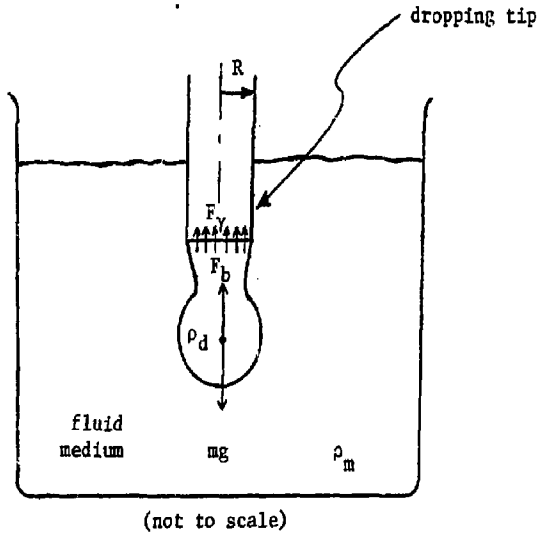
$$= 2\pi R\gamma + \rho_m gV - \rho_d gV$$

$$\gamma = \frac{(\rho_d - \rho_m)Vg}{2\pi R}$$

where:

mg = weight of drop

F_b = buoyant force on drop



(not to scale)

Figure 2.1 Forces on a pendant droplet in a fluid medium.

F_γ = surface tension force on drop

R = radius of dropping tip

ρ_d = density of drop

ρ_m = density of fluid medium

γ = surface tension of drop liquid

V = volume of drop

Actually not all of the drop departs from the tip; as much as 40% may remain. Thus, the above equation is inaccurate; however, correction factors have been derived and tabulated to compensate for this effect. Fortunately it was found that the correction factor (f) is proportional to $(R/V^{1/3})$ and independent of the fluid used. Therefore, the surface tension expression becomes:

$$\gamma = \frac{\Delta\rho V g}{2\pi R f} \quad \text{where:} \quad \Delta\rho = \rho_d - \rho_m, \quad \text{and } f \propto R/V^{1/3}$$

or, expressed in terms of W, the weight per drop:

$$\gamma = \frac{\Delta\rho W}{2\pi R \rho_d f}$$

Measurement Procedure

The drop-weight apparatus is shown in Figure 2.2. The basic procedure for obtaining surface and interfacial tensions is as follows:

1) Fill an appropriate size beaker with the medium fluid so the dropping tip will reach into the fluid. The dropping liquid must be of greater density than the medium fluid for obvious reasons. Record the weight of the beaker and fluid.*

*NOTE: A balance capable of measuring to ±0.0001 gm is needed for sufficient accuracy of weight differences.

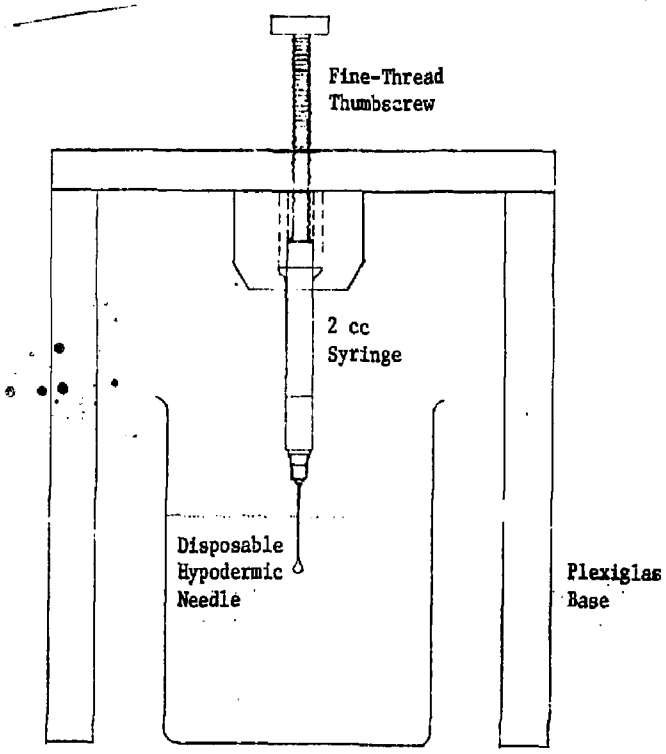


Figure 2.2 Drop-Weight surface tension measuring apparatus.

2) Very slowly form a prescribed number (10-20) of drops off the dropping tip into the medium fluid. About one minute should be allowed to form each drop in order to approach a static situation. Record the new weight of the system and compute the weight difference due to the drops.

3) Better accuracy may be obtained by compensating for weight loss through evaporation and tip wetting.

4) Compute the $R/V^{1/3}$ ratio and find appropriate correction factor (f) from the tables.

5) Knowing $\Delta\rho$, V, g, R, and f one can now easily calculate γ. Error analysis can be applied to obtain limits of accuracy for the measurement.

Results

The Table 2.1 below summarizes the results obtained with the drop-weight apparatus for a variety of liquids and liquid/liquid systems.

Acknowledgment

Greg Kallio was largely responsible for construction of the drop-weight measurment apparatus and for development of the technique by which reproducible results were achieved. Kent Martinek made the measurements shown in Table 2.1.

Droplet Liquid	Medium	Average Result	Temp.	Comparison Value
Acetophenone	10 cS DC-200 Fluid	2.12 Dynes/cm	27°C	2.1 Dynes/cm
Acetophenone	100 cS DC-200 Fluid	2.91	27°C	
Acetophenone	1000 cS DC-200 Fluid	3.78	27°C	
Glycerol	10 cS DC-200 Fluid	24.03	27°C	
Glycerol	100 cS DC-200 Fluid	25.47	27.5°C	
Glycerol	1000 cS DC-200 Fluid	27.74	27.5°C	
Water	1000 cS DC-200 Fluid	33.84	27.5°C	
Acetophenone	Water	13.59	27°C	
Corn Oil (Mazola)	Water	11.00	27°C	
Carbon Tetrachlorid	Water	42.44	27°C	43.7 (25°C)
Freon 113	Water	40.18	27°C	
Fluorinert FC-75	Water	29.17	27°C	
Glycerol	Acetophenone	6.28	26°C	8.9
Glycerol	Air	61.85	27°C	63.4 (20°C)
10 cS DC-200 Fluid	Air	19.35	27°C	20.1 (23°C)
Corn Oil (Mazola)	Air	26.13	27°C	62.2 (23°C)
Transformer Oil (Texaco #55)	Air	22.99	27.5°C	
Castor Oil	Air	35.09	27°C	

Table 2.1 Surface and Interfacial Tension Measurements

3. Charged liquid droplet levitation

Charged droplets of water, which is a relatively good electrical conductor (charge relaxation time $<10^{-6}$ sec), have been dynamically levitated in a quadrupole electrode apparatus [5,6], but similar experiments with droplets of insulating dielectric liquids have been hampered by two problems. First, the insulating nature of dielectric liquids makes them difficult to charge easily. Second, the surface tension of most dielectrics is small compared to water, resulting in a much smaller Rayleigh limit on the maximum stable droplet charge. Also, droplet elongation due to the electric field is more of a problem due to the lower surface tension. In order to determine the impact of the Rayleigh limit, droplet elongation, and electrical breakdown on dynamic charged particle levitation, the three-dimensional quadrupole system shown in Figure 3.1 was analyzed.

Summary of results

The following discussion is based on Research Report #3 [7]. For detailed treatment of these results, the reader is referred to this report. Figure 3.2a shows the effect of elongation, due to the dc gravity cancelling voltage V_g and the Rayleigh limit on the levitation of liquid droplets of H_2 at the triple point. The assumed properties are given in the figure. The breakdown field strength of H_2 at the triple point is not known, so the breakdown limit is not shown in Figure 3.2a. In Figure 3.2b, liquid droplets of Freon-113 are considered. Note that breakdown affects the ability to work with droplets with large charge to mass ratios (Q/m). For convenience, lines of constant elongation (γ equals ratio of semi-major axis to semi-minor axis)

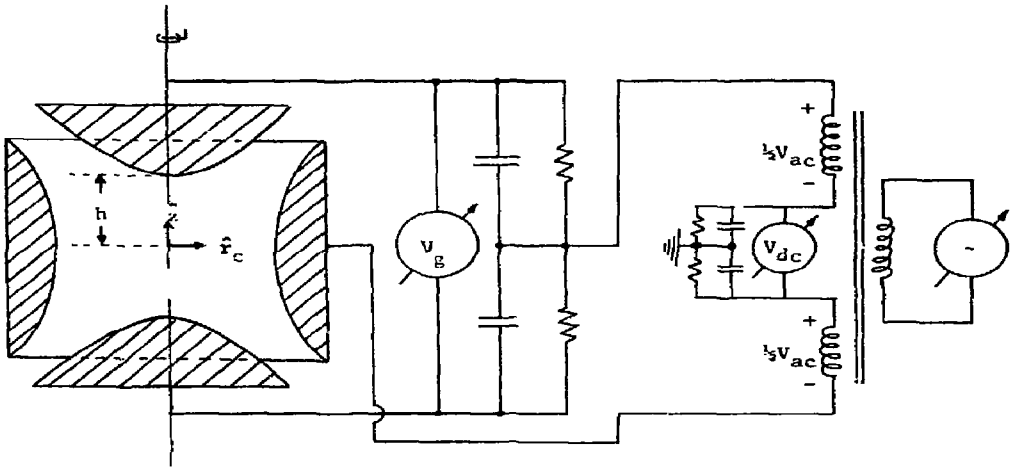


Figure 3.1 Three-dimensional quadrupole electrode structure (shown in sectional view) with high voltage circuit. V_g is the gravity cancelling potential.

