Appendix for Plasma Antennas

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I. Safe Far-UVC as a Type of Plasma Antenna Operating at 222 nm.

Below is a basic Far-UVC prototype built by Haleakala R&D, Inc. This Far-UVC device is similar to a plasma antenna in that it has a plasma tube and an exciter to create the plasma. Instead of say transmitting RF radiation for example, it transmits at 222 nm.

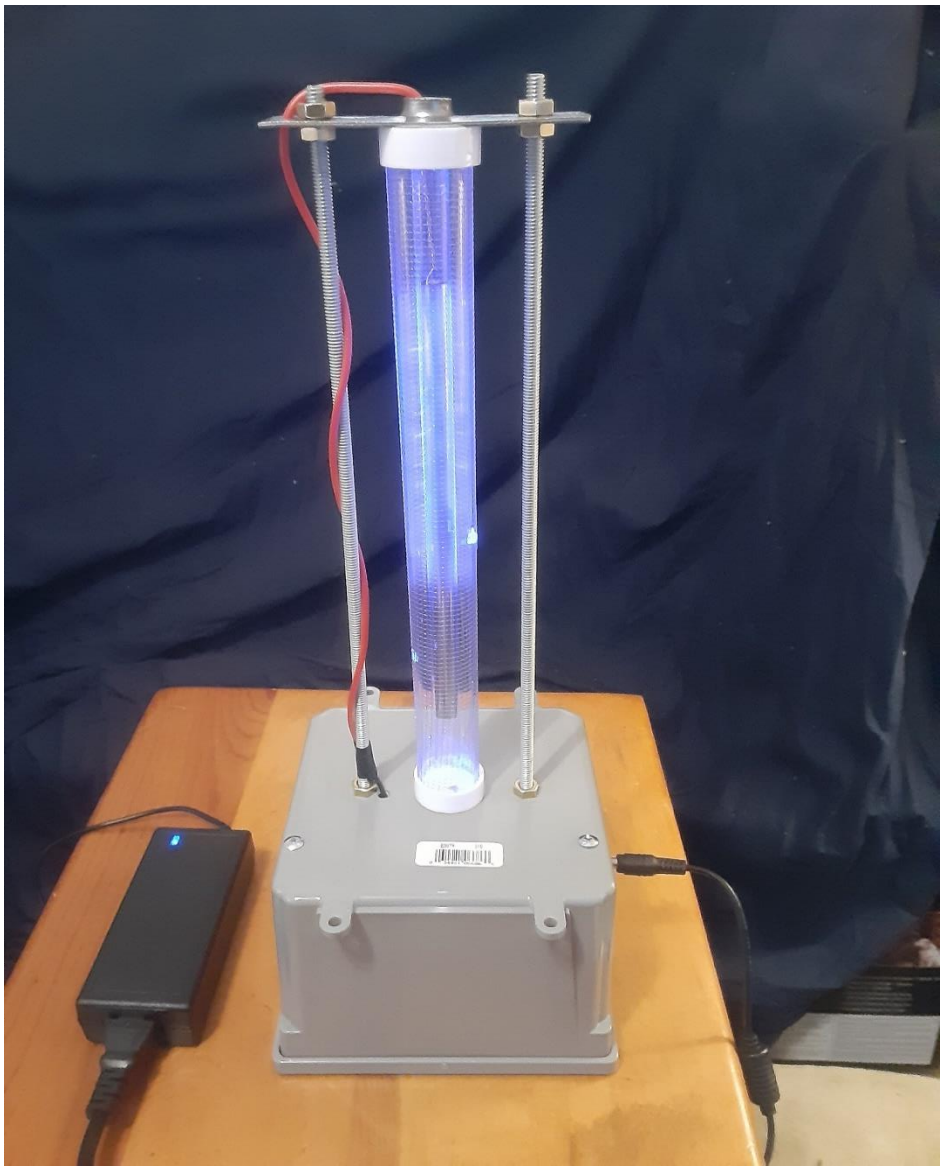

Figure A.1. Basic Far-UVC prototype operating at 222 nm. The structure is similar to a plasma antenna in that there is a tube with plasma that radiates electromagnetic waves and an exciter to create the plasma. For example instead of the plasma tube radiating electromagnetic waves say in the RF frequency range like a special case of a plasma antenna, it radiates at 222 nm. Electromagnetic waves at 222 nm will inactivate viruses without harming humans unlike other UV devices.

II. The Significance of Far-UVC in Virus Inactivation.

The COVID-19 pandemic has heightened awareness of the risks associated with disease transmission by surface- and, particularly, airborne-associated pathogens; this risk awareness brings a desire for solutions. There is unequivocal evidence that UV-C can be used to reduce the incidence of communicable diseases transmitted via fomites and by airborne droplets or aerosols across a range of settings. UV-C disrupts the reproductive cycle of the targeted pathogens, rendering them inactive. Further, recent studies have conclusively shown that UV-C rapidly inactivates SARS-CoV-2, the virus that causes COVID-19, as well as other common airborne pathogens such as influenza viruses. Far UV-C radiation (200-230 nm) is a region of the UV-C spectrum not traditionally used for disinfection, though it has been known to be an effective antimicrobial and antiviral agent. The significance of Far UVC is that, whereas exposure to conventional germicidal UV (250-280 nm) at germicidal doses is potentially hazardous, biophysical and experimental evidence suggest this is not the case for Far UV-C; greater absorption by protective surface layers results much less damage to skin and eye, while maintaining disinfection efficacy. Thus Far UV-C offers the potential to fundamentally change how and where UV-C radiation can be used for surface and, particularly, airborne decontamination, opening the potential for its use in occupied spaces.

