



Defence Research and  
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pour la défense Canada



# **Electromagnetic, ozone and noise emissions from dielectric barrier discharge plasma actuators**

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**Defence R&D Canada – Valcartier**

Technical Memorandum  
DRDC Valcartier TM 2013-591  
November 2013

**Canada**



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## Abstract

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In recent years, there has been considerable interest in dielectric barrier discharge plasma actuators as flow control technology due to their potential use in a variety of applications. For instance, these light-weight devices have low power consumption, low profile, can be laminated to aerodynamic surfaces and provide fast response for active feedback control strategies. One of the major drawbacks of plasma actuators is the high voltage applied signal required for their operation. This is a concern to the implementation of these devices in aerospace and aeronautics or other industries with respect to power supply logistics and more significantly, because the risks to the human health. Other potential health risks associated with plasma actuator implementation include exposure to ozone concentrations and noise levels.

The main purpose of this study was to investigate the severity of electromagnetic, ozone, and noise emissions from an operating plasma actuator and to compare these results with Canadian health and safety standards. This study will be used to determine if eventual action is required to reduce exposure to any of these risk factors and will serve to guide those working with/around plasma actuators as to when countermeasures to mitigate exposures are advisable or necessary. The results obtained from this study will be used to develop new standing operating procedures for plasma actuator operation in DRDC Valcartier, as well as be disseminated into the scientific community.

The plasma actuators in the current work were operated over a range of applied voltages and frequencies representative of those typically reported in the literature. First, the distances from the operating plasma actuator at which the electric and magnetic field strengths met or exceeded the standards for maximum exposure to prevent adverse health effects were found, followed by a characterization of the electric and magnetic fields for various operating conditions. The rate of ozone and the noise levels and frequency spectrum generated by a plasma actuator were found for various voltages and frequencies.

This study demonstrates that safety consideration should be made for electromagnetic and ozone exposure associated with typical plasma actuator use. However, it is shown that noise generated by an operating plasma actuator is below safety standards for hearing damage and should not be considered a health risk.

## Résumé

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Au cours des dernières années, des actionneurs à décharge à barrière diélectrique de plasma ont acquis un grand intérêt en tant que technologie de commande d'écoulement en raison de leur utilisation potentielle dans une variété d'applications. Par exemple, ces appareils légers ont une faible consommation d'énergie, un profil bas, peuvent être laminés sur des surfaces aérodynamiques et fournir une réponse rapide pour les stratégies de contrôle de rétroaction actifs. L'un des principaux inconvénients des actionneurs à plasma est le signal à haute tension utilisé pour leur fonctionnement. C'est une préoccupation pour l'utilisation de ces dispositifs dans les domaines de l'aérospatiale et l'aéronautique en plus des risques de radiation aux champs électriques et magnétiques lors de la mise au point de ces dispositifs.

D'autres risques pour la santé associés à la mise en œuvre de l'actionneur de plasma comprennent l'exposition à des concentrations d'ozone et à des niveaux de bruit. L'objectif principal de cette étude était d'examiner la gravité de la radiation électromagnétique, l'émission d'ozone et les émissions de bruit lors du fonctionnement d'un actionneur plasma de comparer ces résultats avec les normes de santé et de sécurité canadiennes. Cette étude servira à déterminer si d'éventuelles mesures sont nécessaires pour réduire l'exposition à l'un de ces facteurs de risque et servira à guider ceux qui travaillent avec / autour des actionneurs plasma et de proposer des solutions afin d'en atténuer les risques. Les résultats obtenus lors de cette étude seront utilisés pour développer de nouvelles procédures opérationnelles permanentes pour le fonctionnement de l'actionneur de plasma au RDDC Valcartier, ainsi que d'en diffuser les résultats dans la communauté scientifique.

Les actionneurs de plasma ont été opérés sur une plage de tensions et de fréquences représentatives de celles généralement décrites dans la littérature. Tout d'abord, les champs électriques et magnétiques ont été mesurés à différentes distances autour de l'actuateur afin de déterminer le profil de radiation. Par la suite, les zones limites de radiations ont été identifiées en se basant sur les normes d'expositions maximales qui déterminent la zone sécuritaire d'un opérateur afin de prévenir des effets néfastes pour la santé. Le taux d'ozone et les niveaux de bruit sonore ont été aussi mesurés afin de déterminer le risque associé à la santé. L'étude montre que le niveau d'ozone produit peut représenter un risque mais que le bruit généré par un actionneur de plasma est en deçà des normes de sécurité pour des dommages auditifs et ne doit pas être considéré comme un risque pour la santé.

Cette étude démontre que l'examen de la sécurité devrait être fait pour l'exposition électromagnétique et l'ozone associé à l'utilisation typique de l'actionneur à plasma.

## Executive summary

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### Electromagnetic, ozone and noise emissions from dielectric barrier discharge plasma actuators

Rogério Pimentel; Yves DeVillers; Tommy Ringuette; Nicole Houser; Philippe Lavoie; DRDC Valcartier TM 2013-591; Defence R&D Canada – Valcartier; November 2013.

**Introduction or background:** One of the main disadvantages of plasma actuators is the high voltage signal necessary for their operation. This is a concern for the use of these devices in the aerospace and aeronautics higher risk of radiation to electric and magnetic fields during the development of these devices. The large amount of ozone generated during the operation of actuators dielectric barrier discharge plasma is also a major health concern because ozone is a powerful oxidant and is a major respiratory irritant in humans and animals.

**Results:** This study characterized the electromagnetic fields in response to various operating conditions, the locations of maximum exposure limits set by Canadian standards. This study also evaluated the rate of ozone generation and the noise level generated during operation of the actuator. Tested plasma actuators produce electromagnetic emissions and ozone that meet or exceed safety standards and security measures should be taken to mitigate the risk when an operator working near the actuator. Noise levels measured products were found within the limits of safety.

**Significance:** Despite extensive use in laboratory studies of the scientific community have neglected to assess the severity and extent of electromagnetic emissions, ozone, or noise caused by the operation of the plasma actuator. This information, which was until now not available in the literature, is relevant to the safety of people in environments where the plasma actuators are used.

**Future plans:** The results obtained from this study will be used to develop new standing operating procedure for plasma actuators researches in DRDC Valcartier, as well as to disseminate it in the scientific community.

## Sommaire

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### **Electromagnetic, ozone and noise emissions from dielectric barrier discharge plasma actuators:**

**Rogério Pimentel; Yves DeVillers; Tommy Ringuette; Nicole Houser; Philippe Lavoie ; DRDC Valcartier TM 2013-591 ; R & D pour la défense Canada – Valcartier; novembre 2013.**

**Introduction ou contexte :** L'un des principaux inconvénients liés à des actionneurs de plasma est le signal à haute tension nécessaire à leur fonctionnement. C'est une préoccupation pour l'utilisation de ces dispositifs dans les domaines de l'aérospatiale et l'aéronautique en plus des risques de radiation aux champs électriques et magnétiques lors de la mise au point de ces dispositifs. La grande quantité d'ozone produite lors de l'opération d'actionneurs à décharge à barrière diélectrique du plasma est également une préoccupation majeure de santé puisque l'ozone est un oxydant puissant et représente un irritant respiratoire puissant chez l'homme et les animaux.

**Résultats :** Cette étude a caractérisé les champs électromagnétiques en réponse à diverses conditions d'exploitation, indiquant les emplacements des limites maximales d'exposition fixées par les normes canadiennes. Cette étude a également évalué le taux de production d'ozone et à des niveaux de bruit générés pendant le fonctionnement de l'actionneur. Les actionneurs à plasma testés produisent des émissions électromagnétiques et l'ozone qui répondent ou dépassent les normes de sécurité et que des mesures de sécurité devraient être prises pour atténuer le risque lorsqu'un opérateur travaille près de l'actuateur. Les mesures niveaux de bruit produits ont été jugées en deçà des limites de sécurité.

**Importance :** Malgré l'utilisation extensive en laboratoire, les études de la communauté scientifique ont négligé d'évaluer la gravité et l'étendue des émissions électromagnétiques, de l'ozone, ou de bruit causé par le fonctionnement de l'actionneur à plasma. Cette information, qui n'était jusqu'à maintenant pas disponible dans la littérature, est pertinente pour assurer la sécurité des personnes dans des environnements où les actionneurs de plasma sont utilisés.

**Perspectives :** Les résultats obtenus de cette étude seront utilisés pour développer de nouvelles procédures opérationnelles permanentes pour les recherches sur les actionneurs à plasma au RDRC Valcartier, ainsi que de diffuser l'information dans la communauté scientifique.

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# 1 Introduction

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In recent years, dielectric barrier discharge (DBD) plasma actuators herein referred to as plasma actuators, have gained large interest as flow control technology due to their potential use in a variety of applications. For instance, these light-weight devices have low power consumption, a low profile, can be laminated to aerodynamic surfaces and provide fast response for active feedback control strategies. One of the major drawbacks of plasma actuators is the high voltage applied signal required for their operation. This is a concern to the implementation of these devices in aerospace and aeronautics or other industries with respect to power supply logistics and more significantly, because the risks to the human health. Other potential risks for human health include ozone and noise exposure.

Despite extensive in-laboratory usage, studies in the scientific community have neglected to evaluate the severity and extent of electromagnetic radiation, ozone production, and noise generation caused by plasma actuator operation. This information is relevant in the future to protect those in environments where DBD plasma actuators may be implemented for flow control and, more immediately, for the safety of plasma actuator researchers in laboratory environments.

The purpose of this study is to determine the distances from the operating plasma actuator at which the electric and magnetic field strengths meet or exceed the standards for maximum exposure to prevent adverse health effects as well as to evaluate the rate of ozone generated and level of noise generated during operation of these devices. Although there are numerous possible combinations of operating conditions and actuator geometries, the aim of this study is to achieve a basic understanding of electromagnetic, ozone, and noise emission for typical operating frequencies and voltages involved in existing DBD plasma actuator studies.

In accordance with continuously increased concerns with the health effects from exposures to electromagnetic radiation, Health Canada issued guidelines for the limits of human exposure to radiofrequency (RF) electromagnetic energy in the frequency range from 3 kHz to 300 GHz, alternatively known as Safety Code 6 (2009)[7]. This literature specifies maximum levels of human exposure to RF energy at based on ongoing review of published scientific studies. The limits set forth by Safety Code 6 will be used to evaluate the RF field surrounding an operating plasma actuator to establish a safe working distance. Similarly, the Residential Indoor Air Quality Guideline issued by Health Canada [9] will be used to compare the maximum exposure levels of ozone with those found in the environment surrounding an operating DBD plasma actuator. The Canadian Occupational Health and Safety Regulations [18] will be used to evaluate the risk of hearing damage associated with plasma actuators.

This study will be used to determine if mitigation actions are required to reduce exposure to electromagnetic, ozone, and noise emissions for the safety of persons working with plasma actuators. The effects and safety limits of each of these potential health concerns are described in detail in the subsequent sections.

## 1.1 Effects of electromagnetic emissions

### 1.1.1 Health effects of electromagnetic radiation

The increased usage of technological communicative devices has led to growing concerns over the potential health effects caused by exposure to electromagnetic radiation. Of particular interest are the health effects of exposure to radiofrequency sources. Radiofrequency sources operate at frequencies between 3 kHz and 300 GHz on the electromagnetic spectrum. This frequency range supports many widely used applications including but not limited to radar, satellite, navigation, wireless, cellular, and television devices [1].

