Assessment of the UV emission of a pulsed atmospheric arc plasma jet

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March, 2024

1 Introduction

The purpose of this publication is to provide basic understanding of the ultraviolet radiation emitted by the plasma generator PG-31, being part of the atmospheric plasma system PlasmaBrush PB3. Additionally, it may serve as guidance for system integrators and operators to ensure safe operation for typical industrial and laboratory use cases. The description considers the publications of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and its German and Swiss member "Arbeitskreises Nichtionisierende Strahlung" (AKNIR). Finally, the compliance with DIN EN 12198-1:2008-11 Safety of machinery - Assessment and reduction of risks arising from radiation emitted by machinery - Part 1: General principles must be given.

In principle, the damaging effects of artificially generated and natural UV radiation are the same and well described in the literature [3]. However, there are a few differences to note:

- In most cases, artificial UV radiation can be switched off quickly.
- Short-wave radiation of the solar spectrum with $\lambda < 280$ nm is largely filtered out by the atmosphere but can be emitted by artificial sources (e.g. UV-C sources).
- Artificial sources can emit UV light without a visible spectral component and are therefore not recognized as a hazard.

For UV radiation, the ICNIRP recommends limits on the radiant exposure for different spectral regions to ensure protection against hazards such as erythema, photo-conjunctivitis, and photo-carcinogenesis.

2 Mitigation Strategies

To comply with ICNIRP guidelines and ensure the safe operation of an industrial plasma system, several mitigation strategies can be employed and will be assessed in this case study.

1. Monitoring and Measurement: Monitoring of UV emission levels using appropriate instrumentation to ensure compliance with exposure limits and facilitate timely adjustments if necessary.

If the exposure limits are exceeded additional measures must be implemented:

2. Engineering Controls: Implementing engineering controls such as shielding and enclosure designs to minimize UV radiation leakage and direct exposure to personnel.
3. Operational Parameters: Optimizing operational parameters such as voltage, gas flow rate, and electrode geometry to minimize UV emission while maintaining system efficiency.
4. Personal Protective Equipment (PPE): Providing personnel with adequate PPE, including UV-blocking goggles and protective clothing, to mitigate the risk of direct UV exposure during system operation and maintenance.

3 General system classification

An electric arc (or arc discharge) is an electrical breakdown of a gas that produces a current through a normally nonconductive medium such as air produces a plasma, which may produce visible light.

If between a pair of electrodes, the electric field reaches a critical value, depending mainly on the gas composition and pressure, an avalanche process is triggered forming a streamer that quickly propagates trough the gas medium. The propagation speed of this streamer can be much higher than the drift velocity of the generated free charges due to secondary photoionization processes rushing ahead of the streamer front. Once the streamer has completely bridged the distance between the electrodes, a conductive filament-like channel is formed, and the current is quickly rising. Ohmic heating in the rapidly swelling conductive channel drives additional thermal ionization mechanisms (T_{gas}>>1000K). Now gas and electron temperature are strongly coupled, the process moves towards local thermal equilibrium within less than 100 ns.

However, if the current driving the growth of the initial streamer breaks down before reaching equilibrium a fully developed electric arc of high current density will not develop. Hence a pulsed power supply (e.g. PS2000 of the PlasmaBrush PB3) and a turbulent gas flow (e.g. PG-31 of PlasmaBrush PB3) that carries away and dilutes the charge carriers will yield a much lower gas and ion temperature and a different light emission spectrum, e.g. less visible near-infrared (NIR) components.

Atmospheric plasma systems of jet-type (vortex stabilized gliding arc) have gained considerable attention in various applications ranging from environmental technologies to material treatment due to their unique characteristics and versatility. However, concerns regarding potential UV emission hazards have prompted investigations into ensuring compliance with safety standards, particularly those set forth by the International Commission on Non-Ionizing Radiation Protection (ICNIRP).

The PG-31 with axial flow stabilization of the arc and pulsed DC supply (PS2000) for current limitation is, in a sense, a transition type from the class of atmospheric pressure plasma jets.