III. Fundamental Biophysics of Far-UVC to Inactivate Viruses.

1. Introduction.

Transmission of SARS-CoV-2, the beta coronavirus causing COVID-19, is believed to be both through direct contact and airborne routes, and studies of SARS-CoV-2 stability have shown viability in aerosols for at least 3 hours[1]. Far-UVC radiation (207–222 nm) efficiently kills pathogens without causing harm to exposed human tissue[2, 3]. It has been demonstrated that 222-nm Far-UVC light efficiently inactivates airborne influenza virus, human coronaviruses, *e.g.*, alpha HCoV-229E and beta HCoV-OC43[2]. As all human coronaviruses have similar genomic sizes, Far-UVC light would be able to inactivate other human coronaviruses including SARS-CoV-2 with similar dosage efficiency[2]. Based on the beta-HCoV-OC43 results, continuous Far-UVC exposure in occupied public locations at the current regulatory exposure limit (~3 mJ/cm^2/hour) would result in ~90% viral inactivation in ~8 minutes, 95% in ~11 minutes, 99% in ~16 minutes and 99.9% inactivation in ~25 minutes[2]. Thus, while staying within current regulatory dose limits, low-dose-rate Far-UVC exposure can safely provide a major reduction in the ambient level of airborne coronaviruses in occupied public locations.

2. Ultraviolet (UV) Light Exposure is a Direct Antimicrobial Approach

Ultraviolet (UV) light exposure is a direct antimicrobial approach and its effectiveness against different strains of airborne viruses has long been established[4]. The most commonly employed type of UV light for germicidal applications is a low pressure mercury-vapor arc lamp, emitting around 254 nm and more recently xenon lamp technology has been used, which emits broad UV spectrum[5, 6]. However, while these lamps can be used to disinfect unoccupied spaces, direct exposure to conventional germicidal UV lamps in occupied public spaces is not possible since direct exposure to these germicidal lamp wavelengths can be a health hazard, both to the skin and eye..

3. Human Health Risks of Ultraviolet (UV) Light Exposure vs Far-UVC Light.

By contrast Far-UVC light (207 to 222 nm) has been shown to be as efficient as conventional germicidal UV light in killing microorganisms, but studies suggest that these wavelengths do not cause the human health issues associated with direct exposure to conventional germicidal UV light[2, 3]. The reason is that Far-UVC light has a range in biological materials of less than a few micrometers, and thus it cannot reach living human cells in the skin or eyes, being absorbed in the skin stratum corneum or the ocular tear layer. But because viruses (and bacteria) are extremely small, Far-UVC light can still penetrate and kill them. Thus Far-UVC light potentially has about the same highly effective germicidal properties of UV light, but without the associated human health risks. Several groups have thus proposed that Far-UVC light (207 to 222 nm), which can be

generated using inexpensive excimer lamps, is a potential safe and efficient anti-microbial technology and can be safely deployed in occupied public locations.

4. Penetration Depth in Skin and Eyes of Ultraviolet (UV) Light Exposure vs Far-UVC Light.

Far-UVC light in this wavelength range (207to 222nm) has a very limited penetration depth. Specifically, Far-UVC light (207–222 nm) is very strongly absorbed by proteins through the peptide bond, and other biomolecules. Consequently, the ability of Far-UVC radiation to penetrate biological materials is very limited compared with, for example, 254 nm (or higher) conventional germicidal UV. This limited penetration is still much larger than the size of viruses and bacteria, so Far-UVC light is as efficient in killing these pathogens as conventional germicidal UV light. However, unlike germicidal UV light, Far-UVC light cannot penetrate either the human stratum corneum (the outer dead-cell skin layer), nor the ocular tear layer, nor even the cytoplasm of individual human cells. Thus, Far-UVC light cannot reach or damage living cells in the human skin or the human eye, in contrast to the conventional germicidal UV light which can reach these sensitive cells. In summary, Far-UVC light is anticipated to have about the same anti-microbial properties as conventional germicidal UV light, but without producing the corresponding adverse effects to skin and eyes. Should this be the case, Far-UVC light can be used in occupied public settings to prevent the airborne person-to-person transmission of pathogens such as coronaviruses.

5. The Efficacy of 222 nm Light Against Airborne Human viruses

It has been reported that Far-UVC light at 222 nm is more effective than UV light at 254 nm for inactivation of *Staph. aureus* [7]. Importantly, a very small dose (2 mJ/cm^2) of Far-UVC light at 222 nm is highly efficient in inactivating aerosolized H1N1 influenza virus[3]. The efficacy of 222 nm light against two airborne human coronaviruses: alpha HCoV-229E and beta HCoV-OC43 has also been tested. Both the SARS-CoV-2 and the HCoV-OC43 virus are from the beta genus. The inactivation efficacy of Far-UVC light against two human coronaviruses was measured for aerosol droplets of sizes similar to those generated during sneezing and coughing. All coronaviruses have comparable physical and genomic sizes, which is a critical determinant of radiation response. Figure 1 shows the fractional survival of aerosolized coronaviruses HCoV-229E and HCoV-OC43 as a function of the incident 222-nm dose.