Studies on the potential health effects associated with RF radiation have examined concerns such as DNA damage, tumour promotion, human cancers, behaviour and cognitive functions, gene and protein expression, immune response, and reproductive functions [7]. Exposure to RF fields is known to induce internal body currents and energy absorption in tissues [1]. Despite numerous studies on a large variety of health effects of RF energy, adverse effects are predominantly related to the occurrence of tissue heating for frequencies from 100 kHz to 3 GHz and excitable tissue stimulation from acute exposures for frequencies from 3 kHz to 100 kHz [7].

Health Canada's Safety Code 6 [7] provides outlines for the limits of human exposure to radiofrequency electromagnetic energy in the frequency range from 3 kHz to 300 GHz, based on ongoing review of published scientific studies. According to the Safety Code 6, there exists no scientific evidence of chronic and/or cumulative health risks from RF energy at levels below specified limits provided by Safety Code 6.

Safety Code 6 defines controlled environments as those in which RF field intensities have been characterized by means of measurement, calculation, or modelling with appropriate software and exposure is incurred by persons aware of potential for, intensity of, health risks associated with, and mitigation strategies for RF exposure in their environment. Any situations that do not meet these criteria are considered uncontrolled environments in which RF energy has been insufficiently assessed and/or where persons within environment have not receive adequate RF awareness training and lack the means to assess or mitigate their exposure to RF energy. The maximum electric and magnetic field strengths for both controlled and uncontrolled environments are listed in the Table 1.

*Table 1: Field strength limits set by Health Canada's Safety Code 6 [7].*

Environment Type	Electric Field Strength rms V/m	Magnetic Field Strength rms A/m (nT)
Controlled (3 kHz – 1000 kHz)	600	4.9 (6159)
Uncontrolled (3 kHz – 1000 kHz)	280	2.19 (2752)

In the current work, the locations at which these maximum field strengths occur are established in the area surrounding an operating plasma actuator given various excitation voltages and frequencies.

### 1.1.2 Electromagnetic interferences

Electromagnetic interference (EMI), also called radiofrequency interference (RFI) when in high frequency or radiofrequency is disturbance that affects electrical circuits due to either electromagnetic induction or electromagnetic radiation emitted from an external source. The disturbance may interrupt, obstruct, or otherwise degrade or limit the effective performance of the circuit. These effects can range from a simple degradation of data to a total loss of data. The source may be any object, artificial or natural, that carries rapidly changing electrical currents, such as an electrical circuit, the Sun or the Northern Lights.

EMI can be intentionally used for radio jamming, as in some forms of electronic warfare, or can occur unintentionally, as a result of spurious emissions for example through intermodulation products, and the like. It frequently affects the reception of AM radio in urban areas. It can also affect cell phone, FM radio and television reception, although to a lesser extent.

Electromagnetic fields are invisible lines of force due to a combination of electrical fields (produced by voltage) and magnetic fields (produced by current flow) that an object emits. EMI occurs when the signals from an electromagnetic field temporarily interfere with the intended operation of the implanted device.

The effects of EMI are temporary. The closer your implanted device is to the item, the stronger the effect. The farther away, the less effect you will experience. EMI effects do not usually cause harm to the person or the device.

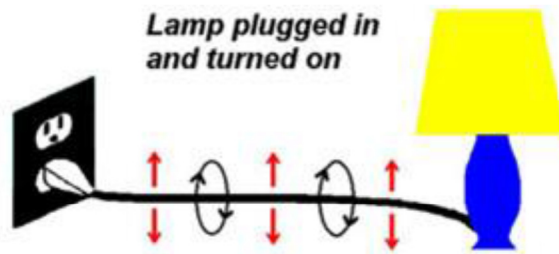
Let's take a look at a common electrical appliance as an example. Voltage is present on the lamp cord (conductor) as long as the lamp is plugged in to an active wall outlet; an electric field is present, even if the lamp is not turned on, as shown in Figure 1.



*Figure 1: Electric field generation.*

Magnetic fields are generated by current flowing through a conductor; the magnetic field encircles the conductor. A magnetic field is generated as soon as a device is switched on, as shown in Figure 2.





*Figure 2: EM field generation.*

Potential sources of RFI and EMI include: various types of transmitters, doorbell transformers, toaster ovens, electric blankets, ultrasonic pest control devices, electric bug zappers, heating pads, and touch controlled lamps. Multiple CRT computer monitors or televisions sitting too close to one another can sometimes cause a "shimmy" effect in each other, due to the electromagnetic nature of their picture tubes, especially when one of their de-gaussing coils is activated. Any high voltage devices can produce EMI that can affect all electronic devices located close to it.

One of the best ways to reduce the effect of electromagnetic interference is to install the high voltage source inside a Faraday cage. A Faraday cage is a metallic enclosure that prevents the entry or escape of an electromagnetic (EM) field. An ideal Faraday cage consists of an unbroken, perfectly conducting shell. This ideal cannot be achieved in practice, but can be approached by using fine-mesh copper screening, for instance. For best performance, the cage should be directly connected to an earth ground.

A Faraday cage operates because an external static electrical field causes the electric charges within the cage's conducting material to be distributed such that they cancel the field's effect in the cage's interior. This phenomenon is used, for example, to protect electronic equipment from lightning strikes and electrostatic discharges.

Faraday cages cannot block static or slowly varying magnetic fields, such as the Earth's magnetic field (a compass will still work inside). To a large degree, though, they shield the interior from external electromagnetic radiation if the conductor is thick enough and any holes are significantly smaller than the wavelength of the radiation. For example, certain computer forensic test procedures of electronic systems that require an environment free of electromagnetic interference can be carried out within a screen room. These rooms are spaces that are completely enclosed by one or more layers of a fine metal mesh or perforated sheet metal. The metal layers are grounded to dissipate any electric currents generated from external or internal electromagnetic fields, and thus they block a large amount of the electromagnetic interference.

## **1.2 Effects of ozone emission**

Ozone is a strong oxidizing agent, found in outdoor as well as indoor environments, which reacts rapidly with exposed surfaces and other constituents in air. Ozone is a colourless gas and as such may go undetected in lower concentrations in indoor environments. The Science Assessment Document for Ground-Level Ozone issued by Environment Canada and Health Canada, 1999 concluded that there is a significant association between ambient ozone levels and adverse human

health effects (mortality and morbidity), as well as reduced vegetation growth and crop yield. Under the Canadian Environmental Protection Act (CEPA), 1999 ozone was declared “toxic” in 2003[9].

In humans, acute exposure to ozone up to 4 hours in healthy adults was shown to decrease forced vital capacity, forced expiratory volume in one second, forced inspiratory volume, and tidal volume. Acute ozone exposure was also shown to increase breathing frequency and cause pain upon deep inhalation. These effects can be seen at an ozone level of 80 ppb [9], which is the Lowest Observed Adverse Effect Level (LOAEL) for this exposure duration in accordance with Health Canada. Prolonged exposure for 4 to 8 hours caused decreased lung functions and increased pain upon inhalation. The Residential Indoor Air Quality Guideline issued by Health Canada (2010) recommends a residential maximum exposure limit of 40  $\mu\text{g}/\text{m}^3$  (20 ppb) ozone based on an averaging time of 8-hours [9]. This exposure limit would still be half of the No Observed Adverse Effect Level (NOAEL) for this exposure duration.

Ozone can be formed through the ionization and breakdown of oxygen molecules in air. Thus, the operation of plasma actuators continuously forms significant amounts of ozone. Although, ozone production by plasma actuators is common knowledge in field, studies have yet to focus on the ozone levels produced by plasma actuation and how they compare with safety standards for ozone exposure. In the subsequent study, the Residential Indoor Air Quality Guideline levels set forth by Health Canada, 2010 [9] will be used to compare the recommended maximum exposure levels of ozone with those found in the environment surrounding an operating plasma actuator. This guideline will be used to determine if action is required to reduce human exposure to ozone during plasma actuator research and the intensity of countermeasures to be taken. Reduced ozone exposure can be achieved by isolating the operation actuator in a closed chamber with proper exhausting. Ozone detection alarms can be used to prevent overexposure to ozone in areas which are certain to contain operating DBD plasma actuators.

### **1.3 Effects of noise emission**

The average human can detect sounds within a range of frequencies between 16 Hz to 20 kHz. There are two main types of hearing-loss: conductive and sensori-neural. Conductive hearing-loss is typically associated with damage to the outer or middle ear, for example, rupture of the ear drum due to high amplitude impulse. Conductive hearing loss is correctible by surgery. Sensori-neural damage, which occurs within the inner ear, can also be noise-induced and is not medically correctable. Noise-Induced Permanent Threshold Shift (NIPTS) is an irreversible lowering of sensitivity of the ears due to noise exposure. This type of sensori-neural hearing damage can occur due to a single high intensity noise exposure or to the prolonged exposure to damaging noise levels. Hearing damage due to noise exposure initiates at the higher frequencies first-typically between 3 and 6 kHz [15].

The intensity of sound is generally measured according to the decibel (dB) scale, which is the logarithm of the ratio between the sound pressure of the noise and a reference sound pressure (20 $\mu\text{Pa}$ ) [18]. A filter known as A-weighting is typically applied to the noise in accordance with International Electro-technical Commission Standard 651 (1979) to be better representative of average human sensitivity and the A-weighted result is expressed in dBA.

To evaluate the maximum exposure level and duration for noise, the equal energy hypothesis is used. It states that equal amounts of sound energy will cause equal amounts of noise-induced permanent damage (or threshold shift) regardless of the distribution of the energy across time [15]. The maximum exposure duration is calculated according to the following the equation:

$$t = \frac{8}{2^{\frac{L_8 - R}{E}}},$$

where

t = maximum exposure duration (hours),

$L_8$  = measure exposure level (dBA),

E = exchange rate (dBA),

R = Recommended Exposure Limit for eight hours (dBA),

*Table 2: Noise exposure limits in Canadian jurisdictions [16]*

Jurisdiction	Recommended Exposure Limit 8h (dBA)	Exchange rate (dBA)
Canada (federal)	87	3
Québec	90	5
Ontario	85	3

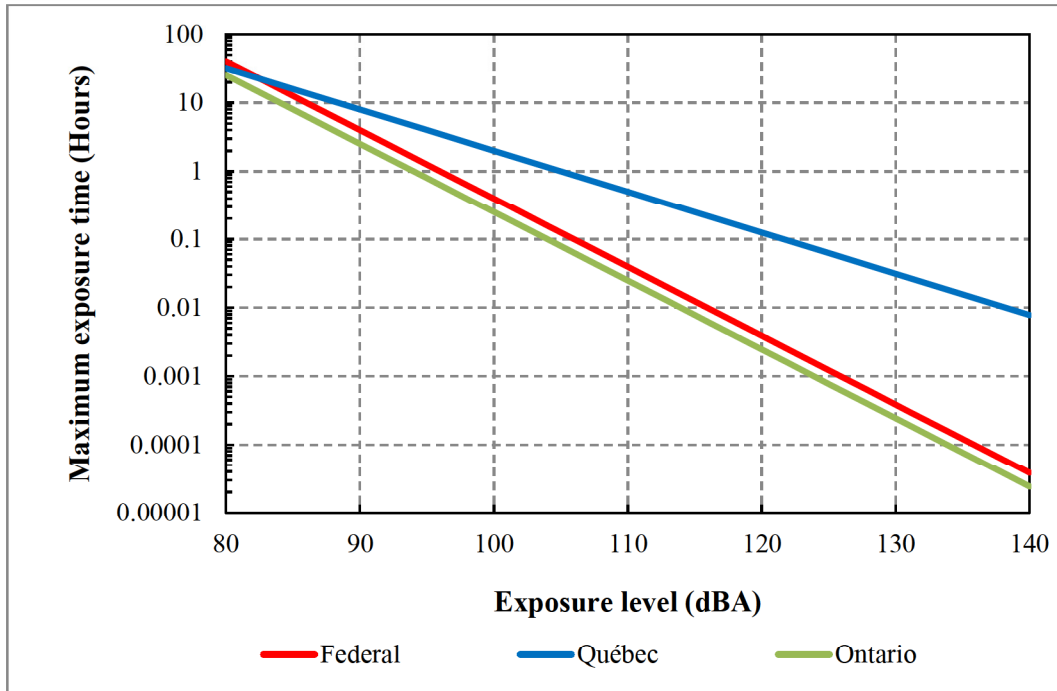


Figure 3: Maximum exposure duration as a function of noise exposure level in various Canadian jurisdictions [16], [18], [19].