As in typical "gliding arc" arrangements [4-6], the arc cannot develop to the full current corresponding to the excitation voltage, as the turbulent flow quickly mixes the generated charge carriers with fresh gas and the current is limited by the pulsed excitation. These characteristics are also found in the optical emission spectrum.

UV Emission in atmospheric plasma systems: UV radiation is an inherent byproduct of the ionization process within plasma systems. The emission spectrum typically includes wavelengths ranging from 100 to 400 nm, with varying intensity depending on factors such as operating voltage, gas composition, and electrode material. UV emission can result from electronic transitions within excited species present in the plasma, as well as from secondary processes such as the recombination of ions and electrons.

When the atmospheric plasma system PlasmaBrush PB3 is operated with air as the working gas, the optical emission spectrum exhibits several characteristic bands due to the excitation and de-excitation processes occurring within the plasma. Some of the prominent bands observed in the optical emission spectrum with air include:

- Nitrogen (N_2)-Bands
- Oxygen (O_2)-Bands

And of lower intensity

- Ozone (O_3) Bands
- Minor constituents of air, such as argon, may also contribute to the spectrum, although their contribution may be less pronounced compared to nitrogen and oxygen.
- Impurity Bands. Depending on the specific conditions and materials involved, impurity bands from contaminants or electrode materials may also be present in the spectrum, although they are typically of lower intensity compared to the main bands from air components.

Overall, the optical emission spectrum of a PB3 system operated with air exhibits a complex combination of molecular and atomic emission bands, primarily originating from nitrogen, oxygen, and their molecular and atomic species. The precise spectral features depend on various factors including operating conditions (e.g., voltage, current, gas flow rate), electrode materials, and the presence of impurities.

During operation in the focused plasma mode, with arc transferred on an electrically conducting surface, additional spectral components in UV range can be expected. It is well known that arc fixed at graphite or steel surfaces is a strong UV emitter in a broad wavelength range, including UVC. As the level of emission depends very much on the material used and the processing configuration, the following results for this application are only valid to a limited extent. They must be checked and possibly adjusted in individual cases according to the local conditions.

The Federal Institute for Occupational Safety and Health (BAUA) provides support and information for the assessment of occupational safety in German-speaking countries for welding systems [9] that are similar to plasma generators in terms of their UV emissions.

4 System description: PlasmaBrush PB3

The plasma system used for the experiments exhibits a typical light emission characteristic for pulsed atmospheric plasma jets operated with air at ambient pressure.

Figure 1*: The PlasmaBrush PB3 is a combination compact plasma jet generator nozzle and a unipolar pulsed high-voltage source used for industrial plasma process integration. Usually, it will be operated with air (CDA).*

The most intense emission stems from the filamentary arc, whereas the secondary plume (seen as a flamelike pale yellowish glow) has a very low relative intensity. The emission of the filamentary arc consists mainly of intense nitrogen lines in the near UV [5-7] whereas the secondary emission is dominated by a broad relaxing NO_2 continuum of low intensity [8].

Some NIR emission from the hot cathodic foot point and released impurities are added as a negligible spectral component, even if they are visible.

If the portion of the radiation emitted by the arc is cut off at an angle of 90° to the plasma beam via a diaphragm, the measured intensity drops by several orders of magnitude. Therefore, the spectral part of the secondary emission is neglected in the following.

The spatial and spectral radiation characteristics in the case of the plasma jet in question therefore follow those of an elongated axial arc of approx. 50 mm in length, most of which is located inside the nozzle and only a small part of which is discharged from the nozzle opening.