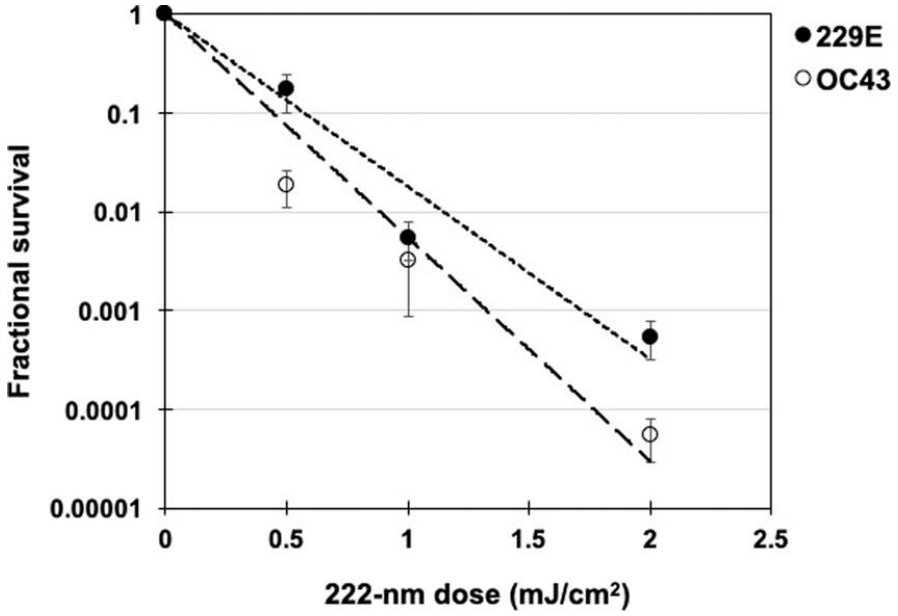

Figure A.2. The fractional survival of aerosolized coronaviruses HCoV-229E and HCoV-OC43 expressed as a function of the incident 222-nm dose (from Buonanno M, et al. (2020) Scientific Reports 10(1)).

Log-reduction is often used to describe the effect of disinfectant treatment against a pathogen population, and it is defined as

$$X = log_{10} \frac{N_0}{N}.$$

For example, 1-log_{10} (X = 1) unit reduction corresponds to 90% reduction of the pathogen from its initial population, or $N/N_0 = 0.1$. To quantify the efficacy of the UV light, the inactivation cross section, D_{90}, was often used. D_{90} depicts the UV dose that inactivates 90% of the exposed virus, following

$$D_{90} = -ln[1 - 0.90]/k,$$

where k is the UV inactivation rate constant or susceptibility factor (cm^2/mJ).

Buonanno *et al.* reported that the corona virus inactivation cross section D_{90} = 0.56 and 0.39 mJ/cm2 for HCoV-229E and HCoV-OC43, respectively[2].

IV. Conventional Far-UVC Technology

Studies and research developing devices emitting ultraviolet (UV) and vacuum UV (VUV) radiation of excimer and exciplex molecules can be traced back to the middle of last century[8]. The common term *excilamp* was proposed as a single designation for all sources of spontaneous emission based on excimer and exciplex molecules[9]. Besides gaseous lamps, solid state emitters

in the Far-UVC range were reported recently[10]. However, these solid state Far-UVC LEDs are limited to μW outputs and exhibit short lifetimes[11], and so do not currently represent a viable technology for effective disinfection.

For gas discharge-based devices, dielectric barrier discharge (DBD) – based excilamps are mostly used and a typical configuration is shown in Fig 2. While various excimers produce useful Far-UVC light (200 to 230 nm) the most common one in lamp use today, and the most investigated for germicidal and SARS-CoV-2 efficacy, is the Krypton-Chlorine exciplex molecule KrCl* (often just called KrCl) that emits Far UVC in a narrow emission line at 222 nm wavelength and is reasonably efficient, typically 10%, at converting exciter power into UV. The KrCl excilamps have a wide variation in gas mixtures and pressures but the generally available lamps have 1-4% percent (by weight) of Krypton and Chlorine with a balance background (or buffer) gas of Argon at total pressures of 1 to 100's Torr. The non-UV emitting Argon gas helps to cool the hot Kr and Cl gases (a small tube plasma is generally only a few percent ionized) that reabsorb the 222 nm UV, a major problem of efficiency reduction. Total UVC power emitted in the gas is dependent on the volume of gas, but the UVC radiation is attenuated through the gas. Therefore, large tubes such as the left one illustrated in Fig. 2, are not efficient as the bulk of the UVC is produced deep within the plasma and is highly attenuated on its way out. The majority of the UVC that is radiated out of the lamp is produced near the surface. A disadvantage is that high voltage is exposed. A way of reducing the reabsorption path length is to reduce the "long path" reabsorption using thinner plasmas such as the coaxial geometry shown in Fig. 2 (right), although the coaxial geometry is more difficult to produce than the round tube. In addition, other configurations such as a planar geometry (not illustrated) was also proposed before, but flat UV grade fused silica tubes are fragile and difficult to manufacture, and they are hence only available in small sizes for low power applications. Another advantage of the thinner plasma configurations is lower exciter frequency and voltage. Because of the corrosive nature of the Far UVC producing halogen excimers, such as Chlorine, conventional metal electrodes, such as used in inert gas (neon, argon, etc) tubes, would react with the halogen and be destroyed, as well as contaminate the plasma and the glass. So, exciters that couple capacitively through the glass, a dielectric, to the plasma are used. High frequency RF, e.g., 1-30 MHz, is commonly used for the round tube configurations, but for the smaller gap higher capacitive configurations, e.g., coaxial and planar, lower frequency is used, e.g. 20-100 kHz. The lower frequency exciters are called DBD exciters[12] and can create plasmas at relatively high pressure, e.g., atmospheric pressure or higher. DBD excited lamps require high voltage to obtain sufficient capacitively coupled current, e.g. 5-10 kV, but modern power electronics produces such DBD voltages cheaply with very high efficiency >90%.