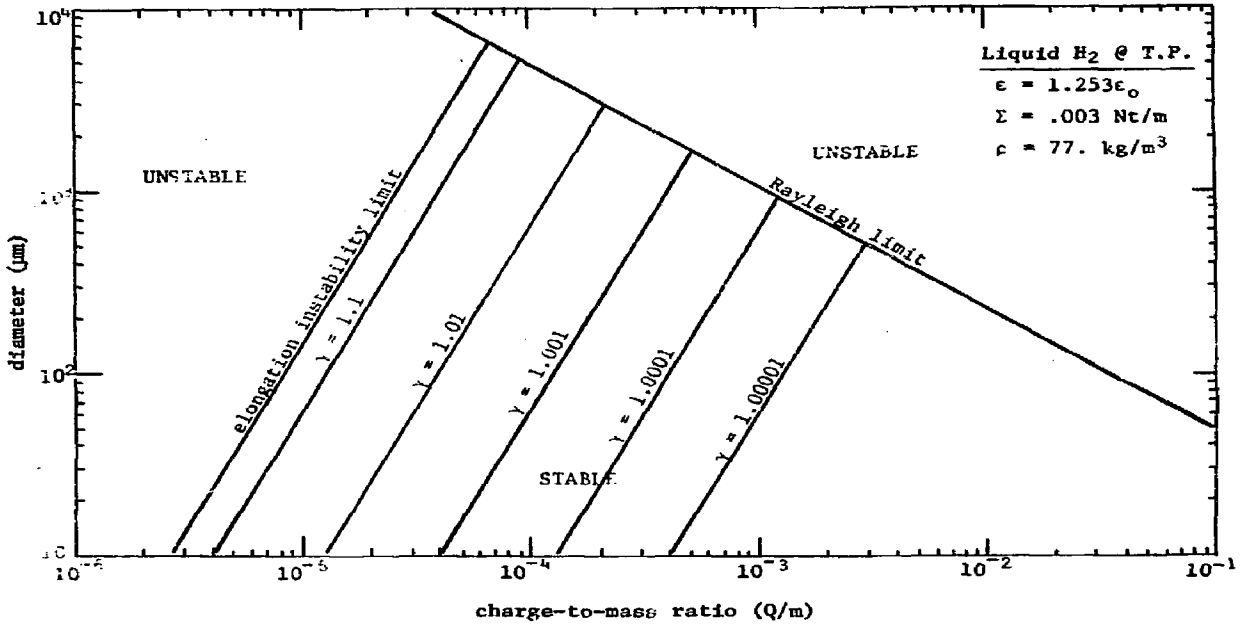


Figure 3.2a Stability map for droplets of liquid H_2 @ triple point (conducting limit).

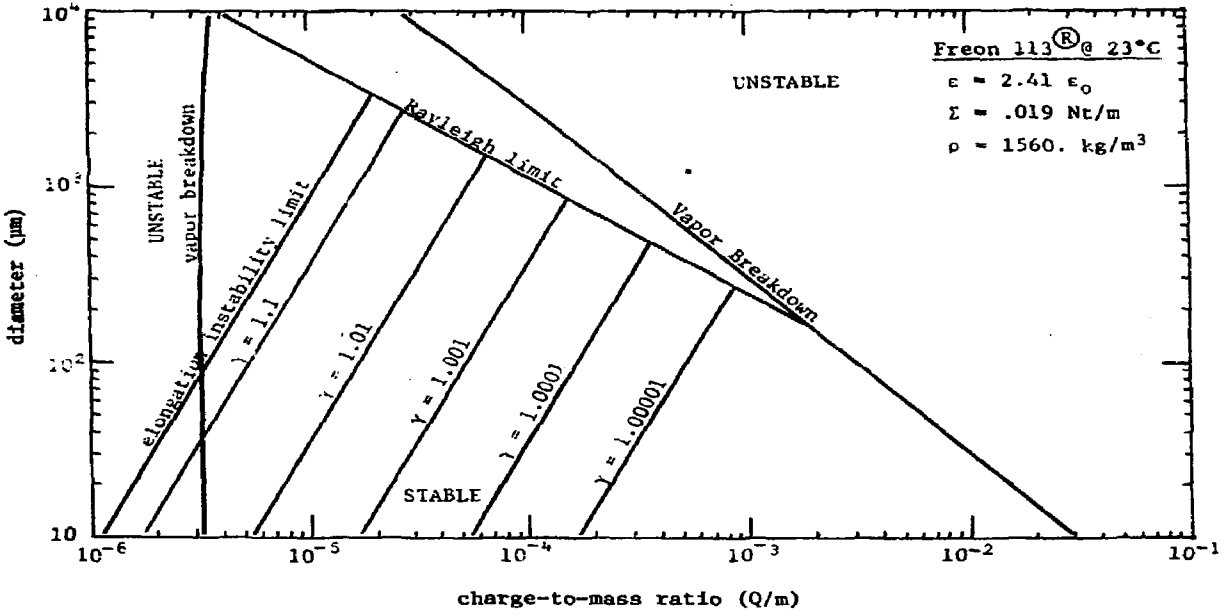


Figure 3.2b Stability map for droplets of Freon-113 R (conducting limit).

are plotted in 3.2a and b. Note that excessive elongation or particle charging results in EHD instability and droplet fragmentation.

Figures 3.2a and b fail to address the voltage and frequency criteria for stable levitation, which result from the characteristic curves of the Mathieu equation. The Mathieu stability criteria are discussed in the report [7], but one aspect of the problem merits mention here. If no gravity cancelling field is used ($V_g = 0$), then the stably levitated particle exhibits a gyrating orbit which is related to its mass. To guarantee that the particle will not strike an electrode surface and be lost before the worst of the motion is damped out, a lower limit on frequency is imposed. The combined effect of Mathieu stability and the trajectory limit are plotted for various Q/m values in Figure 3.3. This plot is seen to place rather stringent limits on frequency f and applied ac voltage V for a 1.0 cm three-dimensional quadrupole levitation. However, the study shows that suitably charged droplets of insulating dielectric liquid in the range of 1.0 millimeter can be levitated dynamically using reasonable voltages and frequencies. Whether the constraints on elongation imposed by target fabrication considerations are too stringent or not remains to be seen.

3ϕ hexapole levitator

A 3ϕ hexapole levitator system has been described by Wuerker, et.al. [8]. The analysis of this device carried out in the report [7] shows that it is limited in much the same way as the quadrupole system, though the voltage requirements are relaxed somewhat. Such a system is shown in Figure 3.4.

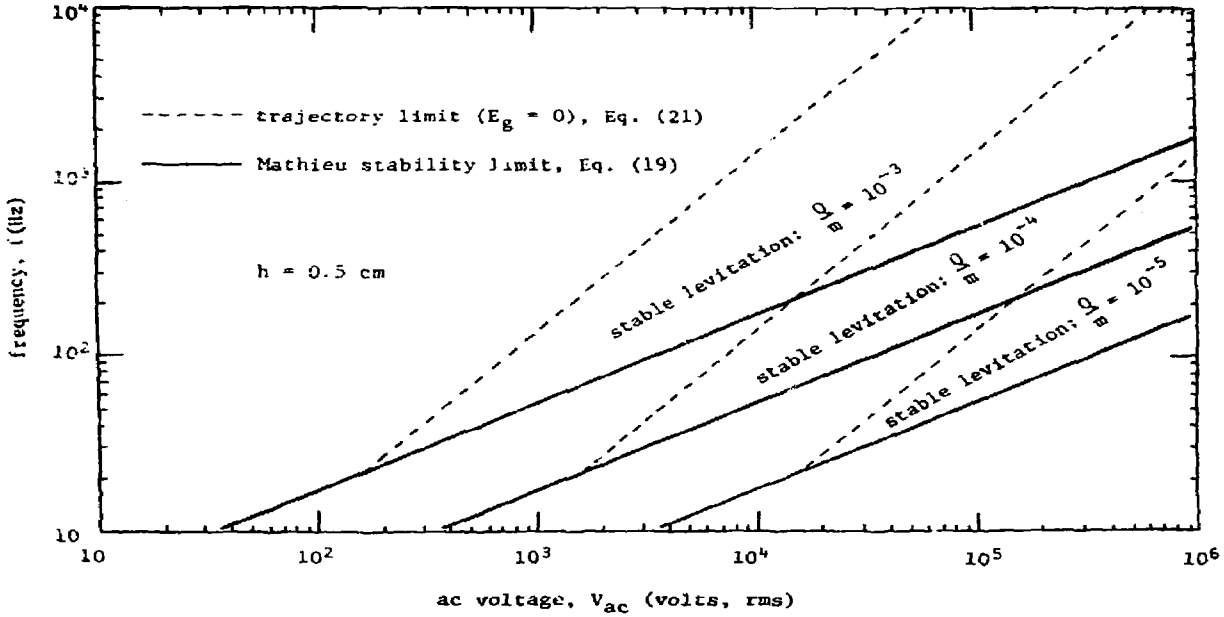
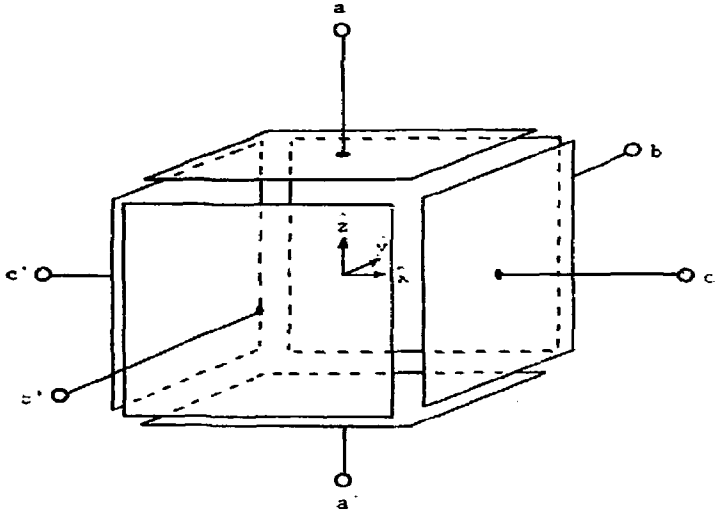
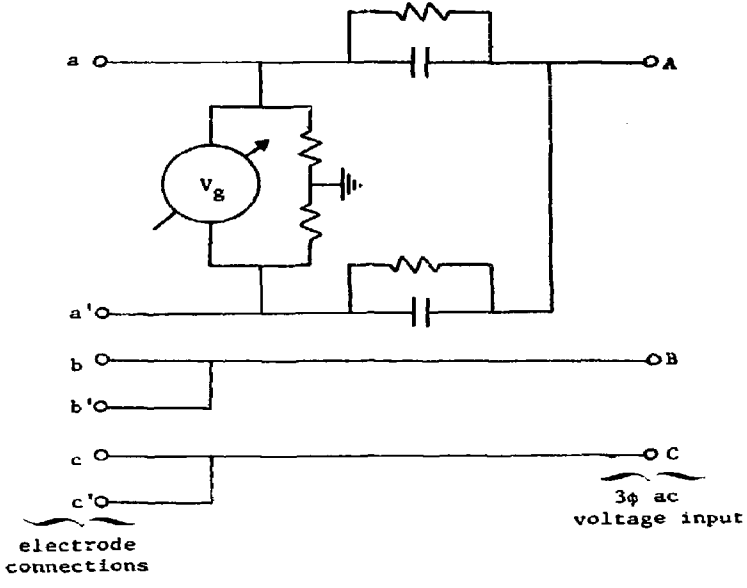