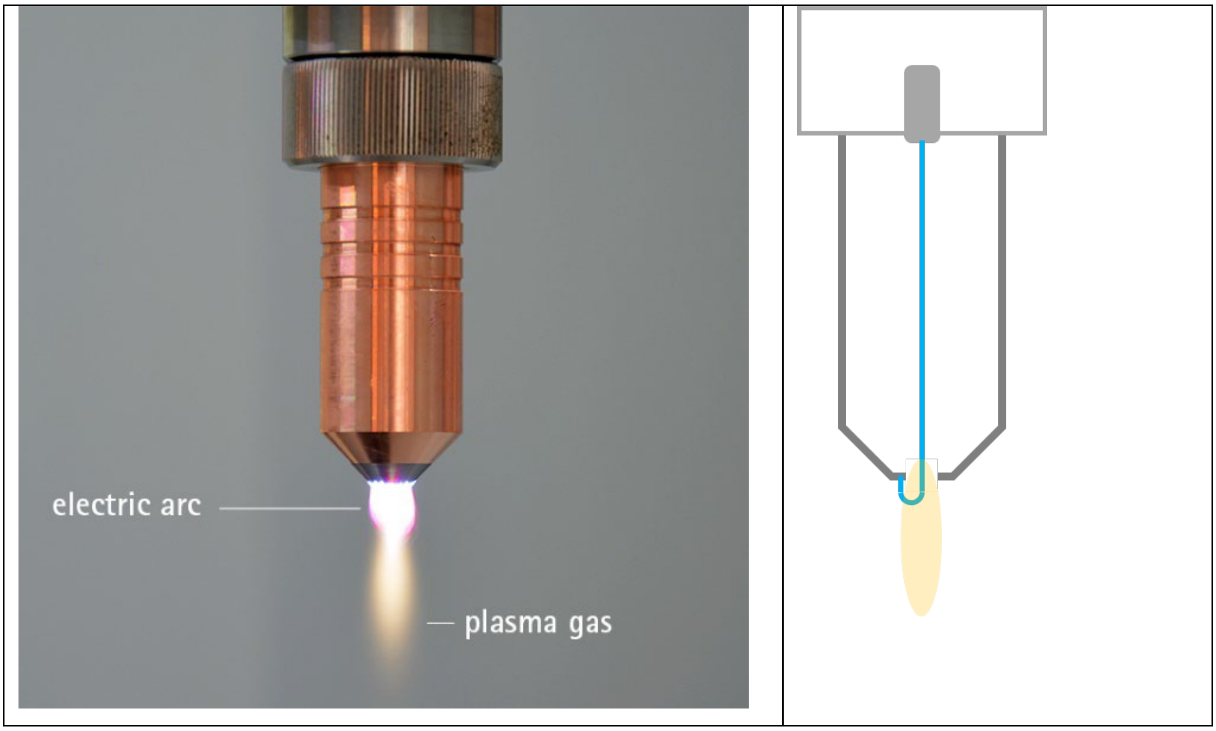

Figure 2: *Photograph of the PlasmaBrush PB3 jet using the A45**1** nozzle operated at full power and an air flow of 50 slm. The right side depicts the simplified position of the filamentary arc stretching from the inner anode to the aperture of the nozzle-shaped copper cathode.*

5 Measurement System and Methodology

5.1 UVA/UVB-measurement

Quantitative intensity measurements in the wavelength band from 280 nm to 380 nm were carried out with the PCE-UV34 UVA-UVB workplace safety measuring device. The nozzle A450 was used, geometrically identic with the A451 shown in figure 2, but without the tungsten core.

Figure 3: *PCE-UV34: UVA - UVB radiation meter*

5.2 Spatially resolved data

A checkered white paper sheet with a high proportion of optical brighteners was used to record intensity distributions. The plasma jet was aimed vertically at the paper at a defined working distance and the image was taken from the back of the paper with a conventional digital camera. The image was then uploaded using a data analysis software (Igor Pro from wavemetrics). Linear response was crosschecked using the UV photodiode device 5 positions in each geometrical setup.

Within the same data processing program fitting procedures for angular distributions and simple ray tracing simulations were performed to span a larger space with good accuracy. A further check of the simulated results with selected intensity measurement points shows that this approach is robust.

5.3 Spectral distribution

To classify the light source according to the ICNIRP standard, the spectral composition of the UV spectrum must be known or, as in this case, taken from plasma sources with similar characteristics. The most important characteristics are gas composition and pressure, and I/U characteristic of the pulsed electric excitation.