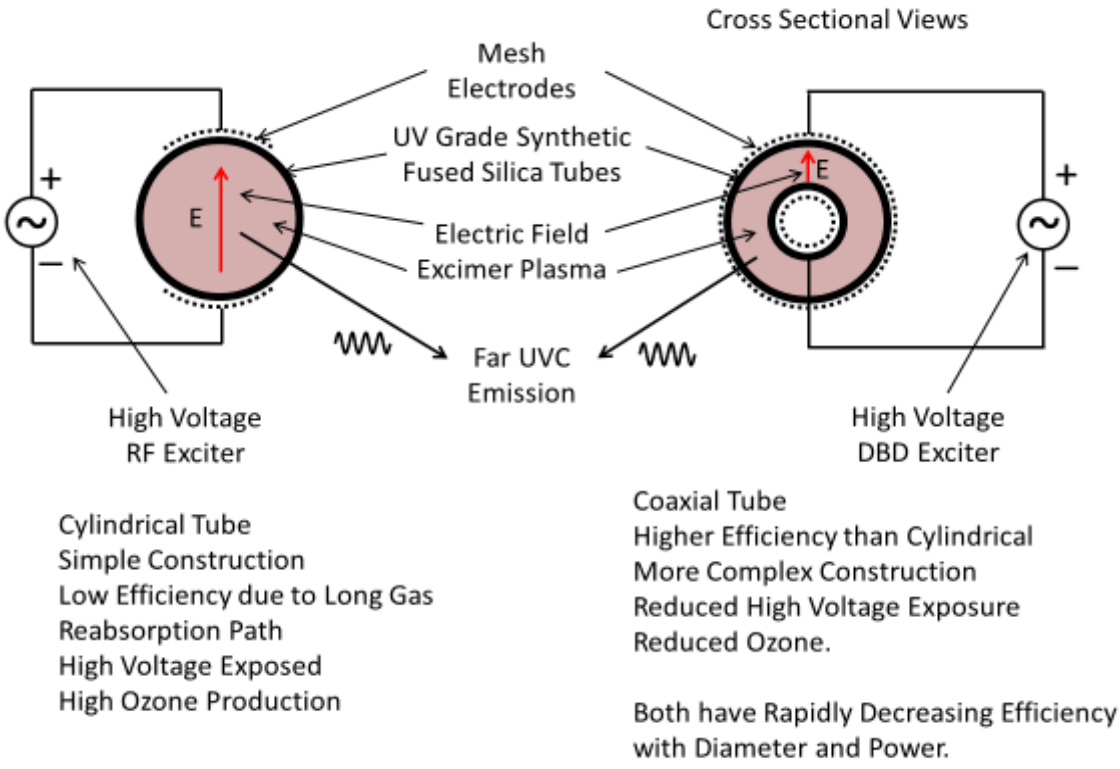

Figure A.3. Conventional Far-UVC excilamp based on DBD plasmas (left) with a simple cylindrical tubular construction, and (right) with a coaxial tubular construction

V. Surface Wave Excitation for New Configurations of Excilamps

We propose to research new configurations of excilamps that utilize surface excitation. Consider the last configuration of Fig 1. The concept is to create highly ionized plasma only near the surface of the tube by putting alternating polarities of DBD or RF driven electrodes (e.g. wires or plated on strips) distributed around the surface. That way the UVC emitting plasma is near the surface, and the interior is non-ionized cold gas. UVC radiation can efficiently escape via the short path to the surface or the long path through the cold interior.

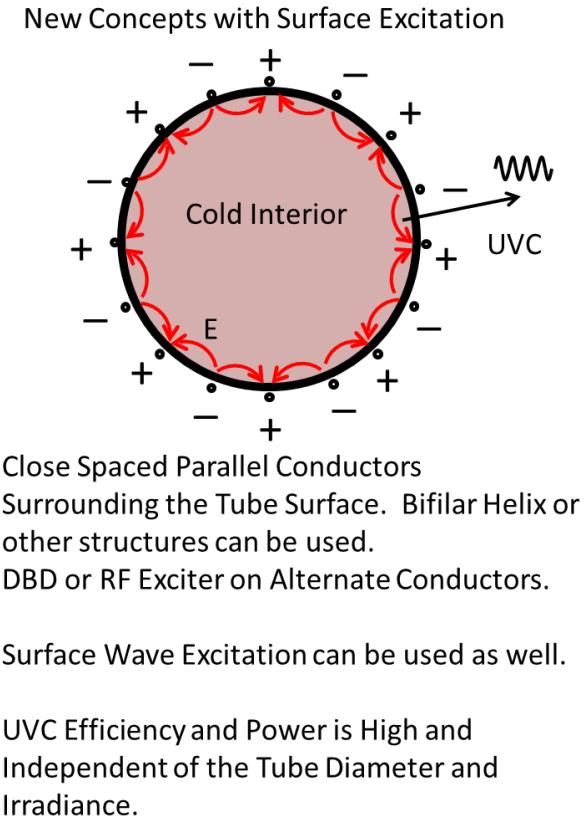

Figure A.4. Conventional bulk plasma excitation excilamps and new surface excitation excilamp.