Figure 3.3 Frequency-voltage map for three-dimensional quadrupole (h = 0.5 cm).



a) three phase multipole



b) three phase circuit with gravity cancelling potential V_g

Figure 3.4 Three phase cubic face multipole electrode levitation system.

Experiments

Efforts to levitate charged droplets in a hexapole 3ϕ system did not meet with success. The problem was traced to the charge injection system. Repeatibility in the droplet charge, mass, and velocity was not achieved. Consequently, attention was diverted to the charged droplet injector system, in the belief that levitation cannot be reasonably expected unless suitable (Q/m) ratios and injection velocities are achieved. It was later ascertained that the Q/m ratios were too low for levitation. The next section covers the droplet injector.

4. Insulating liquid droplet production

The production of charged droplets of insulating liquids such as Freon-113 is complicated by two problems. First, the insulating nature of the liquid means that charge relaxation dominates in the charging time. For pure Freon-113, the important time constant is of the order of seconds, thus making the conventional capillary jet systems with a charging ring more difficult to work with. Another problem is that Freon-113 and most other insulating dielectrics have low surface tension, thus lowering the Rayleigh limit imposed maximum charge-to-mass ratio. These problems contribute significantly to present difficulties in the production of charged droplets of insulating liquids. Because of the interest in producing charged droplets of cryogenic liquids in laser target production related applications, the development of a somewhat different type of droplet generator for insulating liquids was proposed. The application was for injection of droplets into the dynamic levitator system described in section 3. The liquid chosen was Freon-113 because of its ease of handling, good breakdown strength, and its reasonably representative low surface tension and electrical conductivity values.

Droplet generator

The generator was designed for the production of single droplets of controlled diameter and charge-to-mass ratio, delivered at a controlled velocity. The system is shown in Figure 4.1. A thin glass capillary is mounted on the end of a hypodermic syringe needle. The liquid is supplied from a syringe at a carefully controlled rate. A fine tungsten wire inserted in the capillary serves to decrease the droplet charging time substantially. The droplet becomes charged by applications of the voltage

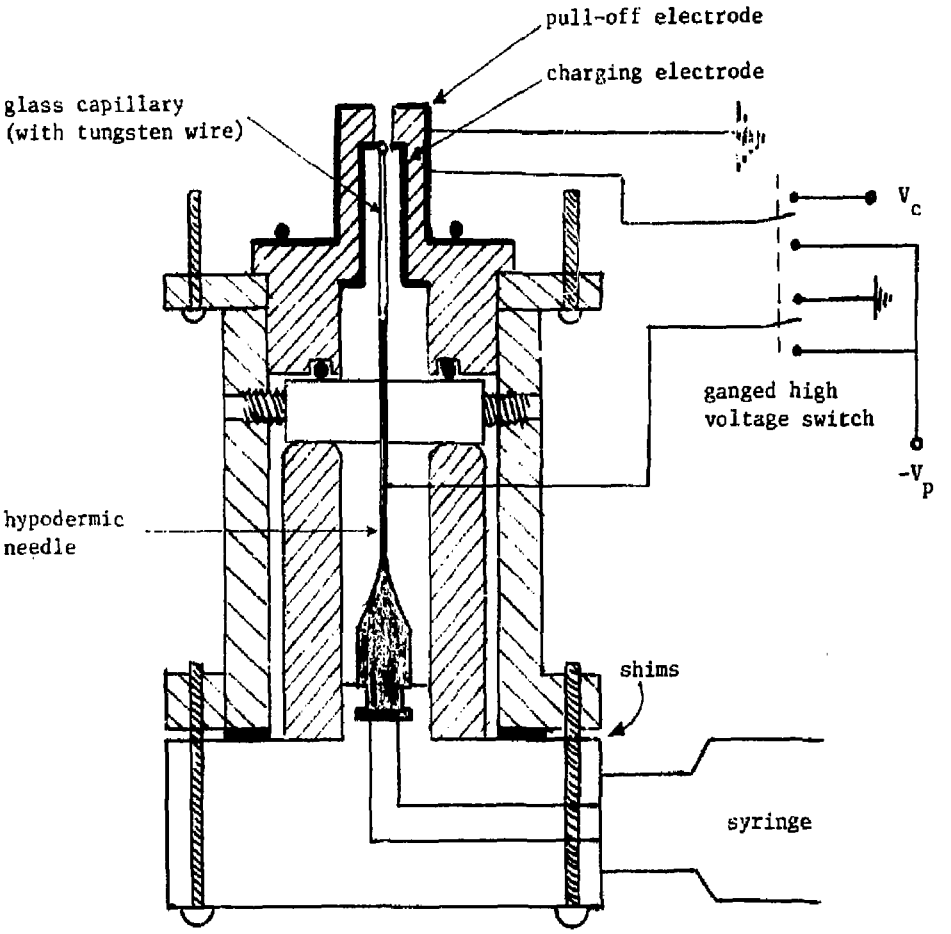
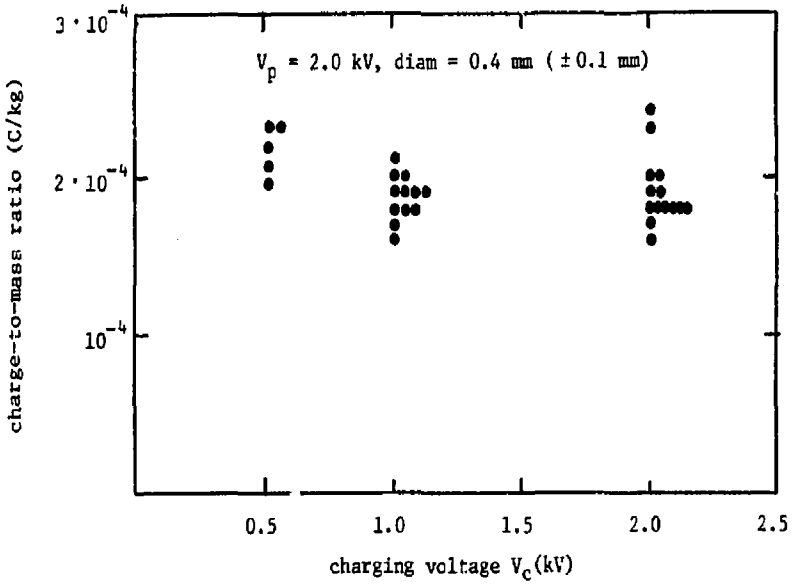

pull-off electrode
charging electrode
glass capillary
(with tungsten wire)
V_c
ganged high
voltage switch
$-V_p$
hypodermic
needle
shims
syringe

Figure 4.1

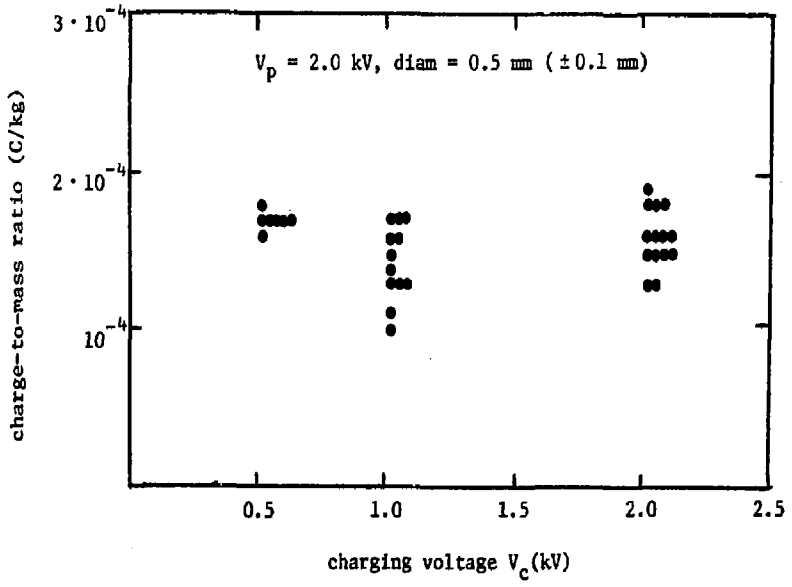
V_c (charging voltage) between the capillary and the charging ring which surrounds the droplet. To guarantee essentially full droplet charge, the charging period must exceed approximately 10 seconds. The droplet is ejected by suddenly reversing the polarity of the charging ring to $-V_p$ and bringing the capillary to the same potential. This creates a strong electric field between the droplet and the permanently grounded pull-off electrode. These voltage changes are accomplished with a ganged double pole high voltage switch immersed in oil and actuated by a solenoid.