To be able to carry out the evaluation according to the ICNIRP standard, various OES spectra for equivalent plasma systems were compiled from the literature and a typical emission spectrum was compiled from this data. The data from these external sources was only taken to get the relative spectral information, carefully checking comparable system behavior to the plasma system used in this study.

The reliability of this method was additionally tested by checking which relative intensity was measured with the UV measuring device after transmission through polycarbonate (PC, 370 nm cutoff), PET (300 nm cutoff) and through borosilicate float glass (250 nm cutoff). The main emissions are clearly in the range between 300 and 400 nm.

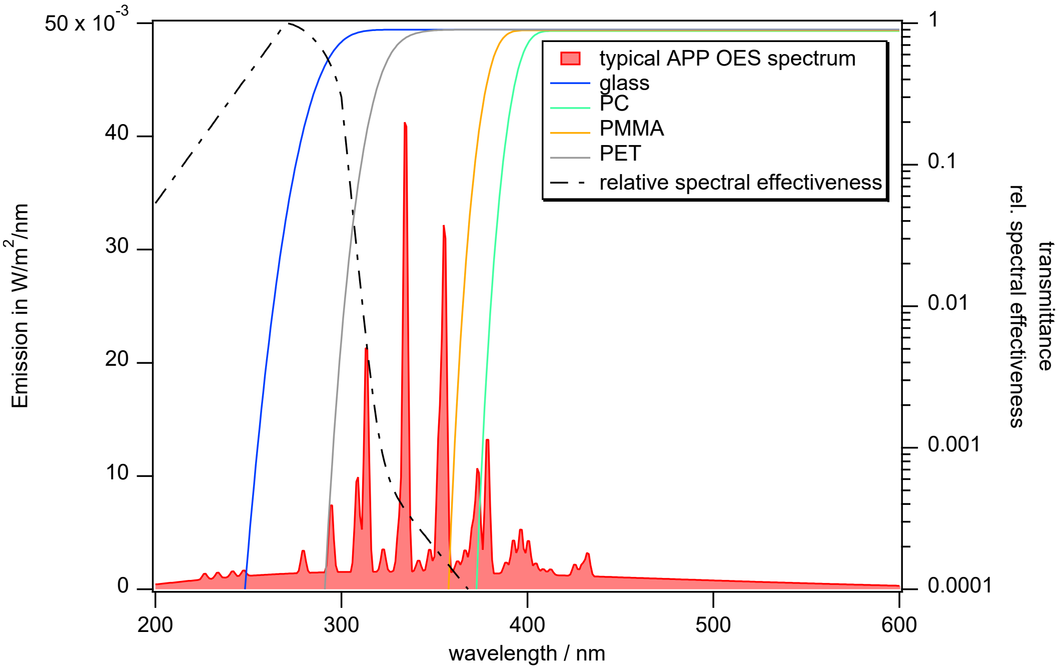

Figure 4: *Data compiled from different sources. [4-8]*

Once the spectral distribution of a broadband source is known. We will have to determine the effective irradiance weighted against the peak of the spectral effectiveness curve (at 270 nm s(l)=1)), following a spectral weighting formula:

E_{eff}=S E_A * s(l)* Dl (1)

a=E_A/E_{eff} (2)

s(l): System specific correction factor (taken from ICNIRP guideline)

E_{eff}: effective irradiance in W/m^2

E_{Af}: spectral irradiance from measurements in W/m^2/nm

Dl: Bandwith of measurment in nm

Given the emission spectrum of a typical atmospheric pressure plasma jet operated with CDA a correction factor can be calculated using the above formula. Each integral value (as measured with a wide band UV/VIS photodiode) must be corrected with this value.

In our case this correction factor is **a = 0.077**.

Then finally the exposures must then be classified according to the table taken from the ICNIRP Guidelines.