For the large majority of people, a constant exposure of 70 dBA or below is not expected to cause hearing impairment even after a lifetime exposure [17]. There is however other problem associated with a high level of exposure to noise below this physical damage threshold. Noise levels of 35 dBA or more will interfere with speech comprehension, as normal speech level is around 50 dBA [17]. Susceptible individuals in the general population may also develop permanent effects, such as hypertension and ischaemic heart disease associated with exposure to high sound levels. As well, workers exposed to high levels of industrial noise for 5–30 years may show increased blood pressure and an increased risk for hypertension [17].

Permissible level of noise and its duration to avoid damage change with the jurisdiction. The maximum noise exposure limits for various Canadian jurisdictions are listed in Table 2, while the maximum noise exposure time limits are shown in Figure 3 as a function of exposure level for these jurisdictions. The Canada Occupational Health and Safety Regulations state that no employee can be exposed to more  $L_8$  of 87 dBA for every 24-hour period. The employer must also provide the employee with written information describing the hazards associated with exposure to high levels of sound for  $L_8$  equal to or greater than 84 dBA [18].

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## 2 Experimental Details

### 2.1 Dielectric barrier discharge plasma actuator

Typical dielectric barrier discharge plasma actuators consist of two asymmetrically arranged electrodes separated by a dielectric material. One electrode is left exposed to the environment while the other is grounded and encapsulated in some insulating material. This configuration, when supplied with sufficient AC signal generates an electric field and the weakly ionization the ambient gas above the encapsulated electrode forming a plasma discharge. The charged plasma experiences a Lorentz force from the electric field and a net body force is generated in the direction of decreasing electric field potential. This body force draws neutrally charged air towards the wall expelling fluid away from the exposed electrode. The resulting pressure drop above the electrodes generates a suction effect pulling air towards the actuator. Collisions between charged ions and neutral fluid couple momentum into the ambient air above the grounded electrode. This ionic wind generates a wall jet away from the exposed electrode, as shown in Figure 4.

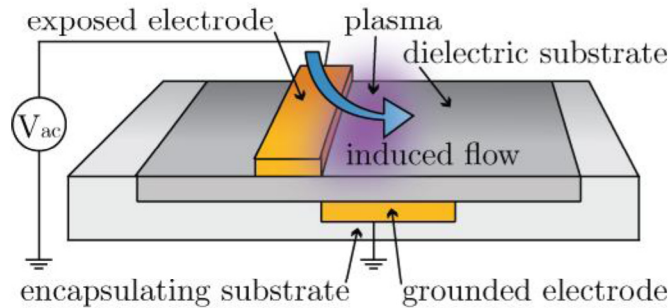


Figure 4: Schematic of DBD plasma actuator.

These devices have gained popularity for their elegance, simplicity and possibility to be operated at higher frequencies in comparison with other flow control actuators, which contain moving or mechanical parts that are often accompanied by weight and/or volume penalty.

Plasma actuators have proven themselves in the laboratory for numerous applications such as separation control [4], [5], aircraft noise reduction and wake control [6], reducing losses in compressor blades [3] and boundary layer control [2].

Two separate EM radiation investigations were conducted in the present work. The actuators used in this study were similar in construction to those used in previous joint studies of DRDC Valcartier and University of Toronto Institute for Aerospace Studies (UTIAS), which were based on those contained in Durscher and Roy [8], as presented in Figure 5.

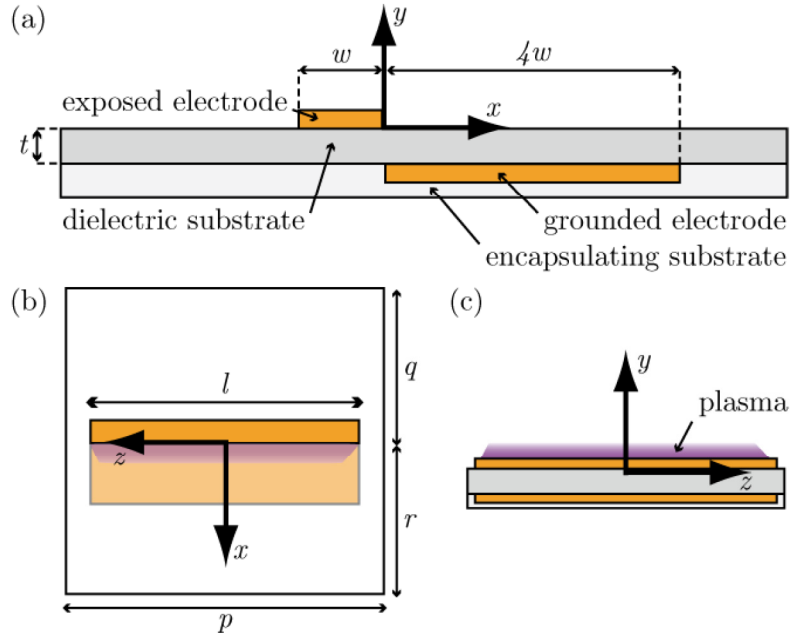


Figure 5: Plasma actuator dimension used in experimentation as seen from (a) cross-sectional view, (b) top-view, and (c) top-view (axis labels correspond to EMF testing with Actuator 1).

The actuators consisted of two asymmetrically arranged 70  $\mu\text{m}$  thick (adhesive included) copper tape electrodes separated by a Poly(methyl methacrylate) (PMMA) dielectric substrate, each with an active length of 12.0 cm and no horizontal gap along the  $z$ -axis between electrodes. The widths,  $w$  and  $4w$  of the exposed and encapsulated electrodes were 0.5 cm and 2.0 cm, respectively. The grounded electrode was encapsulated with 0.27 mm of Kapton<sup>®</sup> tape. The specifications of the DBD actuators analysed in this study are summarized in Table 3.

Table 3: Specifications of the DBD plasma actuator.

Dimension	Actuator 1 (cm)	Actuator 2 (cm)
Exposed electrode width, $w$	0.5	0.5
Encapsulated electrode width, $4w$	2.0	2.0
Electrode thickness	0.007	0.007
Length of actuator, $l$	12.0	12.0
Dielectric thickness, $t$	0.3	0.16
Substrate dimensions, $p/q/r$	15/15/3.5	15/4.5/4.5

The following sections describe the experimental apparatus used during the test campaigns at UTIAS.

## 2.2 Electromagnetic measurements

### 2.2.1 The experimental set-up

Electromagnetic field experiments were conducted in the UTIAS Mars dome at UTIAS which has a ground level diameter of 50 m. The plasma actuators used in the EMF experiments were operated using a Trek Model 20/20C high voltage amplifier. A sine waveform was provided to the amplifier using an Agilent 33220A function generator [13]. A schematic of the plasma actuator circuit is shown in Figure 6.

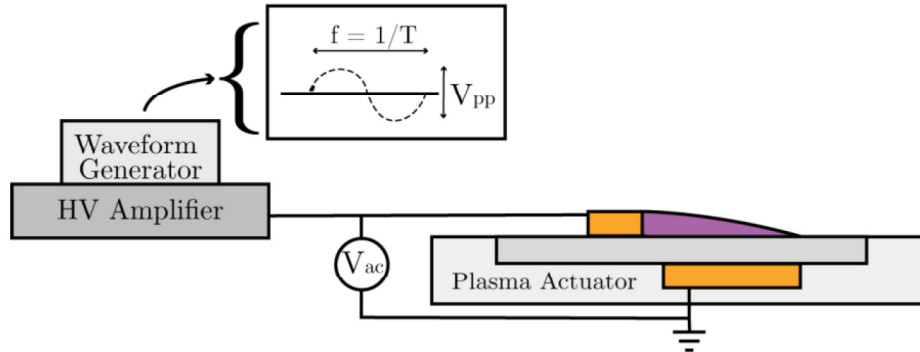


Figure 6: Experimental Set-up.

Both electric field and magnetic field strengths were determined using a hand-held GIGAHERTZ SOLUTIONS ME 3851A field reader [14] shown in Figure 7. Measurements were carried out in accordance with Industry Canada's Guidelines for the Measurement of Radio Frequency Fields at Frequencies from 3 kHz to 300 GHz [7]. The specifications of the low-frequency analyser are presented in Table 4.



Figure 7: The Low frequency Analyser ME 3851A.

Two separate EMF investigations were conducted. In the preliminary set of experiments, the Actuator 1 was operated at 16 kV (peak-to-peak) and 4 kHz. The locations of Health Canada's maximum exposure limits (both controlled and uncontrolled) were found at this operating condition for several orientations about the actuator along a single axis (radial) for several angles about the actuator. In the second set of experiments, the electric and magnetic fields surrounding Actuator 2 were characterized for a variety of operating conditions. For this second round of experiments, the

field strengths were calculated as the resultant of 3-axis measurements, as described in the following section.

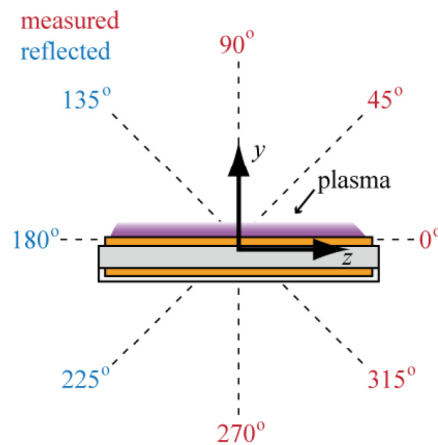
*Table 4: Specifications of the low-frequency analyser.*

Frequency Range:	5 Hz - 100 kHz (compensated, better than -2 dB).
Measurement Range:	Magnetic flux density (one-dimensional): 0.1 - 1999 nT Electric field strength: 0.1 - 1999 V/m
Accuracy:	+/- 2 %, +/- 7 digits @ 50/60 Hz
Sensor:	E-field sensor for electrical LF- fields H-field sensor for magnetic LF-fields (one-dimensional)

### 2.2.2 Preliminary measurement procedure (Actuator 1)

For the preliminary tests with Actuator 1, a spatial grid was constructed with leveled string at various heights adjacent to the actuator parallel to the y-z plane of the actuator. The actuator was rotated with respect to the grid such that the location of the electric and magnetic field limits as described in Section 2 could be determined and recorded. Measurements were repeated to ensure that locations were representative of the fields.

Locations of field limits were found for select rotations of 0°, 45°, 90°, 270°, and 315° from the z-axis of the actuator, as shown in Figure 8.