The critical aspect of the system is the droplet formation and charging at the capillary tip. The droplet must be watched through a stereomicroscope to judge its size and its position on the tip. The manual control of the droplet growth during charging is tricky because if the droplet grows too fast, it can slip down off the tip. If the droplet growth is too slow, the droplet charges too rapidly and develops EHD surface instability or is pulled off the tip prematurely. These problems are minimized if the liquid is fed to the capillary at a constant rate. Then the voltage and flow rate are adjusted to form droplets which have the correct size and charge before ejection. The entire system can be automated to produce droplets at about 10 second intervals.

It is found that the charging voltage exerts little control over the charge for a given droplet size, at least for droplets not in charge equilibrium. This is shown in Figure 4.2a and b. These data were obtained by aligning the droplet gun vertically and shooting the droplets straight up to obtain a height of rise measurement. From stroboscopic records of their trajectories, the charge to mass ratio was determined. The influence of air drag was included. Some separate charge measurements were made later which, within the uncertainty of the droplet size



a) droplet diameter = 0.4 mm (±0.1 mm)



b) droplet diameter = 0.5 mm (±0.1 mm)

Figure 4.2 Charge-to-mass ratio data obtained from height of rise measurements.

estimates, confirmed these data. The data in Fig. 4.3 shows that the charge to mass ratio is a weak function of the pull-off voltage, presumably because the larger voltages cause the droplet to break up into a large droplet and a small satellite.

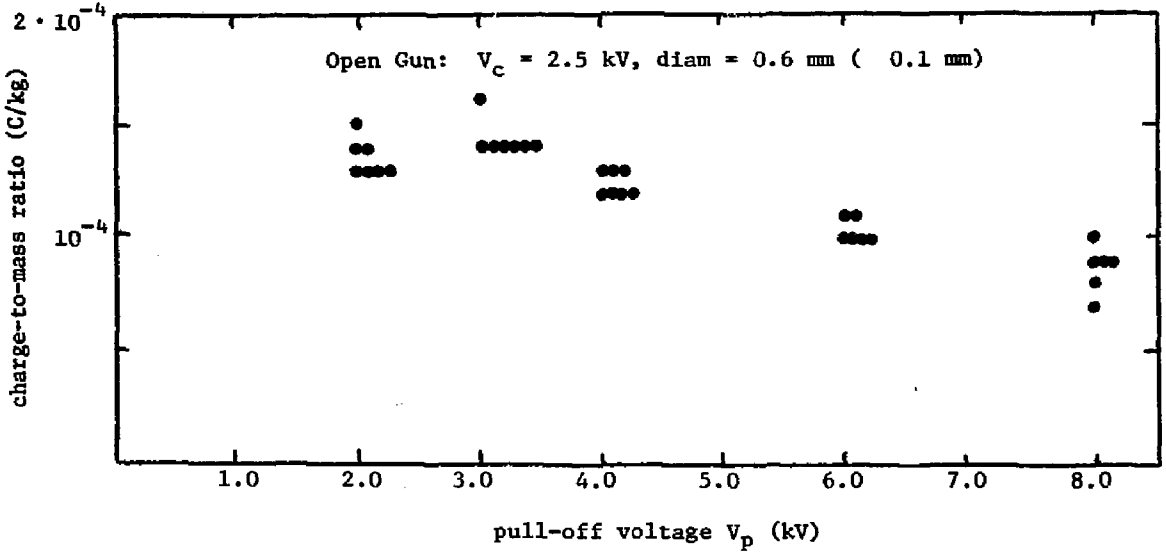


Figure 4.3 Chargo-to-mass ratio data with pull-off voltage varied. Droplet diam = 0.6 mm (± 0.1 mm).

5. Dynamic levitation of polarized particles

An alternative to charged particle levitation is the levitation of uncharged but polarized particles. Jones and Bliss showed that gas bubbles and some liquid droplets can be statically levitated in suitable insulating dielectric liquids [9]. This is dielectrophoretic levitation. The necessary conditions for successful levitation of this type are: (i) that the permittivity of the particle to be levitated be smaller than that of the surrounding fluid, and (ii) that the electric field frequency exceed the reciprocal charge relaxation time of both particle and fluid so that free charge buildup does not occur. The first of these conditions precludes the dielectrophoretic levitation of polarized particles in a vacuum. In an attempt to overcome the limitations of dielectrophoresis, a new dynamic levitation scheme was proposed. In this scheme, a particle is polarized (for example using a quasi-uniform dc electric field, and then dynamically stabilized by an ac field. This levitation scheme is unique because it permits levitation of uncharged (polarized) particles in a vacuum. The dipole moment of the particle is controlled by the dc electric field. In one variation, the scheme shows promise in the realm of molecular dipole mass spectroscopy [10].

Summary of results

The following discussion is based on Research Report #2 [11]. The basic system is shown in Figure 5.1. The electrodes produce an ac three-dimensional azimuthally symmetry hexapole field. The dc voltage produces a polarizing electric field. Numerically calculated equipotential lines for the dc (polarizing) field are shown in Figure 5.2. Analysis of the polarization forces on the particle shows that by proper

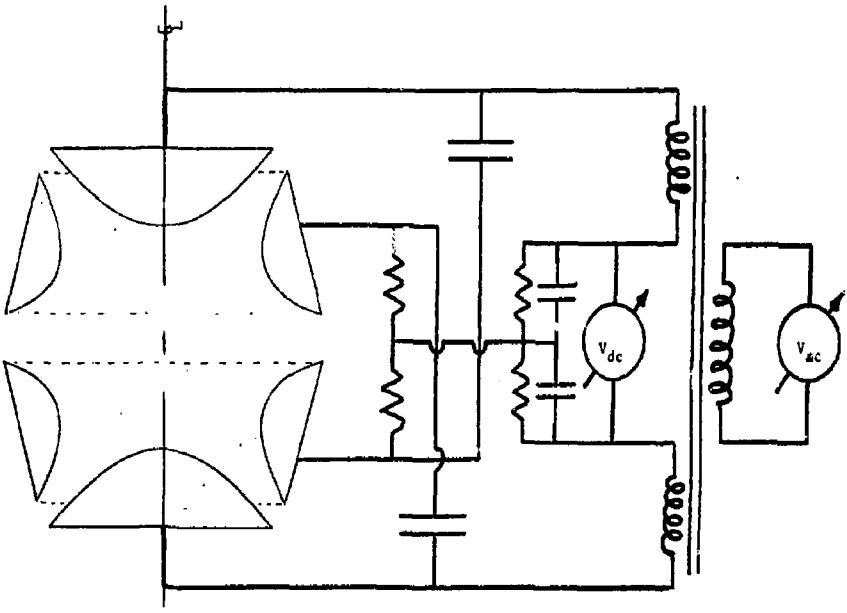


Figure 5.1 Three-dimensional hexapole electrode structure (shown in sectional view) with high voltage supply circuit. V_{dc} is polarizing potential and V_{ac} is dynamic stabilization potential.

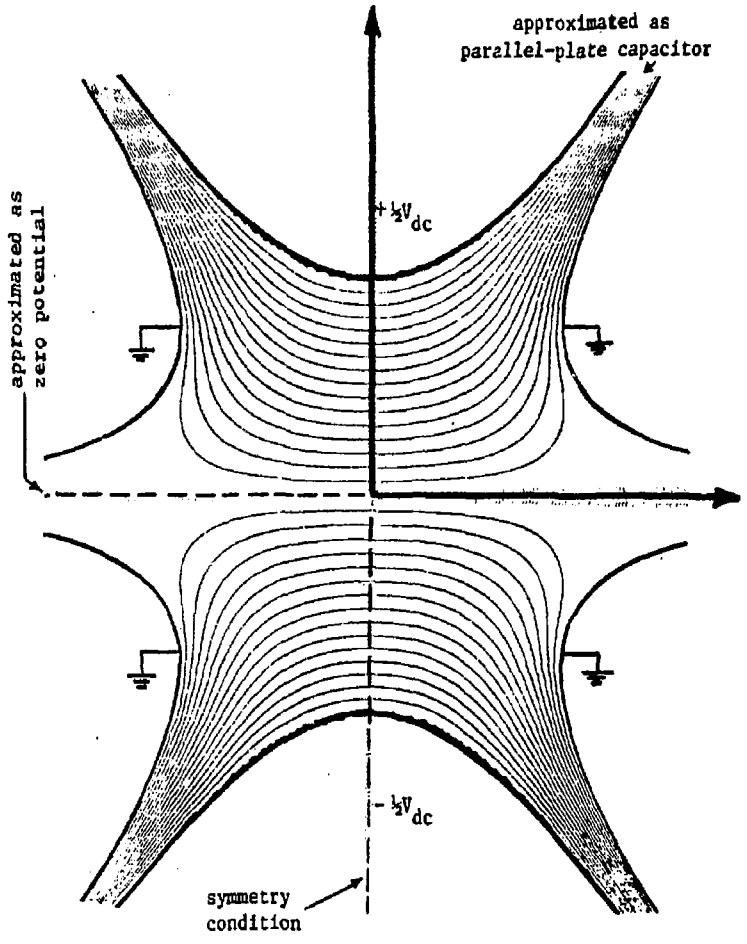


Figure 5.2 Equipotential plot of solution for dc polarizing electric field.

adjustment of the ac and dc voltages, the dc electric field will dominate in particle polarization. Thus, the dipole moment $\bar{p}$ is the dc term

$$\bar{p} \simeq \bar{p}_{dc}.$$

Likewise, the most non-uniform component of the electric field is the ac term. Therefore, the approximate dielectrophoretic force on the particle is

$$\bar{F}^e \simeq (\bar{p}_{dc} \cdot \nabla)\bar{E}_{ac}. \tag{5.1}$$

Assuming that $\bar{p}_{dc}$ is vertically directed, the force $\bar{F}^e$ can be expressed as a function of small displacements of the polarized particle from the center of the hexapole. This force is found to be a linear function of the displacement with the typical time-varying coefficient. It is to be noted that the quadrupole field does not produce a linear restoring force. Thus, the particle system is parametric and fits the form of the Mathieu equation. Stable solutions represent possible levitation zones. Three factors influencing levitation are the Mathieu stability criteria, the geometrical limit due to the influence of gravity, and, for liquid particles, elongation due to the dc polarizing electric field. Figure 5.3 maps regions of stable levitation for a 1.0 mm droplet of liquid hydrogen in a vacuum for a hexapole electrode structure with 2.0 cm spacing between the top and bottom end electrodes. Various values of the elongation parameter γ (semi-major axis to semi-minor axis) are plotted to provide some measure of the particle distortion. Some of this same information is replotted in Figure 5.4 which shows the frequency versus the convenient parameter $(V_{ac}V_{dc})^{\frac{1}{2}}$. A lower frequency limit of ~20 Hz is apparent.