Duration of exposure per day	Effective irradiance	
	E_{eff} (W m^{-2})	E_{eff} (μW cm^{-2})
8 h	0.001	0.1
4 h	0.002	0.2
2 h	0.004	0.4
1 h	0.008	0.8
30 min	0.017	1.7
15 min	0.033	3.3
10 min	0.05	5
5 min	0.1	10
1 min	0.5	50
30 s	1.0	100
10 s	3.0	300
1 s	30	3,000
0.5 s	60	6,000
0.1 s	300	30,000

Table 1*: Limiting UV exposure durations at given effective irradiances [1].*

5.4 Protective housing effects

If a protective housing is provided for the plasma system, which also serves the purposes of collision protection, protection against dangerous high voltages or the extraction of harmful gases and dust, for example, the material acts as an additional filter for UV light.

If such a housing consists of PMMA of 5 mm thickness the additional absorption of UV-Light will lead to a total spectral sensitivity factor of **$5*10^{-6}$** outside the boundaries of the housing for a plasma source emitting with a spectral characteristic such as depicted in figure 4. Such a protection although perfectly transparent in the visible spectrum serves as a very efficient barrier for UV-light.

If such a housing consists of PC of 5 mm thickness the additional absorption of UV-Light will be even higher and the total spectral sensitivity correction factor is **$2*10^{-6}$**.

5.5 Angular distribution

First, UVA/UVB intensity measurements (without spectral resolution) were carried out at different angles and distances of the plasma jet under typical working conditions. The angular distribution of the radiation characteristics of the plasma jet can be determined from this data. If the emission that is emitted directly from the arc is suppressed, the measured light intensity in the UV range is negligibly low. It therefore can be concluded that UV-light emission stems only from the electric arc that stretches from the inner anode to the nozzle aperture and is dragged outside of the nozzle with the rotating air flow.

The angular distribution of the intensity has a pronounced dependence on the distance to the plasma source. In the immediate vicinity of the plasma source (measuring distance comparable to the diameter of the nozzle opening), the radiation characteristic contains a relevant proportion of off-axis intensity. At greater measuring distances, this angular distribution converges to a strongly axial distribution (shadowing effect of the nozzle aperture). Close to the nozzle aperture a broader angular distribution is found. At larger measurement distances the angular distribution exhibits a sharp central peak and some tailing towards higher angles which can be empirically fitted using a double gaussian profile (see figure 5).

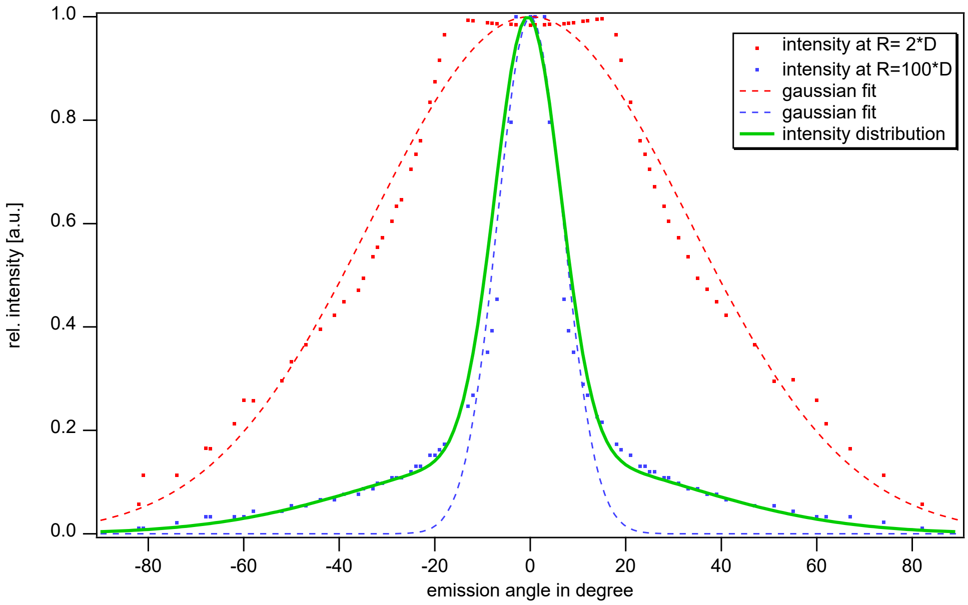

Figure 5: *Normalized intensity emitted at different angles relative to the axis of the plasma jet.*

In all cases the intensity follows basically the $1/R^2$ – law, with R as the designation for the measuring distance. At increased distance to the source the intensity falls quickly.