*Figure 8: Measurement location surrounding Actuator 1.*

The distances for the unmeasured angles were taken to be the same as the measured angle about a reflection on the y-axis. The maximum field locations at these rotations were found at heights above the actuator of 0 cm, 50 cm, 100 cm, and 150 cm. Distances were measured from the centre

of the actuator with estimated uncertainty of  $\pm 5$  cm. All angles and heights measured from the centre of the actuator at the plasma forming interface between the exposed electrode and the dielectric surface.

The background electromagnetic reading was taken prior to actuation to ensure minimal influence on measurements. For the EMF measurements for Actuator 1, readings were taken with the ME 3951A field meter pointed towards the actuators x-axis, parallel to the orientations shown in Figure 8, at various heights.

### 2.2.3 Characterization measurement procedure (Actuator 2)

For the second round of experiments, the 3-axis resultant electric and magnetic field strengths were recorded for various orientations about Actuator 2. The actuator surface was oriented normal to a mock-floor platform surface, as shown in Figure 9 and able to pivot about its centre. Specific distances from the actuators centre were indicated along the length of the platform. A wooden height ladder was constructed such that measurements could be made at specific heights from the actuator centre with the hand-held measurement device. Using the height ladder at the distances indicated on the platform, the field measurements were obtained for a spatial grid of points. The actuator was pivoted about its centre such that this spatial grid of field measurements was obtained at various orientations relative to the actuator as defined in Figure 9.

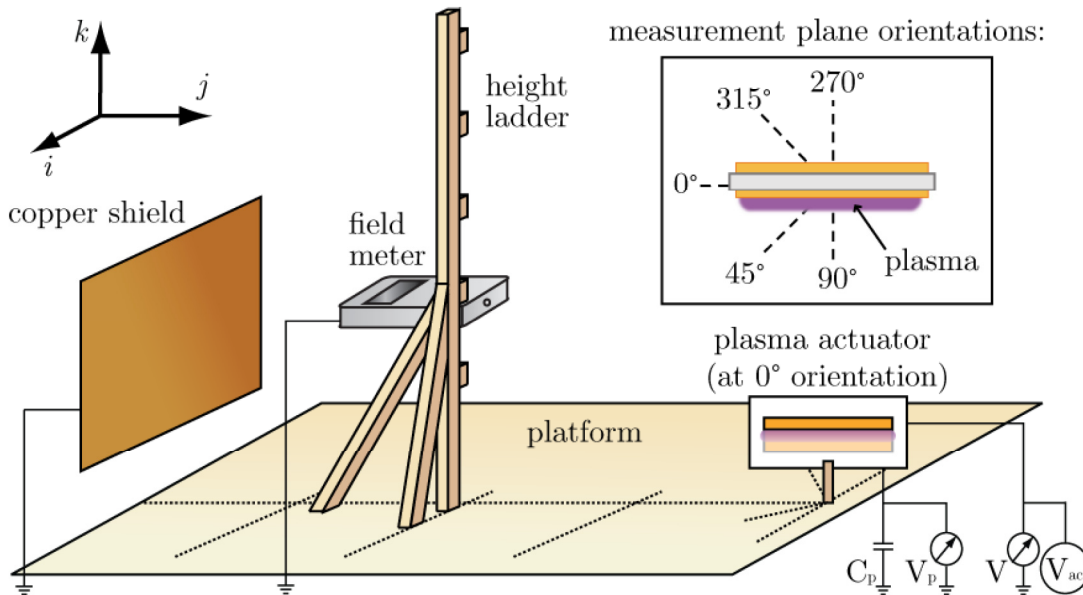


Figure 9: Experimental set-up used for EMF characterization of Actuator 2.

For increased repeatability in electric field measurements, the field meter was grounded and held in front of a square grounded copper shield with dimensions of 50 cm as per the ME 3951A manual[14]. The field meter indicates the RMS value of the field along the axis parallel to the device for electric fields and perpendicular to the display screen for magnetic fields. Each field of interest was measured along three axes, as indicated in Figure 9. The resultant of three-axis measurements was recorded for each height, distance, and orientation in order to quantify the magnitude of the field strength at each of these locations surrounding an operating plasma actuator.

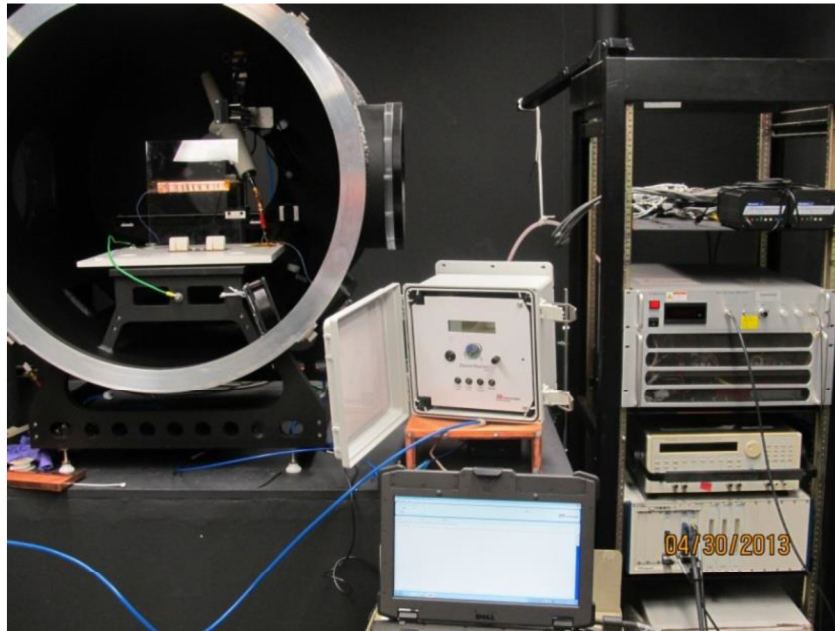


## 2.3 Ozone measurement procedure

For ozone generating measurements, the DBD plasma actuator was placed in the center of a closed cylindrical chamber, 80 cm in diameter and 80 cm in length. A small fan installed inside the chamber was used to improve homogenization of ozone concentration. The ozone concentration was measured every ten seconds for approximately five minutes. The slope of the increasing concentration was used to measure the quantity of ozone being produced in ppb/s, which can be converted to g/s with the known volume of the chamber. The usable internal volume discounting internal equipment and structure is 0.36 m<sup>3</sup>. The experimental set-up used for ozone measurements is pictured in Figure 10.

A function generator, PXI-5402 (14 bit, 20 MHz,  $\pm 10$  V) from National Instrument, and a LabView program were used to generate the zero offset sinusoidal signals applied to the actuator. This signal is then amplified ( $\times 2000$ ) with a Matsusada AMP-20b20. The amplifier is limited to signal between 40 kV (peak-to-peak) at 4 kHz and 4 kV (peak-to-peak) at 20 kHz with maximum current of 20 mA (60 mA spikes). Above those limits the amplifier gives unstable output voltage and eventually fails.

A range of voltages between 2 kV and 20 kV (peak-to-peak) and frequencies between 1 kHz and 20 kHz were investigated. The LabView program is also used to measure the current crossing the electrodes of the actuator, using a PXI-6052E from National Instrument and a current probe from Pearson model 2100.



*Figure 10: Set-up for ozone measurements in the closed chamber.*

The ozone concentration was measured with an Ozone meter model 106-L from 2B Technologies[10], with a NIST traceable precision of 2 ppb or 2%. The electric and magnetic field were measured with the low-frequency field strength meter from GIGAHERTZ SOLUTION model

ME-3951A with a 2% precision, as described previously. The maximum electric and magnetic field measured were 80 V/m and 30 nT, respectively at 20 cm distance around the closed chamber.

## **2.4 Noise measurement procedure**

The same experimental set-up was used for the noise measurement as described for the ozone measurements with the inclusion of a SC310 from CESVA Instruments for the measurement of sound level. The sound sensor was located at a distance of 90 cm from the DBD plasma actuator outside of the chamber at a height of 150 cm from the ground. The frequency spectra and the sound levels were recorded for various actuator operating conditions and with the plasma actuator chamber door both closed and open.

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## 3 Emission measurement results

### 3.1 Electromagnetic measurements

#### 3.1.1 Preliminary electromagnetic measurements (Actuator 1)

The exposure limit locations were found for Actuator 1 following the procedure outlined in Section 2.2.2. The background electric field was measured prior to plasma actuation to be 1 V/m at distances 60 cm away from the actuator. The locations of the maximum electromagnetic exposure limits for both controlled (600 V/m) and uncontrolled (280 V/m) environments containing an actuator operating at 16 kV (peak-to-peak) and 3 kHz are shown from a top-view perspective in Figure 11.

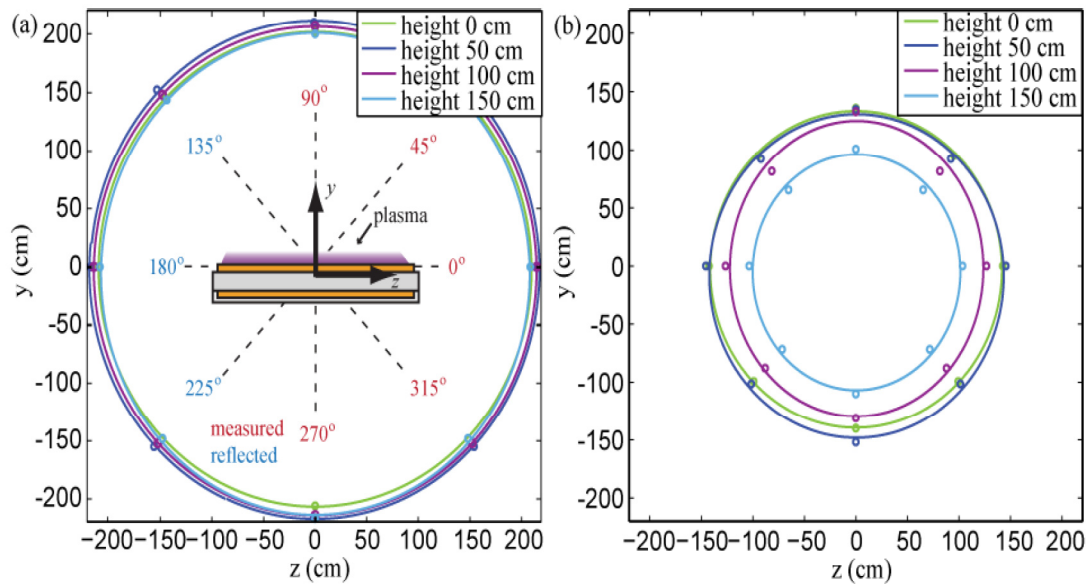


Figure 11: The locations of electric field exposure limits for (a) uncontrolled environments (280 V/m) and (b) controlled environments (600 V/m) with Actuator 1 operating at 16 kV and 4 kHz.

An elliptical fit was approximated using the measured and reflected data based on the assumption of electric field symmetry about the y-axis of the actuator. Three-dimensional representations of the exposure limit locations can be found in Figure 12. At the same operating conditions of 16 kV (peak-to-peak) and 3 kHz, the magnetic field measured at a height of 50 cm for all degrees was approximately equal to 24 nT, which is significantly lower than the recommended maximum for an uncontrolled environment of 2752 nT.