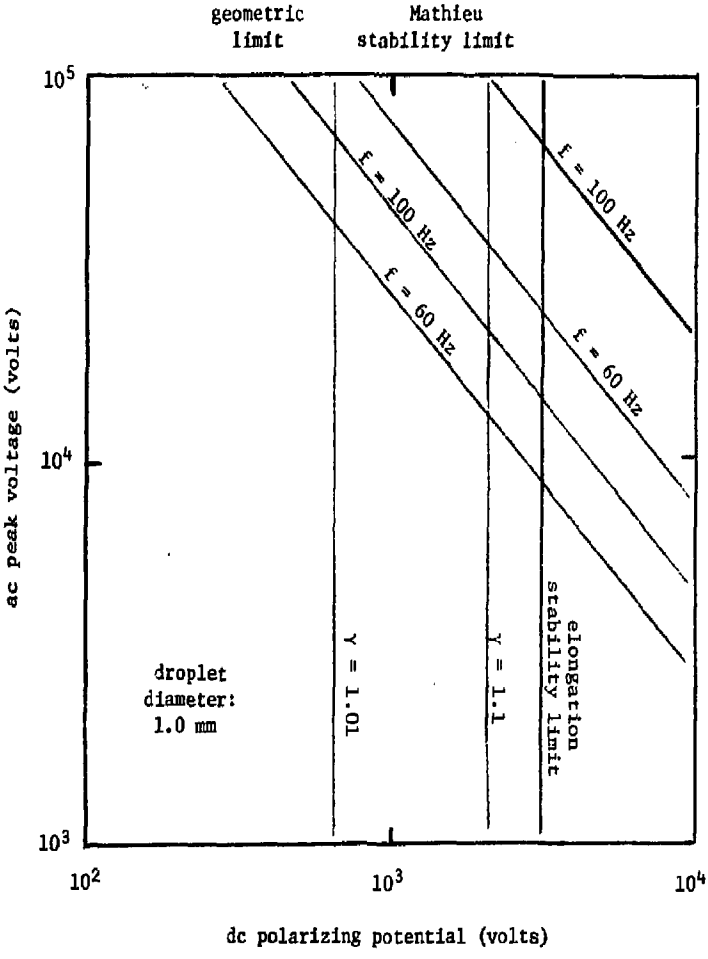


Figure 5.3 Ac peak voltage *vs.* dc voltage for 1.0 mm diam cryogenic hydrogen droplets in vacuum.

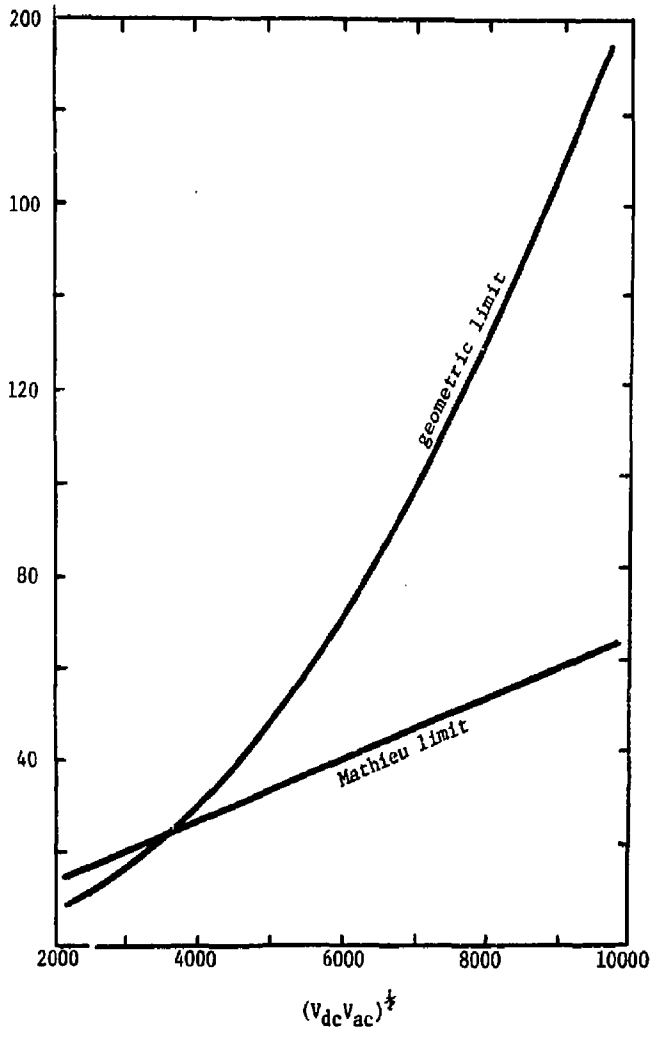


Figure 5.4 Graph of stable levitation conditions for cryogen hydrogen droplet (1.0 mm diam).

The principal problem with the hexapole levitation scheme is the requirement of large voltages, with attendant breakdown problems and other largely practical difficulties. The high voltages are necessitated by the relatively weak nature of polarization forces compared to Coulomb forces. It is clear that the advantages of being able to levitate uncharged particles in a vacuum would have to outweigh the practical disadvantages of the higher voltages before the hexapole levitator could compete with conventional quadrupole charged particle levitation.

Experiment

In an attempt to test the claims of the theory, an experiment was designed. To minimize the voltage requirements, the levitation of magnesium spheres (~1.0 mm diam.) in castor oil was attempted. Magnesium spheres are just slightly heavier than castor oil. Thus, the voltage required for particle polarization and levitation are smaller. The conditions for stable levitation in viscous fluids are discussed thoroughly in Appendix B of Research Report #2 [11].

Considerable effort was devoted to the attempt to levitate the small magnesium spheres in castor oil. However, no success was achieved. In most cases, there was great difficulty in particle injection. Dropping or pushing the sphere through a hole in the uppermost electrode was very difficult. Once into the hexapole electrode test cell, the particle invariably behaved as if it was electrically charged. This charge might have resulted from space charge injected into the castor oil by the dc polarizing electric field, though the presence of such space charge was never verified. Another possible problem is the effect of the very viscous medium on the stability criteria. The criteria

developed in Appendix B of the Research Report #2 [11] have not been tested. The only possible alternative to the reduced gravity simulation experiment attempted would be small conducting spheres in vacuum. However, the voltage requirements are very high.

6. Static levitation of polarized particles

Based on the successful levitation of bubbles [9], considerable effort was devoted to the dielectrophoretic levitation of small dielectric spheres. This work is thoroughly covered by Kallio [12] who experimented with solid dielectric spheres and shells. Theoretical analysis led to frequency-dependent criteria for stable levitation. The theory was compared to extensive experimental results.

Dielectrophoretic levitation

Using a cusped electric field produced by a ring-disk electrode system, small particles and bubbles can be levitated using the dielectrophoretic force. See Figure 6.1. In the familiar high-frequency limit ($\omega >> \sigma/\varepsilon$) where the particle and the surrounding fluid are effectively insulators, the criterion for levitation is $\varepsilon_2 < \varepsilon_1$, where ε_1 and ε_2 are the permittivities of the fluid and the particle, respectively. At low frequencies and dc, however, this criterion is invalid; and so a more general frequency-dependent criterion for lossy dielectric media was sought. The result is shown in Figure 6.2. Particles with relative permittivities $\left(\frac{\varepsilon_2}{\varepsilon_1}\right)$ and conductivities $\left(\frac{\sigma_2}{\sigma_1}\right)$ which plot out in quadrant I can not be levitated; combinations in quadrant III can always be levitated for any frequency. Points in quadrant II can be levitated above some cutoff frequency f_c and points in quadrant IV can be levitated only below this cutoff.

$$f_c = \frac{1}{2\pi}\sqrt{\frac{(\sigma_1 - \sigma_2)(\sigma_2 + 2\sigma_1)}{(\varepsilon_2 - \varepsilon_1)(\varepsilon_2 + 2\varepsilon_1)}} \qquad (6.1)$$

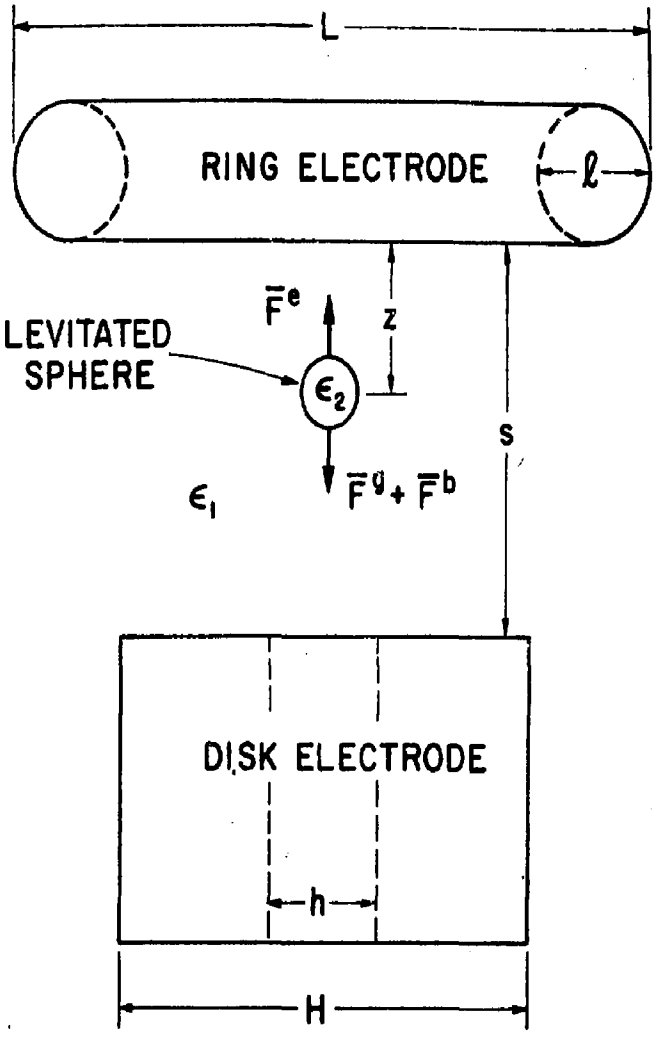


Figure 6.1 Ring-disk DEP levitation electrodes.