An even more advanced concept of a surface excited Excilamp is shown in Figure 2. This uses a plasma exciting device called a Surfatron that launches RF surfaces waves onto the plasma-space

boundary, analogous to water-air surface waves. The surface waves are very short and do not couple or radiate into free space. This concept does not utilize any exposed high voltage electrodes, the RF electrode is totally enclosed and is shielded from free space radiation, and is EMI, spark, and ozone free. It can be used in situations that are dangerous to use high voltage.

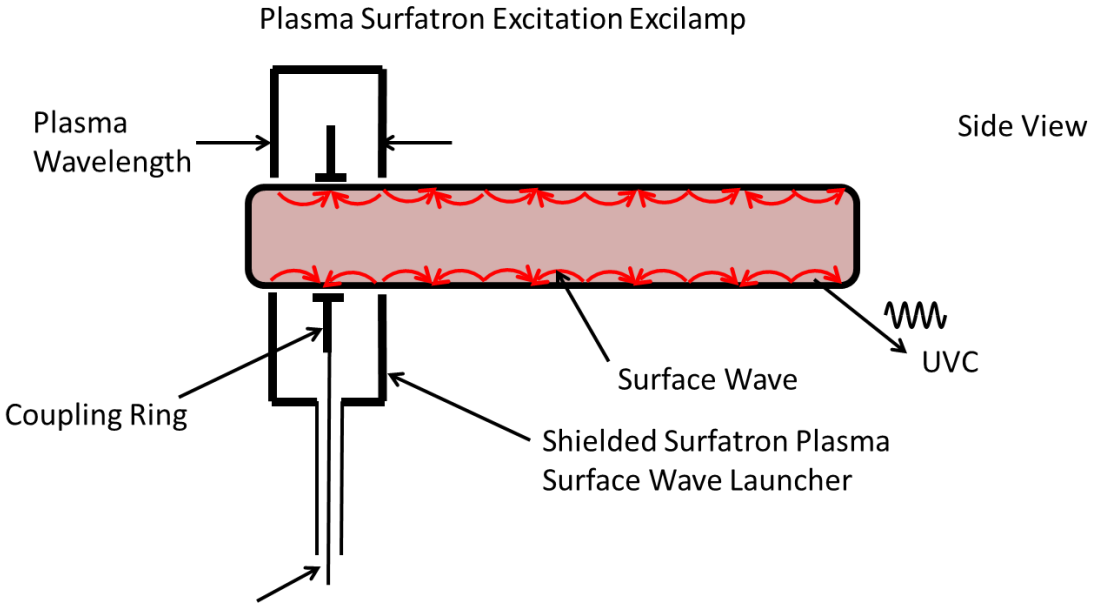

Figure A.5. Surfatron excited Excilamp with coaxial line RF input.

VI. Electrode Geometry

Different electrode configurations including a coaxial geometry, similar as shown in Fig. 2(right), and a surface excitation-based configuration, as shown in Fig. 6, will be investigated. For both geometries, the electrodes may be arranged on the same side or opposite of the dielectric tube, in a way such that pulsed glow discharges (if in a volume), pulsed surface sliding discharge (similar as a surface wave when powered at RF mode), or pulsed DBD will be generated. We will first conduct parametric numerical modeling (using COMSOL Multiphysics, available from the subcontractor at ODU) to estimate the field distribution and thermal transfer for different radii, lengths, and configurations of the gas tube. Theoretical research will be followed to estimate the electron density and gas temperature of the plasma based on previous research from ours [13] and others[14, 15] . The gas tube with electrodes attached will be assembled following the findings from the theoretical research. Copper electrodes will be used for this proof-of-concept testing. Tungsten or Molybdenum may be used for the next step testing when lifetime and cost of manufacturing need to be taken to consideration.

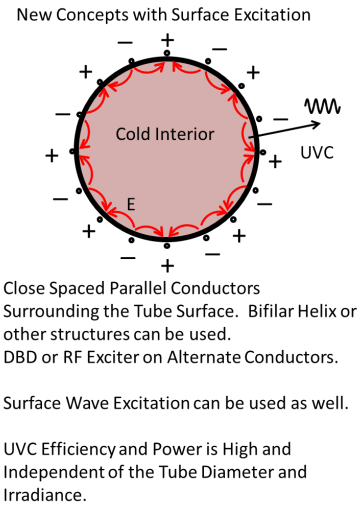

Figure A. 6. Schematic of a new electrode configuration design based on surface excitation