The experimentally measured data for the angular distribution and distance dependencies were used to model a light emitter with this radiation characteristic and then translated into spatial distributions for different ambient geometries using a simple ray-tracing approach.

Then for some given distances and angles the light intensities have been checked against the values from the model calculation. At distances closer than 300 mm the correlation was very good. At higher distances the intensity in the UV-range is quite low and accuracy of the measurement with the available UVA/UVB-measurement device was not sufficient.

However, this is not considered to be critical, since clearly the UV intensity at this higher working distance is less critical anyway.

5.6 Spatial intensity distribution (calculated via ray tracing)

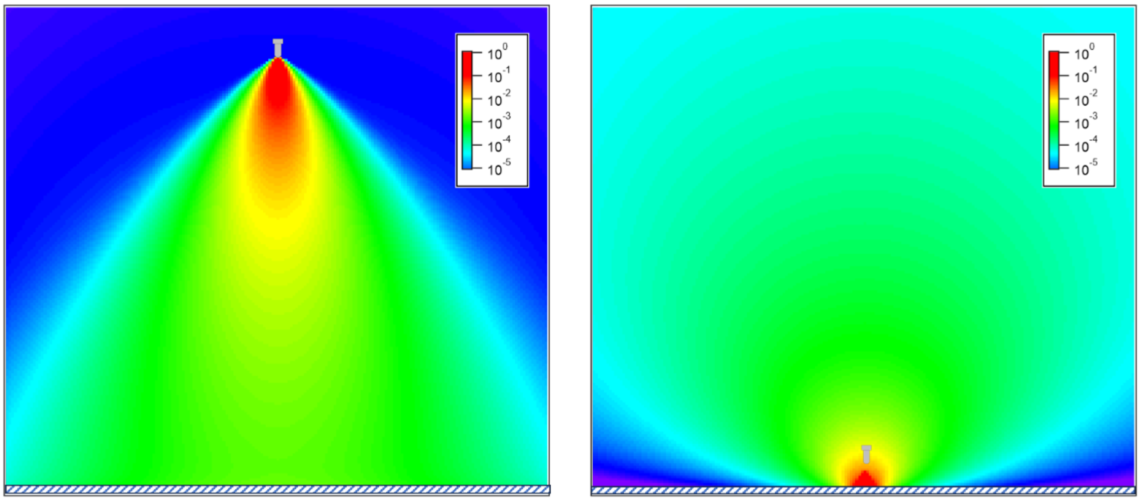

Figure 6: *The images show the spatial distribution of light intensity (W/m^2) in virtual box of 2m edge length and a 100% diffuse reflector on the bottom. Field of view 2 m x 2 m.*