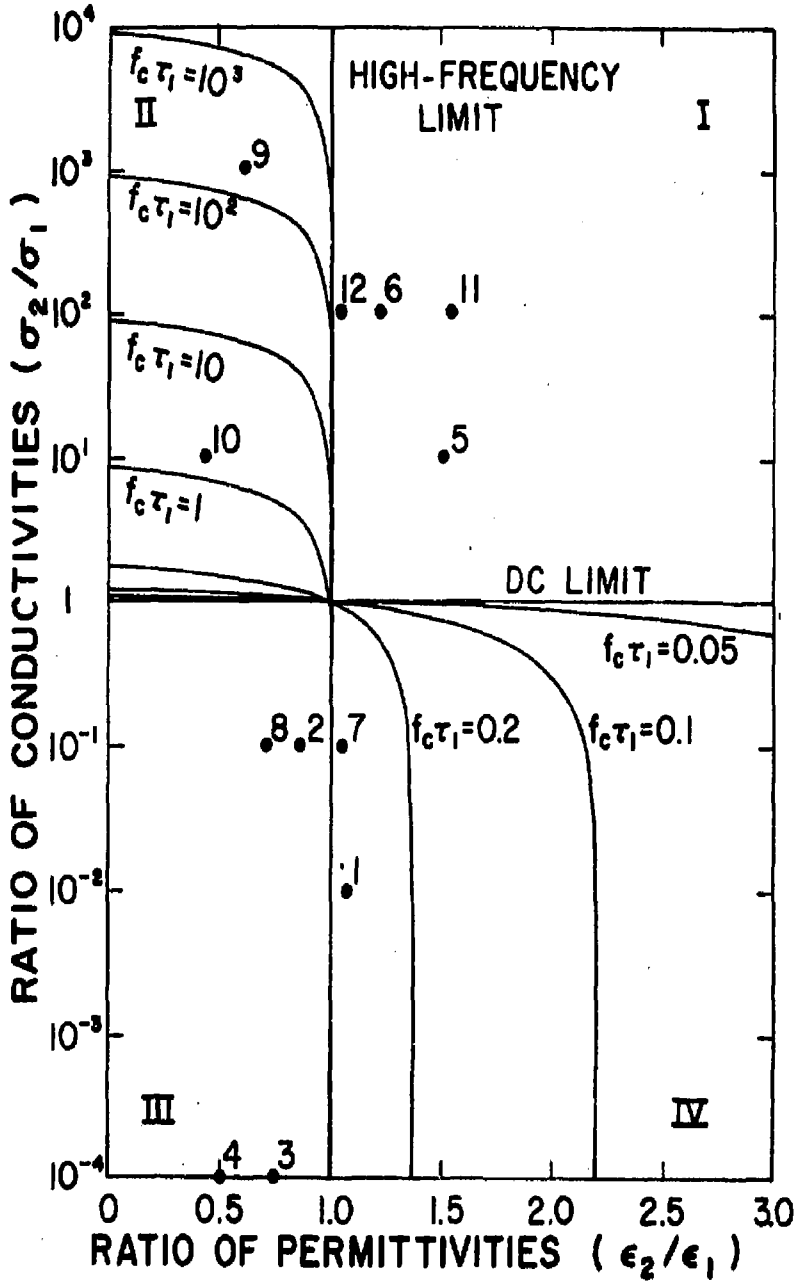


Figure 6.2 DEP levitation plot with frequency criteria.

TABLE 6.1 Results of some levitation experiments for ac and dc voltages. See Figure 2.

POINT	SPHERE	LIQUID	experiment ac*	experiment dc
1	Polystyrene	Transformer Oil	NO	NO
2	"	Silicone Fluid	YES	—
3	"	Corn Oil	YES	—
4	"	Castor Oil	YES	YES
5	Polyvinyl acetate	Transformer Oil	NO	NO
6	"	Silicone Fluid	NO	—
7	"	Corn Oil	NO	NO
8	"	Castor Oil	YES	—
9	Glass Microballoon	Transformer Oil	YES	NO
10	"	Corn Oil	YES	NO
11	"	Corn Oil	NO	—
12	"	Castor Oil	NO	—

*$f \geq 45$ Hz for all ac experiments.

The numbered points in Figure 6.2 refer to experiments, the results of which are tabulated in Table 6.1.

Table 6.2 contains a more complete tabulation of the ac experiments performed, showing the voltages required to levitate each sphere at the same position. These experimental results were obtained from two test cells which are quite similar geometrically and which are illustrated in Figure 6.1. Some readily available physical property data for the experimental dielectrics used is summarized in Table 6.3. Probably the least well-characterized are the glass and acrylic microballoons. The shell thickness values are known to little better than a factor of two, while the conductivities are at best known to within a factor of ten. Of all the particles levitated, only the glass microballoons exhibited

TABLE 6.2 AC dielectrophoretic levitation results (T = 25°C, f = 100 Hz).

Test Cell	Sphere or Shell	Typical Diameter (mm)	Medium Liquid	Levitation Voltage (Kv, rms)
	Air	0.2 - 1.0	Transformer Oil	19.4
	"	"	Silicone Fluid	16.7
	"	"	Corn Oil	14.3
	"	"	Castor Oil	11.0
#1	Acrylic Microballoon	~0.07	Transformer Oil	18.8
	Glass Microballoon	~0.24	" "	21.4
	" "	"	Corn Oil	14.4
	Glass (solid)	0.17 - 0.18	Castor Oil	Unsuccessful
	Sodium Nitrite	~1	" "	"
	Air	0.2 - 1.0	Silicone Fluid	20.3
	"	"	Dowtherm® A	17.5
	"	"	Corn Oil	17.4
	"	"	Castor Oil	13.4
	Polystyrene	0.4 - 1.2	Transformer Oil	Unsuccessful
	"	"	Corn Oil	12.2
#2	"	"	Castor Oil	5.7
	Polyvinyl Acetate	0.7 - 1.3	Corn Oil	Unsuccessful
	" "	"	Dowtherm® A	"
	" "	"	Castor Oil	12.3
	Epon® Resin	0.9 - 2.1	" "	25.0
	Polyester Resin	~1	" "	Unsuccessful
	Torr Seal® Epoxy	~2	" "	"

TABLE 6.3 Properties of liquids and solids used in levitation experiments

a. Spheres and Fluids

Dielectric Material	Mass Density, $\rho(kg/m^3)$	Relative Permittivity, $\varepsilon/\varepsilon_0$	Electrical Conductivity, σ(siemens)
Air	~1	1.00	——
Polystyrene	1055	2.4 - 2.65	$<10^{-14}$
Polyvinyl Acetate	1190	?	$<10^{-11}$
Epon® Resin[1]	1160	?	?
Transformer Oil[2]	893	2.23	$1.1 \cdot 10^{-12}$
Silicone Fluid[3]	971	2.75	$1.0 \cdot 10^{-13}$
Corn Oil[4]	914	3.1	$\sim 5 \cdot 10^{-11}$
Dowtherm® A	1056	3.26	$1.6 \cdot 10^{-10}$
Castor Oil[5]	958	4.3 - 4.7	$\sim 10^{-10}$

b. Microballoons[6]

Dielectric Material	Typical Diameter (10^{-6} m)	Ave. Shell Thickness (10^{-6} m)	Mass Density, $\rho(kg/m^3)$	Rel. Perm. of Shell, $\varepsilon/\varepsilon_0$	Elec. Cond. of Shell, σ(siemens)
Glass	240	~5	~2300	4-6	?
Acrylic	70	0.2 - 0.3	1180-1190	~3	$<10^{-13}$

[1]Epon® 828 cured with agent Y.
[2]Texaco #55.
[3]Dow Corning 200® fluid, 1000 cs.
[4]Mazola®.
[5]Humco, Diamond Quality.
[6]Samples obtained from Lawrence Livermore Laboratory, California.

frequency-dependent behavior. At lower frequencies, the microballoons required higher levitation voltages. This is consistent with the relatively conducting nature of the glass. Glass microballoons would certainly be located in quadrant II of Figure 6.2.

Dc levitation experiments

Table 6.1 shows that only polystyrene balls in castor oil could be levitated using dc electric fields. The required voltage was low because the polystyrene was almost neutrally buoyant in castor oil. Other combinations were tried without success. These failures have been attributed to dc electroconvection which disrupts dielectrophoretic levitation by liquid motions which sweep the particle out of the cusped electric field. In the case of polystyrene spheres in castor oil, the required levitation voltage was apparently below the electroconvection threshold.

Another interesting feature of dc levitation is the possibility of electrostatic repulsion caused rotation of the spheres. This Quincke rotation was observed in levitated polystyrene spheres. This type of rotation might be important in promoting uniform coatings for dielectric spheres.