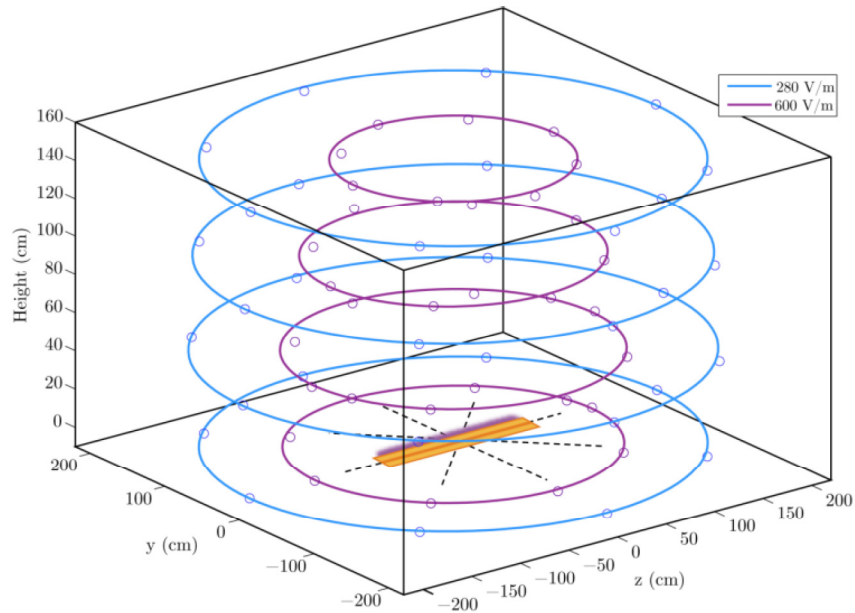


Figure 12: Radial locations of maximum electric field exposure limits for actuation at 16 kVpp, 3 kHz.

### 3.1.2 Electromagnetic characterization measurements (Actuator 2)

The electric and magnetic fields were characterized for various operating conditions according to the procedure detailed in Section 2.2.3. The uncertainties in resultant electric and magnetic field strengths were calculated in quadrature according to Taylor [11] using individual component error of  $\pm 2\%$  as per the field meter specifications for both sensors. Uncertainty in the radial distance to the actuator centre was estimated at  $\pm 4\%$ . The background electric and magnetic field strengths in experimental area were smaller than the resolution of the EMF analyser, i.e. 0.1 V/m and 0.1 nT, respectively.

Using the approximation that the field about the actuator is independent of orientation, the mean electric field for each position was calculated over all orientations. The deviations of individual measurements from the location averaged electric field strength are shown graphically in Figure 13 for an operating voltage of 12 kV (peak-to-peak), 4 kHz.

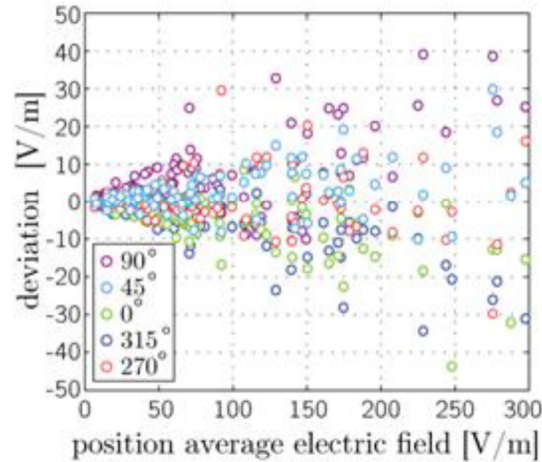


Figure 13: The deviation of each measurement from the position averaged electric field strength for all operating conditions.

On average, measurements taken at the 90° orientation were 10% higher than the location averaged field strength. This tendency can be intuited by considering the location of the high-voltage electrode. In the 90° orientation, the distance from the field meter to the source is smallest and free of obstructions. The average deviations of all other orientations were  $\leq 7\%$ . The radial symmetry of the electric field strength is further shown in Figure 14, as the contours are approximately the same for all orientations examined.

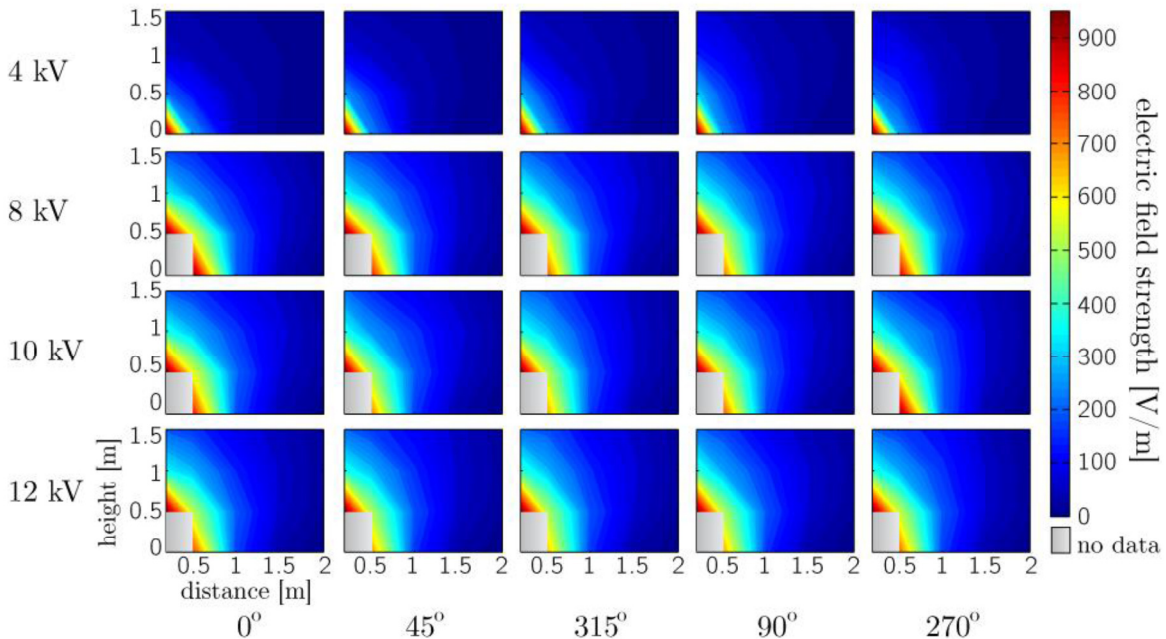


Figure 14: The resultant electric field strength at all orientations in response to various operating voltages (at 4 kHz).

From the contours plots in Figure 14 two major conclusions can be drawn. Firstly, the electric field strength,  $|\vec{E}|$ , is a function of the radial distance,  $r$ , from the actuator centre regardless of position about the actuator. Secondly, the increase in operating voltage increases the strength of the resultant electric field. These results are more explicitly expressed in Figure 15. For various operating voltages, the trend  $|\vec{E}| \propto 1/r^2$  was found, consistently over all orientations tested. This is the same result one would expect with the electric field generated by a charged point source.

Since the electric field strength is dependent on the radial distance from the actuator, the effect of various operating voltages was compared at specific grid coordinates, the radial distances of which are displayed in Figure 15b. The linear relation  $|\vec{E}| \propto V_{pp}$  was found, consistently, for all orientations tested. The effect of operating frequency on resultant field strength was also investigated. No significant correlation was observed between electric field strength and operating frequency.

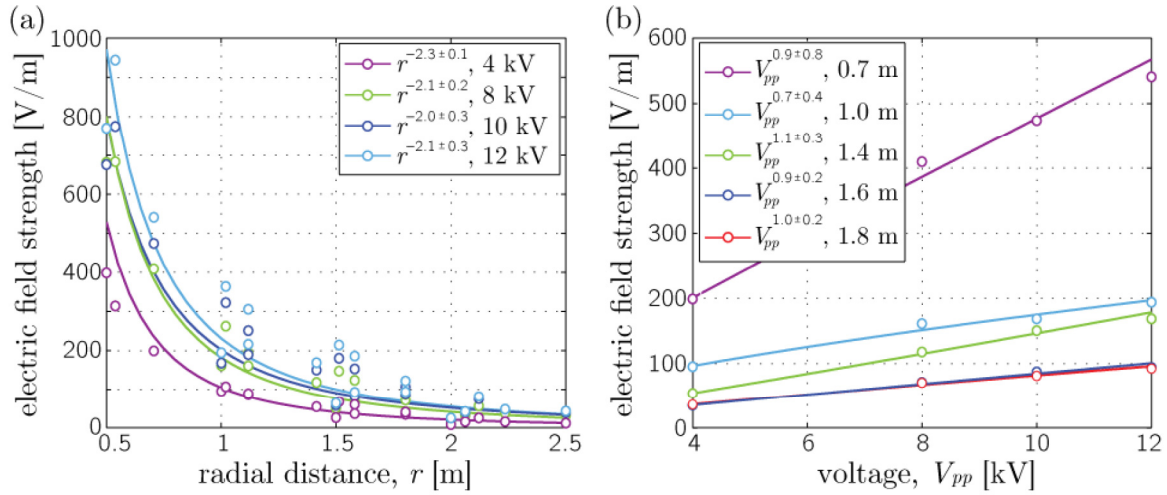


Figure 15: The resultant magnetic field strength at 90° orientation as a function of (a) radial distance from actuator centre for various operating conditions and (b) operating voltage at various radial locations (at 4 kHz).

From the contour plots of the resultant magnetic field strength,  $|\vec{B}|$ , shown in Figure 16, it is shown that the magnetic field induced by the plasma actuator is quite weak, dropping to essentially zero by a radial distance of approximately 1.5 m.

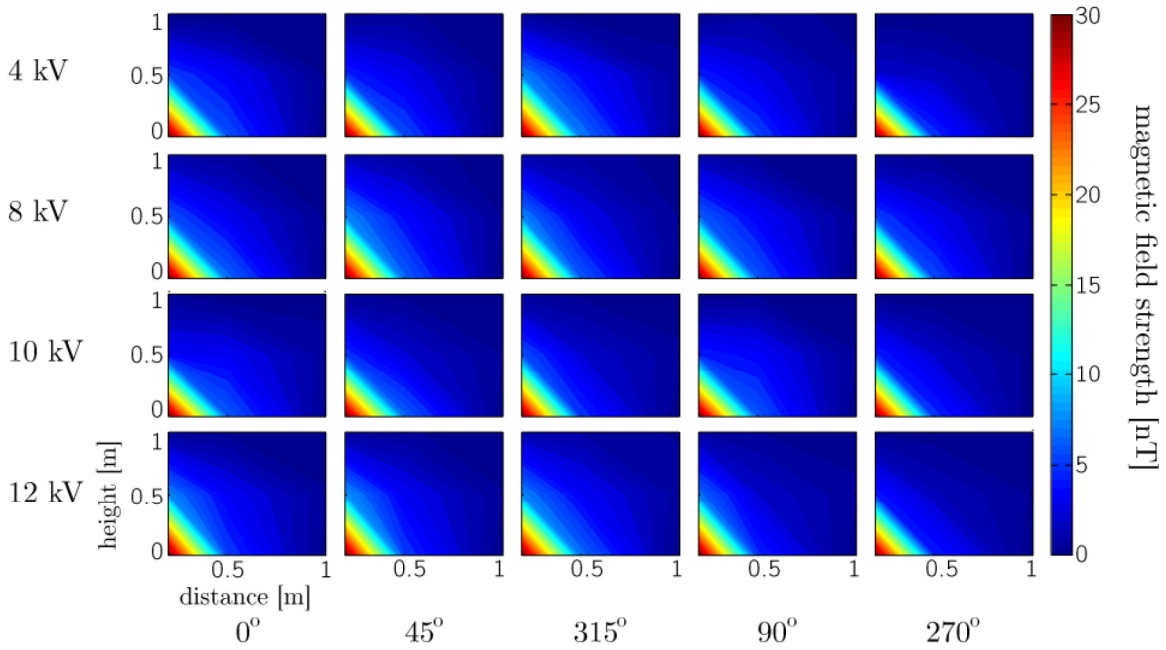


Figure 16: The resultant magnetic field strength at all orientations in response to various operating voltages (at 4 kHz).