5.7 Exposure mapping

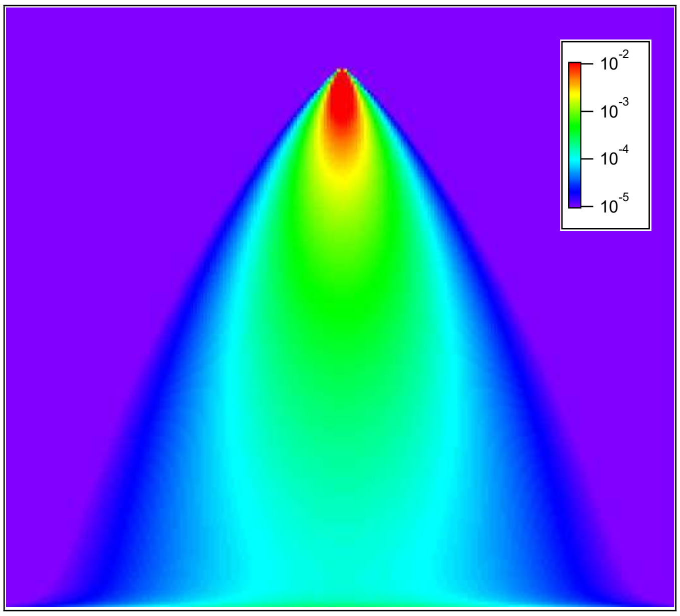

Figure 7: *UV light exposure map (light emission of jet weighted with the spectral sensitivity according to ICNIRP) generated by a* ***plasma jet directed into an open environment*** *(bottom plate of the box assumed to be a diffuse lambert emitter). Field of view 2 m x 2 m.*

Within the **red zone** around the plasma jet daily exposure should not exceed 5 minutes. However, this distance is at only about 50 mm of the nozzle aperture and therefore not of practical relevance since general safety considerations (temperature, high voltage) exclude unprotected human manipulation of a running plasma this close.

Within the **green zone**, operation is safe for 8 h.

The **blue/purple zone** would have no physiological relevant UV-light intensities to be measure.

Generally, we see that the axial direction carries more intensity, therefor keeping lateral distance of more than half a meter from the jet always keeps you safe from critical light exposure.

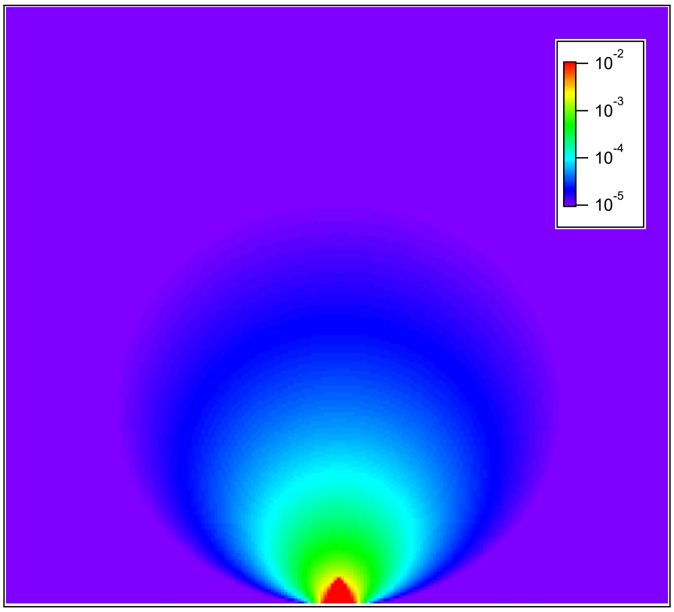

Figure 8: *UV light exposure map generated by a* ***plasma jet directed onto a metallic substrate*** *(bottom plate of the box), acting as a diffuse lambert emitter without losses. Field of view 2 m x 2 m.*

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Within the **green zone**, operation is safe for 8 h.

The **blue/purple zone** would have no physiological relevant UV-light intensities to be measure.

6 Conclusion

In summary, for the operation of the PlasmaBrush PB3 plasma system in the diffused plasma mode in air it can be said that:

1) the light emission at normal working distances (>500 mm) is not a safety risk in the sense of the ICNIRP guideline.

2) In the immediate vicinity <200 mm in axial direction, protective measures for skin and eyes are recommended if this work lasts longer than a few minutes a day. (E.g. when inserting an object to be treated). However, the plasma system should typically be paused briefly during such a plannable process.

3) Work at distances below 100 mm should always be avoided for further reasons of protection (high voltage, temperature, etc.).

A protective housing made of transparent, uncolored polycarbonate or kind of welding curtain, will provide complete protection against UVA/UVB radiation in systems in which several plasma sources are used in parallel, either in diffused or in focused plasma mode. In addition, an enclosure with extraction is recommended anyway as protection against unwanted contact and harmful gas emissions.

7 References

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