Dielectric constant measurement

The ring-disk levitator has been proposed as a means of measuring the dielectric constants of liquids and small spherical particles [12]. The measurement scheme relies on a calibration of the electrodes using a standard liquid of well-known dielectric constant. Calibration is performed by levitating a small gas bubble in the standard liquid at a predetermined position. Then all unknown particles or bubbles in unknown liquids are levitated at the same position. Thus, only an accurate

voltage measurement is required, and no quantitative knowledge of the cusped electric field is required. To guarantee a precision measurement, an accurate standard liquid is required. Also required are accurate high voltage measurement, a hypodermic syringe to produce small bubbles, and a low power microscope, preferably with a reticle eyepiece to permit precise positioning of the bubble or particle before measurements are made.

The system is simple and easy to use. No precision machining is required in fabrication of the electrode measurement cell. The system is rather insensitive to leveling. No accurate capacitance measurements are called for. With a very simple system, Kallio reports accuracies of ~3% in liquid dielectric constant measurement at low frequencies [12].

7. Droplet and bubble elongation

Garton and Krasucki [13] showed that insulating and conducting droplets or bubbles fluid media elongate under the influence of electric fields. The elongation is further complicated if dc electric fields are considered and if electrohydrodynamic surface pumping is taken into account [14]. The purpose of studying this matter here was to arrive at some conclusion about the problem of droplet deformation in insulating fluids when the deformation is small. The tolerance requirement for laser targets suggest that even very small deformation might be unacceptable. Thus, approximate, first-order expressions for the deformation of insulating and conducting droplets and bubbles were derived and used to perform calculations for some interesting fluids [15].

Typical calculated results are shown in Figures 7.1 and 7.2. In these plots, the ratio of semi-major to semi-minor axes minus one is plotted versus the applied uniform electric field. From these graphs it is clear that elongation is a more serious problem with large droplets and bubbles.

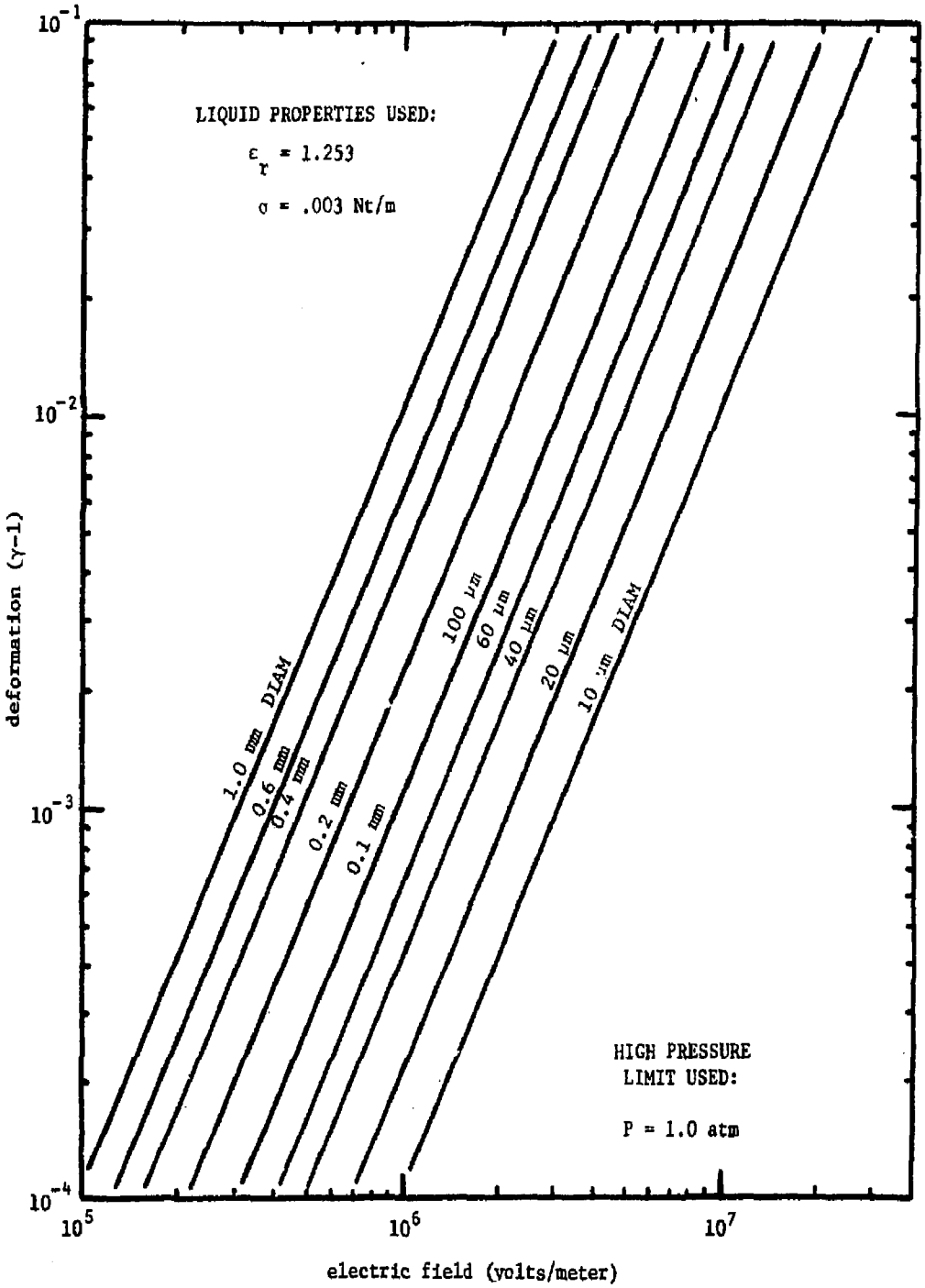


Figure 7.1 Deformation of an incompressible droplet of liquid hydrogen (H_2) at the triple point.

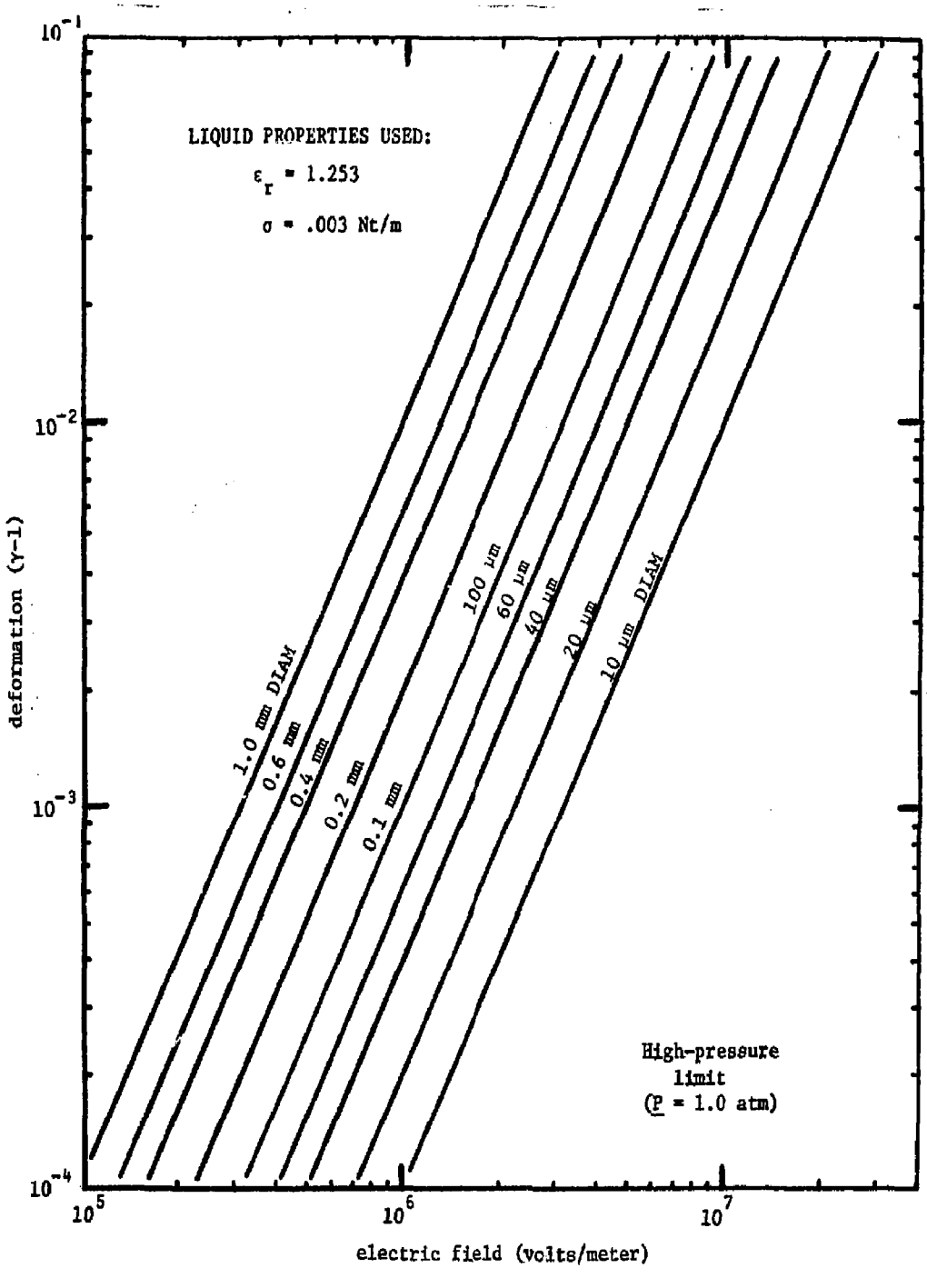


Figure 7.2 Deformation of a compressible bubble in liquid hydrogen (H_2) at the triple point.