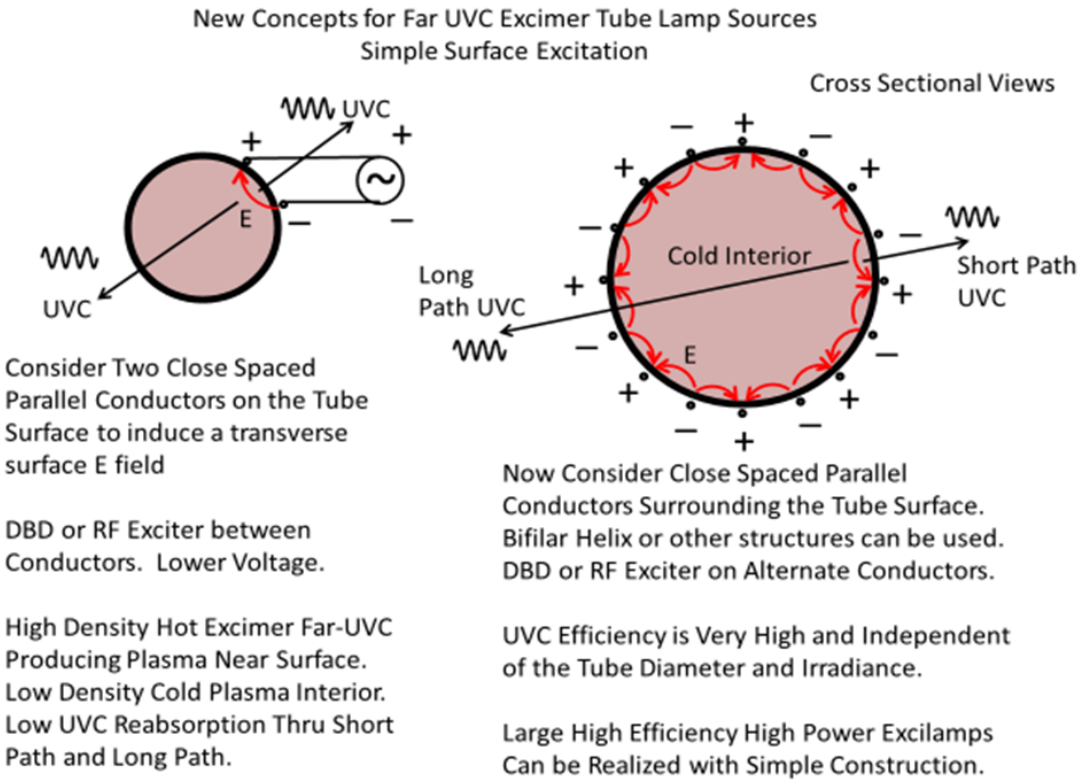

Figure A.7.

VII. Pulsed Excitation

We are aware of some pulsed LED experiments with 265 to 280 nm LED UV lights that show interesting results in increasing germicidal efficacy [2]. Fig 3 shows a plot from [3] that shows how effective a 222 nm Excilamp is compared to a conventional mercury 254 nm lamp on Staph bacteria. The second plot, from [2] shows a marked improvement of inactivation on E.Coli simply by pulsing a 280 nm LED with 50 uSec pulses at 1 kHz (5% duty).

UV at 265 to 280 nm is relatively germicidal ineffective compared to Far UVC 200-230 nm. We are not aware of any attempts to pulse Far UVC excilamps which we expect to be even more effective. When a device is pulsed the peak power to average power increases. As a device has an average power limit the peak power can increase substantially. As suggested by [2] microbes are sensitive to peak power. Therefore, we believe that pulsed Far UVC should be tested down to very short pulse widths at low duty but high average power. We propose in Phase 2 to germicidal test pulsed excilamps from pulse widths of ~ 30 uSec down to ~ 30 nSec or less, with average powers comparable to CW (continuous wave or 100% duty) operation, at an approved laboratory such as Intertek [4]. It is beyond our time frame and scope to do actual germicidal tests in Phase 1. However, in Phase 1 we propose to prepare for such testing particularly with generating pulsed UV and measuring the pulsed UV output. We are aware with our experience with pulsed RF that

often power measuring devices, usually calibrated with CW, are inaccurate at pulse. It is possible that references that claim an improvement in germicidal efficacy with pulse are simply due to inaccuracies in measuring pulsed dosages. We do not want to make such a mistake.

We will pulse LED and Excilamp sources at pulse widths of 30 uSec to 30 nSec and develop accurate UV irradiance measurements. In particular we want to measure UVC with a fast PIN diode detector and relate that measurement to our available UVC power meters and spectrometer.

Further Advanced Concepts for Far UVC Excimer Plasma Lamp Sources

1) Pre-Conditioning of the Fused Silica Glass for 222 nm Excilamps with Chlorine in a high temperature furnace or high temperature chlorine plasma for long lamp life. Lifetime testing would be in Phase 2.

2) The use of pulsed excilamps, e.g. a few 10's of nanoseconds to a few 10's of microseconds pulse width (including pulse modulated RF), may increase Germicidal Efficacy. Efficacy improvement with slow pulsing, 1 kHz at 50-5%duty, has been demonstrated with 265 to 285 nm LED sources [2], relatively germicidal ineffective wavelengths, but (to our knowledge) has not been demonstrated at Far UVC such as with 222 nm Excilamps. Initial pulse UVC measurements would be in Phase 1.