Figure 17 shows magnetic field strength as a function of both radial distance from the actuator and operating voltage. The trends  $|\vec{B}| \propto 1/r^2$  and  $|\vec{B}| \propto V_{pp}$  were found via weighted least squares regression, consistently over all orientations tested. These relations mimic those of the electric field strength, as expected as a result of the relationship between electric and magnetic fields,  $|\vec{E}| \propto |\vec{B}|$ .



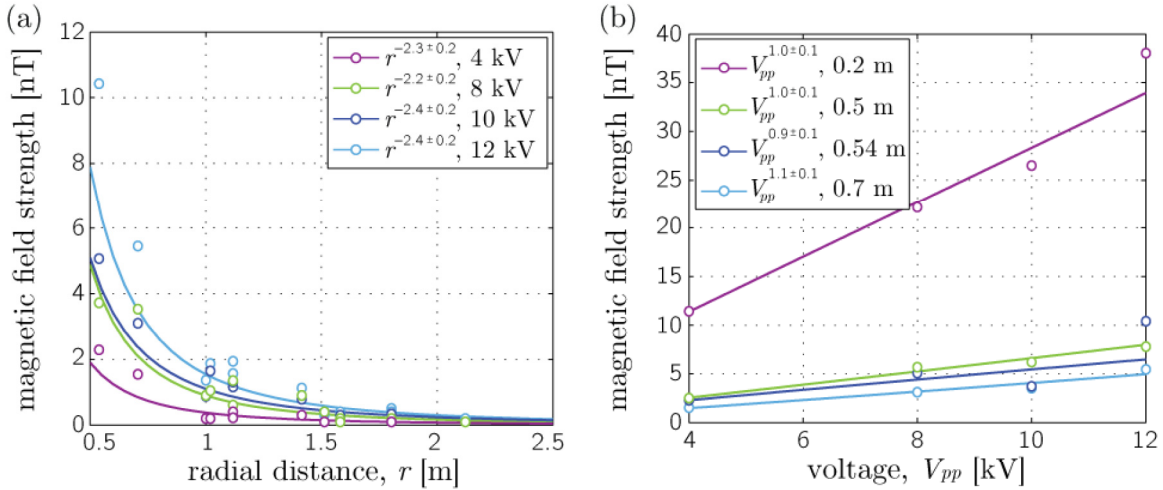


Figure 17: The resultant magnetic field strength at 90° orientation as a function of (a) radial distance from actuator centre for various operating conditions and (b) operating voltage at various radial locations (at 4kHz).

It should be noted that operation of the plasma actuator at 4 kV (peak-to-peak) failed to produce visible plasma discharge. This falls under the heading of ‘dark discharges’ where part ionization of the gas and electron avalanche occurs for operating voltages below the breakdown voltage of the gas. From the electric field and magnetic field contour sets, as well as Figure 15 and Figure 17, it can be seen that operation of the plasma actuator in the dark discharge regime does not differ from operation in the glow discharge regime with respect to electric and magnetic field behaviour. This emphasizes the importance of EMF awareness for researchers working with or in close proximity to plasma actuators, as even operation below breakdown field strength can generate measurable EMF radiation.

For the Actuator 2, maintaining a distance of 1.5 m guaranteed EMF radiation exposure below the limits set forth by Health Canada, for the range of operating conditions considered here. A simple EMF survey was recorded at the location of the author's workstation chair for a plasma actuator experimental set-up. In this set-up, operation of a micro-fabricated plasma actuator [12] at 10 kV (peak-to-peak), 4 kHz generated an electric field of approximately 44 V/m at a radial distance of approximately 2.55 m from actuator centre. This location represented the approximate location of the head of a person seated at the workstation computer.

The electric field strength was found to decrease at vertical positions closer to the floor since the actuator was approximately at head level. Reassuringly, this reading was significantly below the recommended limits for exposure to EMF radiation stated in Safety Code 6. Although, the workspace is considered a safe distance from the operating actuator according to Health Canada, the ME 3951A user manual recommends exposure limits of 1 V/m (electric field) and 20 nT (magnetic field) for frequencies above 2 kHz in areas where people spend substantial amounts of time, such as the workplace. As such, for the EMF experiments presented in the current work, prolonged exposure to any operating plasma actuators was minimized and ample distance was kept between persons and live actuators. Evaluation of EMF exposure is an important consideration in experimental set-up design for health and safety of both humans and equipment.

## 3.2 Ozone measurements

Ozone generation rate was quantified for a closed chamber within 5 minutes actuator operation. The Residential Indoor Air Quality Guideline issued by Health Canada (2010) recommends a residential maximum exposure limit of 40  $\mu\text{g}/\text{m}^3$  (20 ppb) ozone based on an averaging time of 8 hours. The plasma actuator generated up to 350 ppb/s during the experiments, which would rapidly exceed the amount recommended by the Health Canada guideline in a small room. In this case, a closed chamber with proper exhausting is mandatory for DBD plasma operation.

The ozone generation as a function of applied voltage (peak-to-peak) is shown for various frequencies in Figure 18a. The ozone production was found proportional to  $V_{pp}^{3.5}$ ,  $V_{pp}^{2.9}$ , and  $V_{pp}^{3.0}$  for operation at 1, 2, and 3 kHz, respectively. Ozone generation is also shown as a function of operating frequency for several applied voltages in Figure 18b.

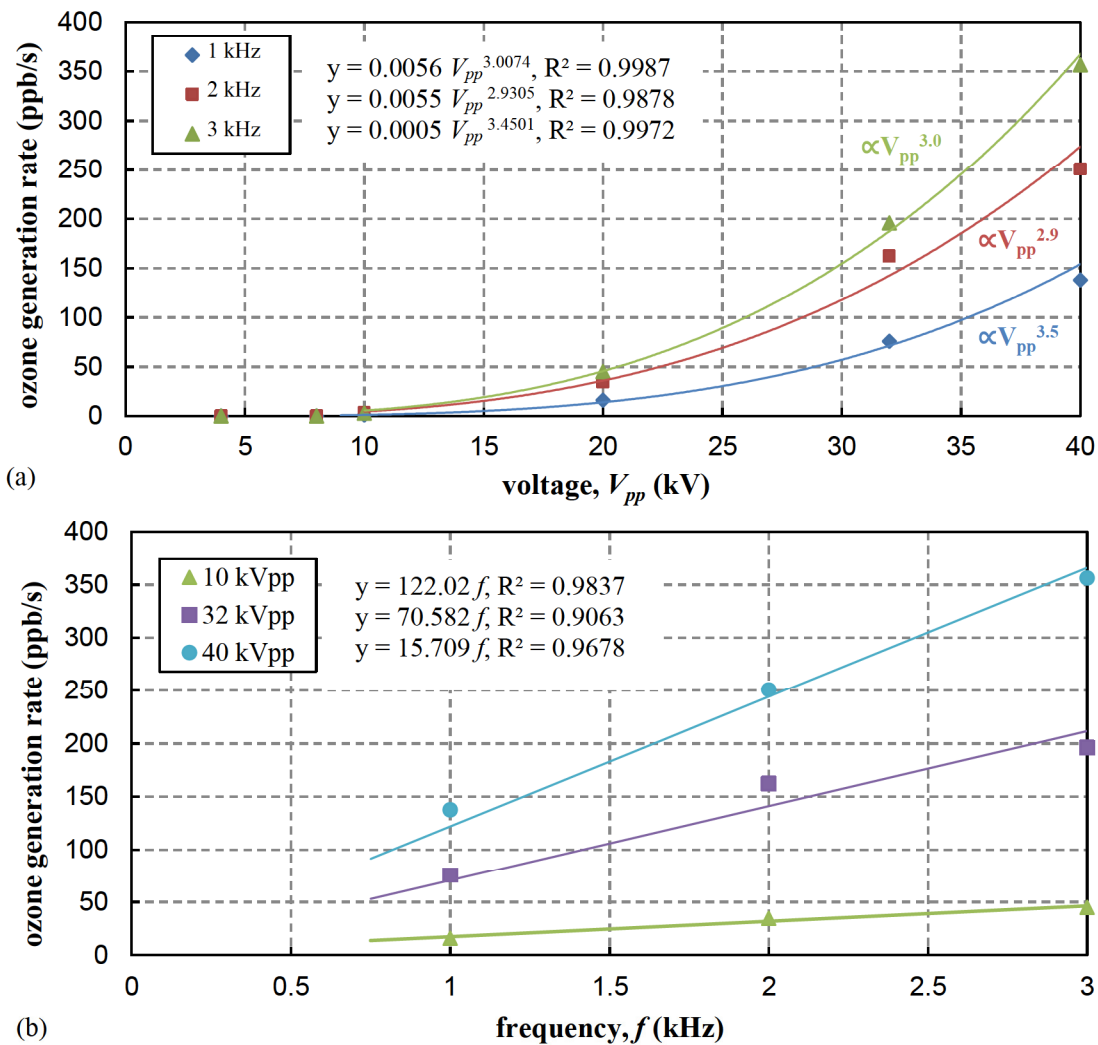


Figure 18: Ozone generation as a function of (a) applied voltage (peak-to-peak) at various frequencies and (b) operating frequency at various voltages.

It is shown that ozone generation scales with operating frequency in a nearly linear fashion. The power law behaviour of ozone production with voltage is reminiscent of the relation between power consumption and applied voltage typically reported in the literature. The relation between power consumption and applied voltage is commonly reported as  $P \propto V_{pp}^n$  with  $2 \leq n \leq 3.5$  [4], [20]. Similarly, the relation between power consumption and operating frequency is often described, or approximated as linear in plasma actuator studies [21], [22]. The results shown in Figure 18 indicate that the ozone production is proportional to the power consumed by an operating actuator.

Figure 19 shows the ozone generation at 4 kV (peak-to-peak) over a larger range of operating

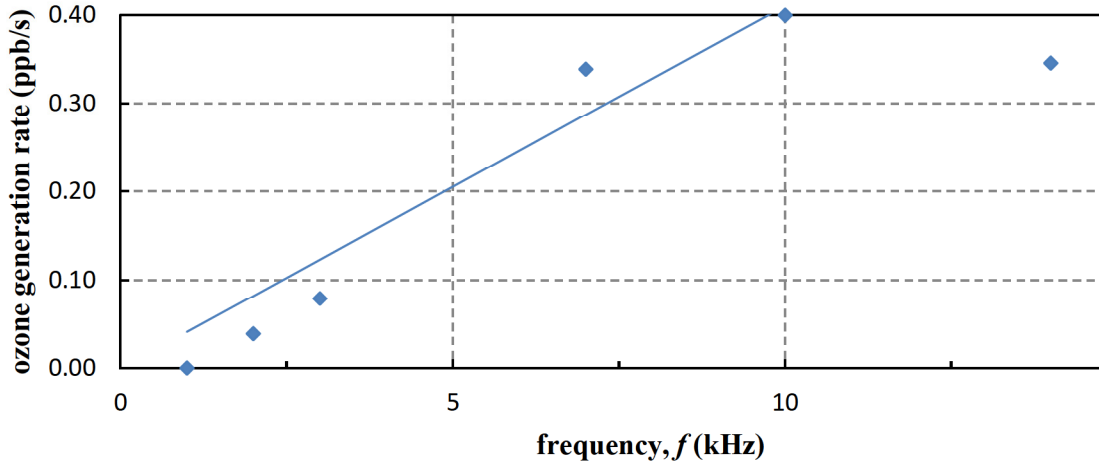


Figure 19: Ozone generation as a function of operating frequency at 4 kV (peak-to-peak).