8. Synchronous DEP pumping of bubbles and particles

A promising application of dielectrophoresis in laser target fabrication and processing is in the remote handling of microballoons in cleaning solutions or ultrasonic baths. Experience with the levitation of bubbles, microballoons, and solid particles (see section 6) indicates that the dielectrophoretic force can be used to hold such particles at a precisely controlled position. This unique capability is subject to the practical restriction that both the liquid medium and the particle are relatively good electrical insulators. Another important requirement for remote handling of laser targets in cleaning solutions is to be able to move these targets from place to place. The nature of the dielectrophoretic force and the charge relaxation time constants of typical dielectrics restricts us to synchronous interactions. A dielectric particle of permittivity ϵ_2 in a surrounding liquid medium of permittivity ϵ_1 will seek an electric field minimum. If this minimum is made to move, the particle will tend to follow it. It will be held back by the viscous drag force exerted on the particle by the liquid. Obviously, if the synchronous speed is too great, the viscous drag can exceed the maximum DEP pumping force and the particle will pull out of step with the electric field. This behavior is analogous to that of an ac synchronous alternator. Once the particle falls out of step, it is questionable whether any net force can be exerted. The long charge relaxation times would seem to preclude any effective induction (non-synchronous) pumping mechanism.

Synchronous bubble pump

The following is a description of the proposed bubble pump. The electrode structure consists of rings mounted on a common axis and

energized by multiphase ac high voltage. See Figure 8.1. The multiphase voltage produces a travelling potential wave with regularly spaced electric field nulls. The discrete nature of the electrodes poses the same problem as the discrete pole and winding sizes of rotating machines, namely harmonics. These harmonics affect the behavior of the field nulls causing an irregular cyclic motion which is superimposed on the average synchronous motion. Harmonics can pose a problem because the motion of the particles in a liquid is viscous- rather than inertial-dominated.

In an attempt to learn more about the behavior of these nulls due to three-phase excitation, an electrolytic tank was constructed and used to obtain equipotential plots at different times (phases) of the ac voltage cycle. One of these plots is shown in Figure 8.2. Due to the tedious nature of the method required to obtain the plots only a few plots have been obtained, yet from these certain features of the travelling wave behavior may be ascertained. First, the "sharpness" of a given null varies as it moves along. This means that the dielectrophoretic force will more firmly hold the particle during certain times of a cycle. During other times the DEP force strength will be weaker. The pull-out condition is most certainly controlled by the shallowest null which exists during a cycle. A quantitative calculation of the electric fields, taking into account the finite size of the electrode rings, might be possible using the method employed by Masuda, et.al. [16]. However, it appears now that the experimental approach is fully warranted at this point.

No experimental pump has yet been built, but the design of such a device has been considered. The required voltages depend in a very

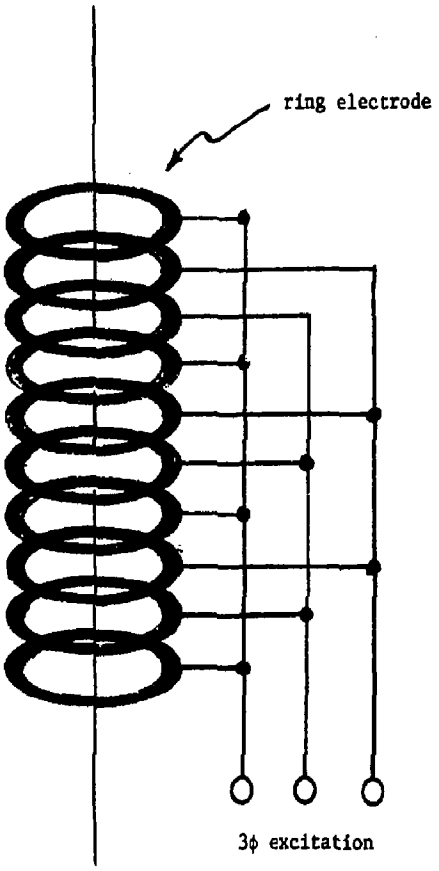


Figure 8.1 Three phase excited DEP bubble/particle pump.

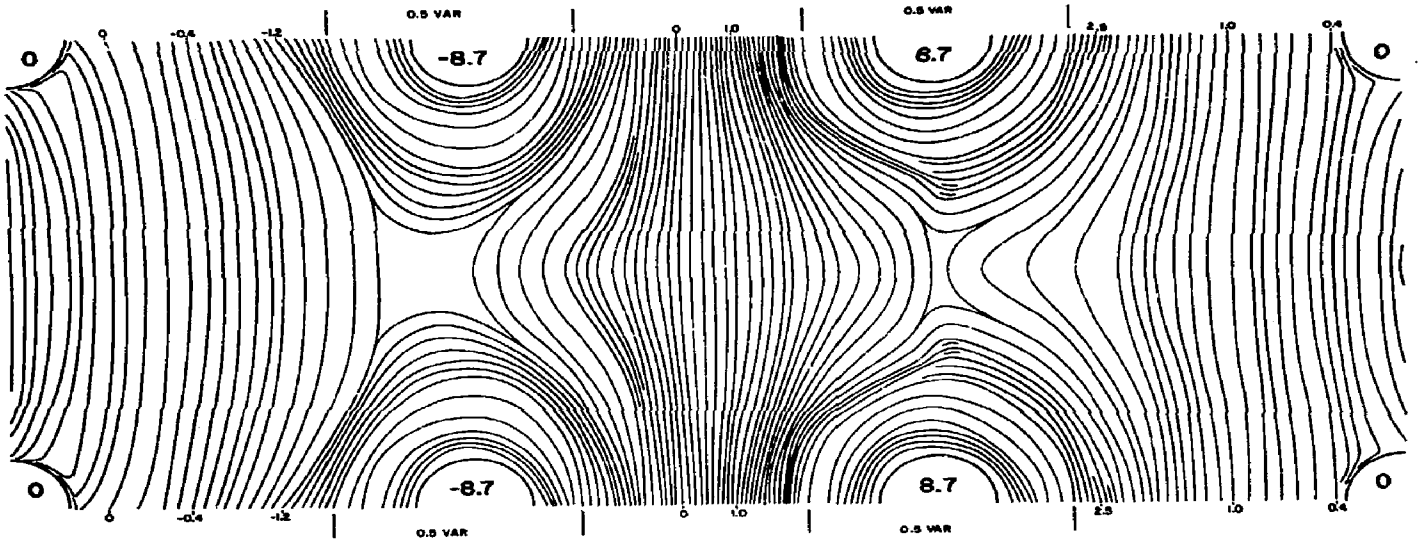


Figure 8.2 Equipotential plot of 3ϕ bubble pump.

complex way on the electrode spacing. The synchronous speed v_s is related to the wavelength and frequency

$$v_s = \lambda f.$$

The viscous drag to be overcome depends linearly on v_s. Therefore, the product of the wavelength λ and frequency f should be small. The wavelength depends on the minimum electrode spacing. Refer to Figure 8.1 where λ is defined for three-phase excitation. A reasonable *minimum* value for λ is 1.0 cm, given the electric field strengths common in DEP levitation. If the synchronous speed is to be 1.0 cm/sec, then f = 1.0 Hz. For a synchronous speed of 10 cm/sec, f = 10 Hz. Higher velocities require stronger electric fields where electrical breakdown and electroconvection become serious problems. Therefore, the experiments appear to be limited to low frequencies. A three-phase voltage supply in the range of 1.0 - 10 Hz is required. Standard H.V. transformers do not function properly at these frequencies.

Experiments have been conducted with single-phase excitation of the ring structure shown in Figure 8.1. The results confirm the existence of regularly spaced nulls. One or more particles can be trapped in each null. By decreasing and then increasing the particles will move up or down under the influence of gravity, stopping at each null. This is not pumping, but it may be useful in handling large numbers of particles sequentially.

9. Silane rheotaxy experiment

It was proposed by Jorgenson [17] that a gas bubble containing silane gas could be used in the formation of glass microballoons. The gas bubble is held in position by a DEP levitator while the reaction occurs. If the reaction of silane and oxygen can be controlled to occur only at the interface, then a glassy film would presumably form, which could be annealed at high temperatures or using an intense laser beam.

Simple calculations for the mass required to form a glass shell of suitable thickness indicate that high pressures (tens of atmospheres) would be required. Efforts to design and fabricate the experiment have shown that the approach is very complex and potentially dangerous, due to the high pressures and the spontaneously explosive character of SiH_4. Therefore, a simpler experiment was first conducted to ascertain the likelihood of controlling the normally violent reaction. In this experiment, a 1.0" diameter pyrex tube is mounted vertically with a high-pressure gas chromatographic septum mounted in the bottom cap. The tube is filled with Viscasil^R, a highly viscous silicone fluid and it is zone heated to ~100°C. Two gas chromatography syringes are used to create a bubble with silane and a mixture of oxygen and helium. The purpose of the helium is to moderate the reaction. The bubble once formed rises slowly at first until in encounters the heated layer of viscasil. The added heat usually promotes the reaction which occurs explosively. Under these conditions, the experiment itself is not dangerous because of the very small volume of silane reacted, but elaborate safety precautions are still necessary in order to vent any unreacted silane still in the system to the outside. After a reaction,

the gas bubble is always very cloudy. This indicates the presence of fine silica powder in the gas bubble which now contains helium and water vapor. This reaction is probably occurring too fast to be of value in forming a uniform SiO_2 film on the surface of the bubble. Better temperature and pressure control would be needed to decrease the speed of the reaction. Getting this reaction to occur at the gas/liquid interface at a controlled rate is the real problem. Once formed, the glass would probably require annealing.

The field of rheotaxy, where reactions are promoted and controlled at a liquid interface, is undeveloped. Silane chemistry is imperfectly understood as well. Therefore, it is clear that the elaborate initial experimental undertaking was quite premature. A well-planned series of modest experiments, designed to learn the conditions under which the silane/oxygen reaction can be promoted and controlled at a liquid interface, would have been a better strategy. This experiment appeared to be very attractive initially because it made use of the bubble levitator in a novel microballoon fabrication process. There is no reason to doubt that the bubble levitator would work under the high-pressure and high-temperature conditions desired for silane rheotaxy. Rather, the difficulties lie in the high pressure system itself and in control of the normally explosive silane/oxygen reaction. Given the present research emphasis on vacuum and plasma/chemical processing of laser targets, there is little reason to pursue silane rheotaxy further.

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