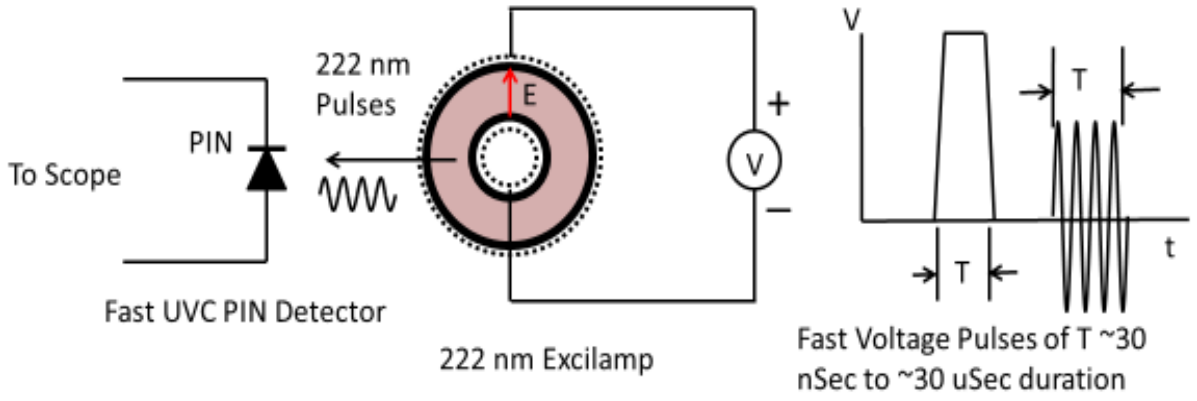

Figure A.8.

This first plot from [3] shows a germicidal kill rate for a typical Far UVC 222 nm Excilamp source compared to a 254 nm Hg source where the 222 nm is much more effective than 254 nm (log scale) by nearly 2 orders of magnitude at >3 mJ/cm2 dose. This 2nd inactivation plot from [2] shows the effectiveness of 50 uSec 1kHz pulsing a 280 nm LED. Pulsing a 222 nm Excilamp is expected to be even more effective. Actual Germicidal Efficacy testing would utilize an approved testing laboratory in Phase 2 using the exciters and lamps of Phase 1.

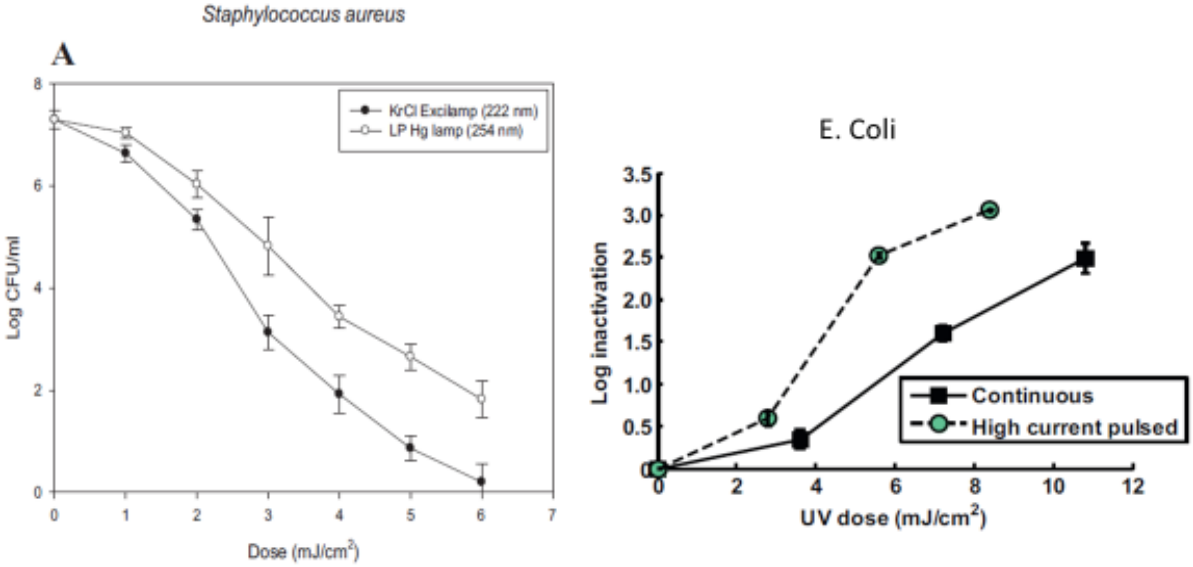

Figure A.9. There are some pulsed LED experiments with 265 to 280 nm LED UV lights that show interesting results in increasing germicidal efficacy [31]. Fig 3 shows a plot from [32] that shows how effective a 222 nm Excilamp is compared to a conventional mercury 254 nm lamp on Staph bacteria. The second plot, from [32] shows a marked improvement of inactivation on E.Coli simply by pulsing a 280 nm LED with 50 uSec pulses at 1 kHz (5% duty).

A recent comparison study of *E. coli* inactivation by UV-LED irradiation at 265 and 280 nm showed pulsed UV irradiation enhanced the log-reduction of *E. coli* comparing to the continuous UV irradiation[7]. More importantly, the log-reduction of *E coli* increased substantially as the duty cycle decreased from 100% to 5% at the same UV dose[7]. It is well-known that UV-LEDs are limited for high current/power operation, and pulsed mode allows the LEDs to be able to output higher irradiance with higher peak current operation. In the meantime, living microorganisms and cells respond to external electromagnetic signals at a relatively slower time scale, which corresponds to different penetration of the cells, *e.g.*, at the membrane or internal organelle [16, 17]. It is hence not surprising to see that pulsed UV irradiation would enhance the antimicrobial efficacy and increase the energy efficiency.

Our previous experience on excimer research showed that pulsed operation can significantly increase excimer emission in a xenon glow discharge[13]. Short-duration pulsed power allows application of higher voltages for plasma excitation without inducing glow-to-arc transition and promises higher energy efficiency for various applications including light emission. In atmospheric pressure air, the glow-to-arc transition time was considered in the order of tens of nanoseconds [18]. The avalanche development time for a streamer was typically in the range of 10 – 200 ns [19-21]. Numerous studies have shown that short, particularly in nanosecond time scale, pulsed electric field excitation scheme allows a highly non-equilibrium state in a gas discharge, producing fast electrons with minimal gas heating, and hence achieves a transient yet stable plasma that would not be possible by any other excitation schemes [15, 22-24].