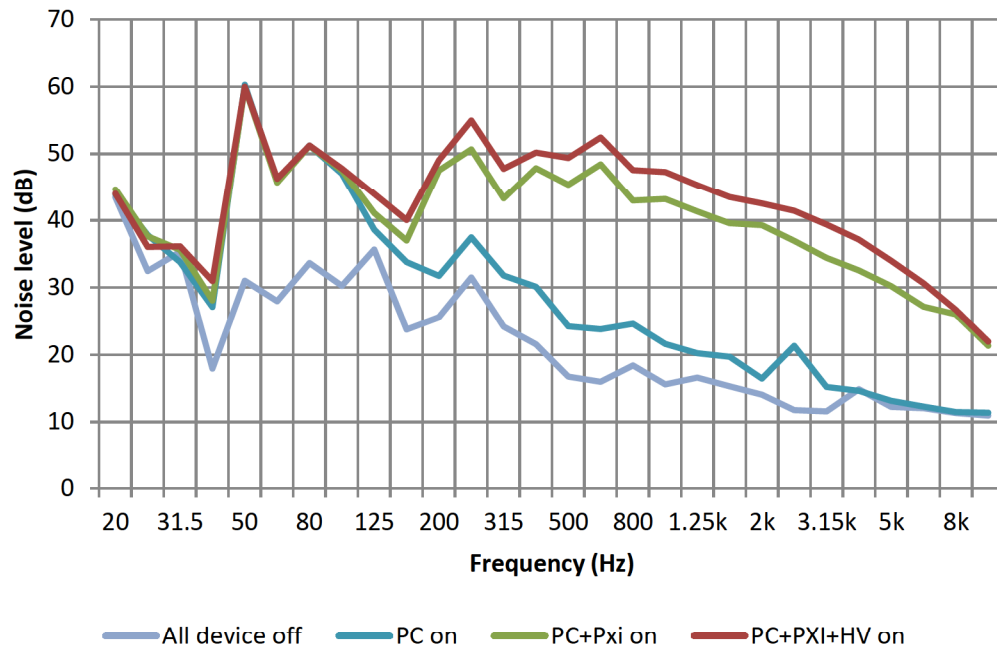
frequencies than shown in Figure 18. The linear behaviour of ozone generation with frequency is demonstrated in Figure 19 for frequencies up to 10 kHz. The data point in Figure 19 at 14 kHz does not follow the linear behaviour. This is attributed to the effects approaching the maximum current limit of the high voltage amplifier (20 mA) resulting in unstable output.

### 3.3 Noise measurements

The average noise level with all experimental equipment on but with the plasma actuator inactive was 57.3 dBA. Note that the background noise level in the laboratory is subject to large fluctuations within a small time frame due to other noise factors in the building such as pumps, heating, other people, etc.

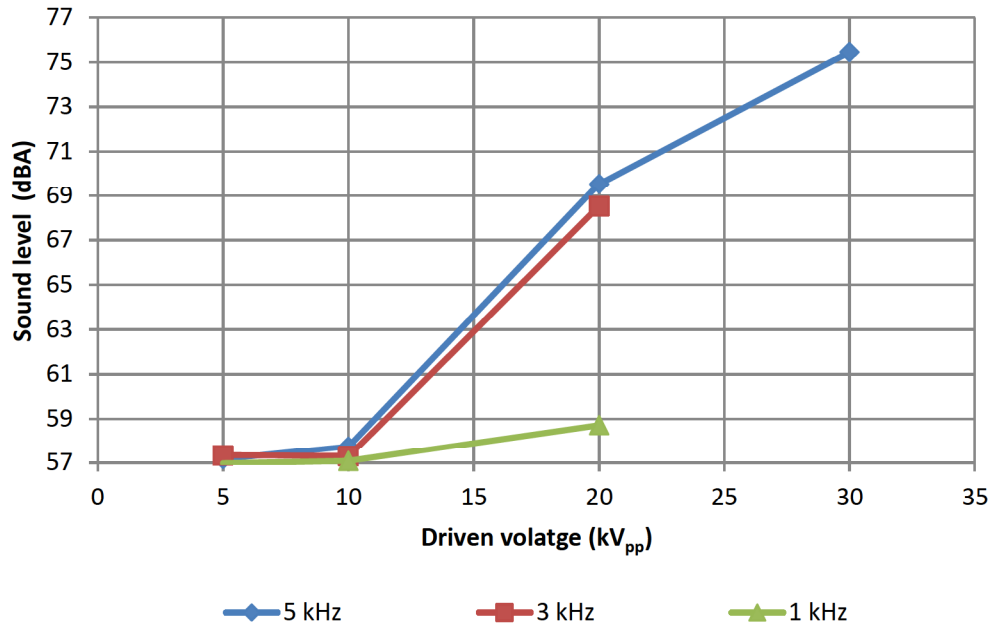
It is shown in Figure 20 that the personal computer (PC) emitted low frequency noise, most likely produced by the internal fans. The PXI-6052E function generator (PXI) and Matsusada high voltage amplifier (HV) also contain fans which in contrast to the PC they always operate at full RPM. It is also shown in Figure 20 that the PXI and HV devices contribute relatively high frequency noise to the frequency spectrum compared to the PC.





*Figure 20: Frequency spectrum in the laboratory with contributions from various electronic equipment (without A-weighting).*

Figure 21 demonstrates that both the voltage and frequency influence the measured sound level. The maximum sound level reached by the operating DBD plasma actuator, operating at 30 kV (peak-to-peak) and 5 kHz was 75.5dBA. Operation at 30 kV (peak-to-peak) represents the upper limit of operating voltages found in the literature and can be expected to generate a higher noise level than the average plasma actuator experiment. At this operating condition the noise level generated was well below the 87 dBA Canadian Federal limit. To receive the equivalent energy dose would require exposure to the plasma actuators noise level for more than four days.



*Figure 21: Sound level recorded by device with actuator chamber door open as a function of operating voltage for various frequencies.*

When the door to the chamber containing the operating actuator is closed, the sound level is reduced to 57 dBA. Figure 22 shows the effect of closing the chamber door on the frequency spectrum both with and without plasma generation at 5 kHz, 20 kV (peak-to-peak). It is demonstrated that the door mitigates the actuators high frequency noise at 5 kHz and above. The increase in noise level at around 60 Hz with the door closed is presumably caused by background noise reflecting on the door towards the sensor located outside the chamber.

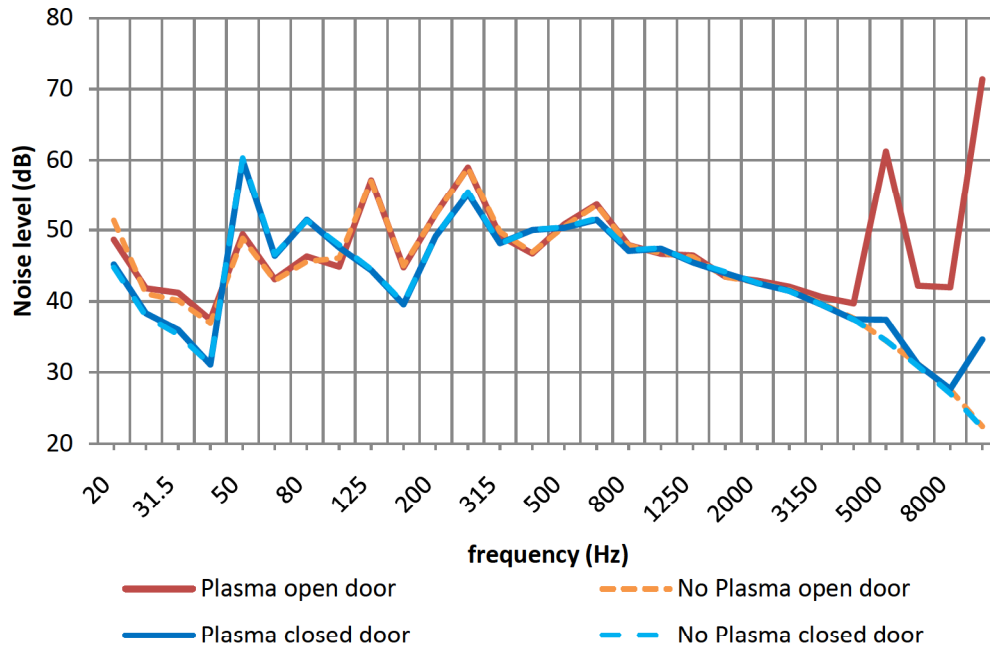


Figure 22: Frequency spectrum of the DBD plasma actuator operated at 5 kHz and 20 kV (peak-to-peak) with chamber door closed and open (without A-weighting)

Figure 23 shows the frequency spectrum of a plasma actuator operated at 20 kV (peak-to-peak) for various frequencies. The frequency spectra for each case show a peak in sound level at the operating frequency and another at double the operating frequency (with a higher noise level than observed for the operating frequency peak). A sound level peak may also occur at three times the driven frequency as can be seen for the 1 kHz case. However, the range and resolution of the device cannot confirm this occurrence for the higher frequency cases.

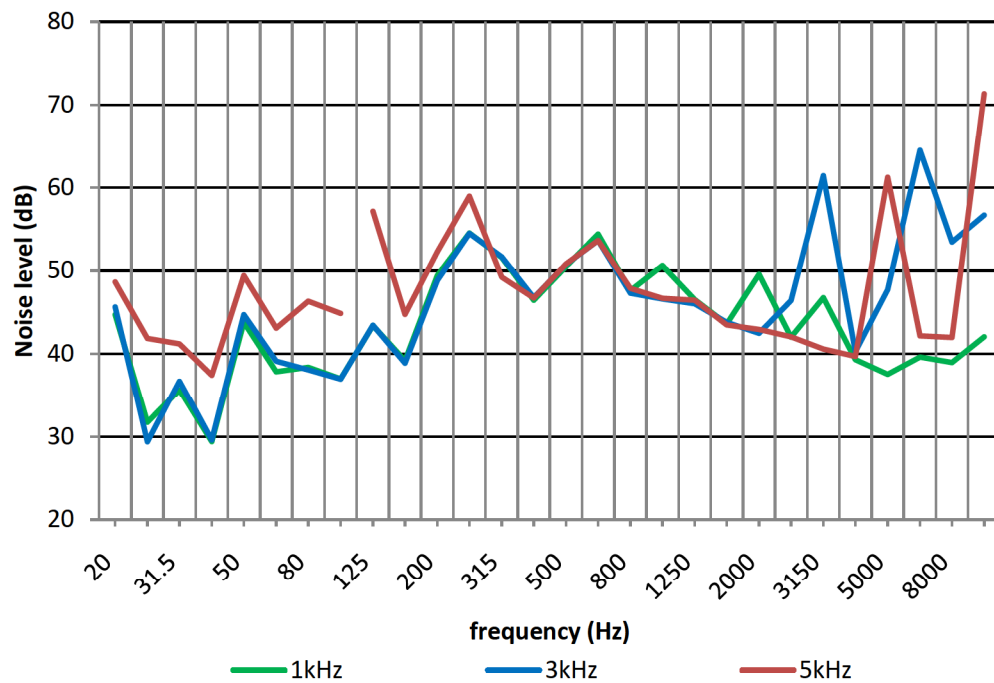


Figure 23: Frequency spectrum for DBD plasma actuator operating at 20 kV (peak-to-peak) as a function of operating frequencies (without A-weighting).