For this Phase I study, we will employ repetitive nanosecond pulsed power to drive the electrodes for KrCl excimer emission. The Plasma and Pulse Power Lab at ODU is equipped with nanosecond pulse generators for a range of selections in pulse duration (min. 10 ns FWHM), pulse repetition frequency (PRF ≤10 kHz), voltage amplitude (10 kV for ≥200 ns-FWHM, 30 kV for 30 ns-FWHM, and polarity. We will focus on 10 ns – 200 ns pulse duration and conduct a systematic study on the duration dependence of the Far-UVC irradiation. Note that the breakdown voltage will depend on the electrode geometry, gas pressure, pulse duration, and PRF. The electrode geometry will be pre-determined based on the first step theoretical studies. We expect the stronger emission is associated with the higher pressure used. Pilot studies will be carried out to find out the optimal operation condition for the specific geometry.

Accurate measurement of fast pulses with rise time <10 ns applying to an electrode system is nontrivial. Problems such as impedance mismatching, insertion loss at the connection between the transmission line and electrode, or narrow bandwidth of the voltage or current probes must be solved before the correct power measurements are obtained. For fast-pulsed plasma system, we will apply a customized broadband V-I monitor [25] inserted between the transmission line and high-voltage electrode. The voltage and current probes will be in direct contact with the electrode, and the contact resistance will be measured and minimized (<1Ω). A recent in-line V-I monitor has been designed and tested in a 10 kV, 10-ns pulsed plasma system[26, 27]. Bandwidth up to 600 MHz was calibrated for the high voltage probe. The current monitor integrated a current sensor (Pearson 6585) that has a rated usable rise time of 1.5 ns.

UV at 265 to 280 nm is relatively germicidal ineffective compared to Far UVC 200-230 nm. We are not aware of any attempts to pulse Far UVC excilamps which we expect to be even more effective. When a device is pulsed the peak power to average power increases. As a device has an average power limit the peak power can increase substantially. As suggested by [2] microbes are sensitive to peak power. Therefore, we believe that pulsed Far UVC should be tested down to very short pulse widths at low duty but high average power. We propose in Phase 2 to germicidal test pulsed excilamps from pulse widths of ~ 30 uSec down to ~ 30 nSec or less, with average powers comparable to CW (continuous wave or 100% duty) operation, at an approved laboratory such as Intertek [4]. It is beyond our time frame and scope to do actual germicidal tests in Phase 1. However, in Phase 1 we propose to prepare for such testing particularly with generating pulsed UV and measuring the pulsed UV output. We are aware with our experience with pulsed RF that often power measuring devices, usually calibrated with CW, are inaccurate at pulse. It is possible

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600 MHz was calibrated for the high voltage probe. The current monitor integrated a current sensor (Pearson 6585) that has a rated usable rise time of 1.5 ns.

VIII. Far-UVC radiation measurements

To ensure accurate assessment of the Far-UVC irradiation output from nanosecond pulsed light source, fast response detectors and UVC sensitive optics are required. For this project, an optical collection system will be assembled using UV-grade mirrors (e.g., Edmundoptics UV mirrors) to collect the emission output into a UVC spectrometer/power meter, to allow repeatable measurements of 222-nm UVC emission and to determine the optimal operation condition of the plasma source. The spectral width of the pulsed emission will be resolved with a spectrograph/monochromator (Princeton Instrument, Acton SP-2758) coupled with a fast, UVC-sensitive photomultiplier tube. Fast PIN diode or other broadband detector that is sensitive to UVC may also be used for calibration and tuning of the system. Spatially resolved 222-nm emission will also be conducted systematically to assess the excilamp design efficiency in terms of the UVC radiation and absorption.

IX. Excilamp Lifetime Research

Commercially available 222 nm KrCl Excilamps are known to have lifetimes of only ~2000 hours. As they are expensive then increasing the lifetime is valuable. The identified reason is that Chlorine ions are imbedded into the surface of the SFS glass and the Chlorine gas is depleted reducing the number of possible KrCL2 molecules and hence the 222 nm emission. Simply adding extra Chlorine is usually not acceptable because Chlorine emits a broad UV line at ~ 256 nm, a wavelength similar to mercury 254 nm lamps that is not safe to humans. A patent [34] has a remedy of heating the glass with infrared radiation to release the trapped Chlorine. We have the concept of pre-saturating the glass with Chlorine in a high temperature furnace, and/or using an intense Chlorine plasma. If the glass is saturated, i.e. using the glass as a reservoir, then impacting ions should release trapped Chlorine.

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In addition, the germicidal test of the pulsed excilamps and further optimization of the design and power delivery will be conducted in Phase II. The ODU Plasma and Pulsed Power Lab is affiliated with the Center for Bioelectrics at ODU and has access to facility and equipment for microbiology testing. The Plasma and Pulsed Power Lab had recently engaged in surface disinfection using atmospheric pressure plasma jets to inactivate *S. aureus* and *A. baumannii* [29]. The protocol of pulsed Far-UVC irradiation on microorganisms including virus will be prepared and submitted to the ODU institutional review board (IRB) for review during Phase I. IRB approval to conduct the microbiology testing of Far-UVC excilamps.

X. References:

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