## 4 Conclusions and recommendations

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### 4.1 Electromagnetic measurements (Actuator 1)

For Actuator 1, operating at 16 kV (peak-to-peak) and 3 kHz in an open area, the maximum electric field strength of 600 V/m for a controlled environment was found to be approximately radial in the y-z plane with, in general, a decreasing radius with increasing height above the plane of the actuator. Although radius decreased with vertical distance, the trend was not radial in the x-z plane. The maximum electric field strength of 280 V/m for an uncontrolled environment was found also to be approximately radial. The distances however demonstrated less of a trend with respect to height above the actuator.

Since measurement technique was subject to uncertainties of  $\pm 5$  cm, the discrepancies between vertically separated measurements matches that of the uncertainties between the measurements, thus a trend is not observed. For these operating conditions, safe working distance as outlined by Health Canada's Safety Code 6 is located beyond a radial distance of 140 cm in a controlled environment and 215 cm in an uncontrolled environment from the y-z plane of the plasma actuator. At the same operating conditions magnetic field is of negligible concern according the Safety Code 6. The magnetic field was measured as 24 nT radially at a height of 0 cm in the y-z plane of the actuator. This is much lower than the safety standard for even the uncontrolled case.

When operating inside a closed chamber, the maximum electric and magnetic field measured from the DBD plasma actuator were reduced to 80 V/m and 30 nT, respectively at 20 cm distance around the chamber. These values are below to the limit specified by Health Canada's Safety Code 6, i.e. 280 V/m and 2752 nT, respectively.

### 4.2 Electromagnetic measurements (Actuator 2)

The electric and magnetic fields surrounding Actuator 2 were characterized at various voltages and frequencies. The resultant electric field strength (3-axis measurements) generated by a plasma actuator was found to be a function of radial distance, described by  $|\vec{E}| \propto 1/r^2$ , the same relation which applies to a point charge. The electric field was directly proportional to the applied voltage,  $|\vec{E}| \propto V_{pp}$ . For magnetic fields, the relations  $|\vec{B}| \propto 1/r^2$  and  $|\vec{B}| \propto V_{pp}$  were found, as to be expected from the relationship between electric and magnetic fields ( $|\vec{E}| \propto |\vec{B}|$ ). No correlation was found between the applied frequency and the electric or magnetic fields. Interestingly, it was found that the electromagnetic field behaviour was unchanged for a plasma actuator operating in the 'dark discharge' regime (no visible plasma), emphasizing the importance of EMF analysis in the lab space. Even for operation below breakdown field strength, EMF strength exceeded the exposure limits found in Safety Code 6 developed by Health Canada. These exposure limits, human health effects, and lab equipment concerns are discussed in Section 2.

For the highest operating voltage tested, 12 kV (peak-to-peak), the controlled environment electric field limit of 600 V/m was exceeded between 0.5 m and 0.7 m of the actuator, while the uncontrolled environment limit of 280 V/m was exceeded within approximately 1.0 m of the actuator. For the lowest operating voltages tested, 4 kV (peak-to-peak), the controlled environment

electric field limit of 600 V/m was exceeded with between 0.2 m and 0.5 m of the actuator, while the uncontrolled environment limit of 280 V/m was exceeded within approximately 0.5 m of the actuator. The largest resultant magnetic field recorded was only 0.6% and 1.4% of the controlled and uncontrolled environment magnetic field limits, respectively.

Aside from human safety concerns, EMF radiation can also pose a risk to damaging electronic lab equipment through static build-up. AC electric fields can induce currents in conductive materials in the field. Accumulation of potential on a conductive surface, such as an ungrounded metallic equipment casing, can result in electrostatic discharge (ESD) with grounded (or lower potential) objects, such as a human body. ESD can cause damage to delicate electronic components. For this reason it is important that all lab equipment be properly grounded in the vicinity of an operating plasma actuator. EMF radiation can also influence sensitive measurement tools to give corrupt readings, for example thermocouples or the strain gauges of an electronic balance. Care should be taken when plasma actuator experiments occur in the same workspace as other experiments for the sake of both lab equipment and the safety of other researchers who may not be aware of the EMF radiation safety standards

### **4.3 Ozone measurements**

Ozone generation rate was quantified within a closed chamber within 5 minutes actuator operation. The Residential Indoor Air Quality Guideline issued by Health Canada (2010) recommends a residential maximum exposure limit of 40  $\mu\text{g}/\text{m}^3$  (20 ppb) ozone based on an averaging time of 8 hours. The DBD plasma actuator generated during the experiments up to 350 ppb/s, which would rapidly exceed the amount recommended by the Health Canada guideline in a small room. In this case, a closed chamber with proper exhausting is mandatory for DBD plasma operation.

### **4.4 Noise measurements**

The noise level produced by an operating plasma actuator was measured from outside the device containing chamber with the chamber door open and closed. The Canada Occupational Health and Safety Regulations (2012) states that the maximum exposure limit  $L_8$  must be 87 dBA or below. The noise levels recorded in the presence of the operating actuator were 75.5 dBA with the chamber door ajar and around 57 dBA when the door was shut. Both measurements are below the threshold for damage for 8 hours of exposure. This study demonstrates that plasma actuator experiments should not be considered a risk for permanent hearing damage, and that noise levels surrounding an active device can be attenuated by enclosing the device.



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## List of symbols/abbreviations/acronyms/initialisms

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AC	Alternating current
AM	Amplitude Modulation
CEPA	Canadian Environmental Protection Act
CRT	Cathode ray Tube
DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
DBD	Dielectric barrier discharge
DNA	Deoxyribonucleic acid
EM	Electromagnetic
EMF	Electromagnetic field
EMI	Electromagnetic interference
ESD	Electrostatic discharge
FCET	Flow Control and Experimental Turbulence
FM	Frequency modulation
kVpp	Kilo-Volt peak-to-peak
LF	Low frequency
LOAEL	Lowest Observed Adverse Effect Level
NIST	National Institute of Standards
NOAEL	No Observed Adverse Effect Level
PMMA	Poly(methyl methacrylate)
ppb	Parts per billion
R&D	Research & Development
RF	Radiofrequency
RFI	Radio-frequency interference
rms	Root mean square
SOP	Standing Operating Procedure
UTIAS	University of Toronto Institute for Aerospace Studies

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### 13. ABSTRACT

In recent years, there has been considerable interest in dielectric barrier discharge plasma actuators as flow control technology due to their potential use in a variety of applications. For instance, these light-weight devices have low power consumption, low profile, can be laminated to aerodynamic surfaces and provide fast response for active feedback control strategies. One of the major drawbacks of plasma actuators is the high voltage applied signal required for their operation. This is a concern to the implementation of these devices in aerospace and aeronautics or other industries with respect to power supply logistics and more significantly, because the risks to the human health. Other potential health risks associated with plasma actuator implementation include exposure to ozone concentrations and noise levels.

The main purpose of this study was to investigate the severity of electromagnetic, ozone, and noise emissions from an operating plasma actuator and to compare these results with Canadian health and safety standards. This study will be used to determine if eventual action is required to reduce exposure to any of these risk factors and will serve to guide those working with/around plasma actuators as to when countermeasures to mitigate exposures are advisable or necessary. The results obtained from this study will be used to develop new standing operating procedures for plasma actuator operation in DRDC Valcartier, as well as be disseminated into the scientific community.

The plasma actuators in the current work were operated over a range of applied voltages and frequencies representative of those typically reported in the literature. First, the distances from the operating plasma actuator at which the electric and magnetic field strengths met or exceeded the standards for maximum exposure to prevent adverse health effects were found, followed by a characterization of the electric and magnetic fields for various operating conditions. The rate of ozone and the noise levels and frequency spectrum generated by a plasma actuator were found for various voltages and frequencies.

This study demonstrates that safety consideration should be made for electromagnetic and ozone exposure associated with typical plasma actuator use. However, it is shown that noise generated by an operating plasma actuator is below safety standards for hearing damage and should not be considered a health risk.

Au cours des dernières années, des actionneurs à décharge à barrière diélectrique de plasma ont acquis un grand intérêt en tant que technologie de commande d'écoulement en raison de leur utilisation potentielle dans une variété d'applications. Par exemple, ces appareils légers ont une faible consommation d'énergie, un profil bas, peuvent être laminés sur des surfaces aérodynamiques et fournir une réponse rapide pour les stratégies de contrôle de rétroaction actifs. L'un des principaux inconvénients des actionneurs à plasma est le signal à haute tension utilisé pour leur fonctionnement. C'est une préoccupation pour l'utilisation de ces dispositifs dans les domaines de l'aérospatiale et l'aéronautique en plus des risques de radiation aux champs électriques et magnétiques lors de la mise au point de ces dispositifs.

D'autres risques pour la santé associés à la mise en œuvre de l'actionneur de plasma comprennent l'exposition à des concentrations d'ozone et à des niveaux de bruit. L'objectif principal de cette étude était d'examiner la gravité de la radiation électromagnétique, l'émission d'ozone et les émissions de bruit lors du fonctionnement d'un actionneur plasma de comparer ces résultats avec les normes de santé et de sécurité canadiennes. Cette étude servira à déterminer si d'éventuelles mesures sont nécessaires pour réduire l'exposition à l'un de ces facteurs de risque et servira à guider ceux qui travaillent avec / autour des actionneurs plasma et de proposer des solutions afin d'en atténuer les risques. Les résultats obtenus lors de cette étude seront utilisés pour développer de nouvelles procédures opérationnelles permanentes pour le fonctionnement de l'actionneur de plasma au RDDC Valcartier, ainsi que d'en diffuser les résultats dans la communauté scientifique.

Les actionneurs de plasma ont été opérés sur une plage de tensions et de fréquences représentatives de celles généralement décrites dans la littérature. Tout d'abord, les champs électriques et magnétiques ont été mesurés à différentes distances autour de l'actuateur afin de déterminer le profil de radiation. Par la suite, les zones limites de radiations ont été identifiées en se basant sur les normes d'expositions maximales qui déterminent la zone sécuritaire d'un opérateur afin de prévenir des effets néfastes pour la santé. Le taux d'ozone et les niveaux de bruit sonore ont été aussi mesurés afin de déterminer le risque associé à la santé. L'étude montre que le niveau d'ozone produit peut représenter un risque mais que le bruit généré par un actionneur de plasma est en deçà des normes de sécurité pour des dommages auditifs et ne doit pas être considéré comme un risque pour la santé.

Cette étude démontre que l'examen de la sécurité devrait être fait pour l'exposition électromagnétique et l'ozone associé à l'utilisation typique de l'actionneur à plasma.

### 14. KEYWORDS, DESCRIPTORS or IDENTIFIERS

dielectric barrier discharge; DBD; SDBD; electro-hydro-dynamic; EHD; flow control; ozone emissions; noise emissions; electromagnetic emissions





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