TECHNICAL REPORT

Tests, measurements and verification of good performance of unit: ‘Ultraviolet sterilizer of surfaces and air UVC Wemax-CK1000/Zhuzhou Wavelane Technology Co., LTD

SUBMITTED TO

THE RIGHT CHOICE IKE

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GREECE

PATRAS, GREECE

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TERMINOLOGY / ΟΡΟΛΟΓΙΑ			
IRRADIANCE	RADIATION INTENSITY	ΕΝΤΑΣΗ ΑΚΤΙΝΟΒΟΛΙΑΣ	W/m2
UV	ULTRAVIOLET	ΥΠΕΡΙΩΔΕΣ	10nm<400nm *
UVA	ULTRAVIOLET A-BAND	ΥΠΕΡΙΩΔΕΣ Α	315nm-400 nm
UVB	ULTRAVIOLET B-BAND	ΥΠΕΡΙΩΔΕΣ Β	280nm-315nm
UVC	ULTRAVIOLET C-BAND	ΥΠΕΡΙΩΔΕΣ C	200nm-280nm
VUV	VACUUM UV	ΥΠΕΡΙΩΔΕΣ ΚΕΝΟΥ	100nm-200nm
EUV	EXTREME UV	ΑΚΡΑΙΟ ΥΠΕΡΙΩΔΕΣ	10nm-100nm
NUV	NEAR ULTRAVIOLET	ΕΓΓΥΣ ΥΠΕΡΙΩΔΕΣ	300nm-400nm
VIS	VISIBLE	ΟΡΑΤΟ	400nm-700nm
IR	INFRARED	ΥΠΕΡΥΘΡΟ	0.7 μm -200μm
NIR	NEAR-INFRARED	ΕΓΓΥΣ ΥΠΕΡΥΘΡΟ	0.7 μm -3.0μm
EXPOSURE TIME		ΧΡΟΝΟΣ ΕΚΘΕΣΗΣ	(sec)
EXPOSURE DOSE	DOSE	ΔΟΣΗ ΕΚΕΘΣΗΣ	J/m^2
*NOTE /ΣΗΜΕΙΩΣΗ:	ALL SPECTRAL RANGE LIMITS ARE SET BY CONVENTION	ΟΛΑ ΤΑ ΟΡΙΑ ΦΑΣΜΑΤΙΚΩΝ ΠΕΡΙΟΧΩΝ ΟΡΙΖΟΝΤΑΙ ΚΑΤΑ ΣΥΜΒΑΣΗ	

SYNOPSIS

This Technical Report presents the results of the project ‘Tests, measurements and verification of good performance of unit: ‘Ultraviolet sterilizer of surfaces and air UVC Wemax - CK1000/Zhuzhou Wavelane Technology Co., LTD, performed in June 2022 on the initiative and for the purposes of THE RIGHT CHOICE IKE, by the Photonics nanotechnology Research Laboratory (PNRL) of the Department of Materials Science (Prof. N. A. Vainos) in collaboration with the Laboratory of Biological Chemistry of the Department of Medicine (Prof. C. Stathopoulos) of the University of Patras, Greece.

The work comprises the tasks:

1. **Pilot Use** of UVC sterilizer WeMax-CK1000 S/N 2020043646
2. **Absolute radiation measurements** (a) Irradiance [W/m^2] of UVC radiation emitted in the range of λ=200nm-300nm by use of (a) quantum and (b) bolometric detectors calibrated under NIST. Measurements performed in free space as a function of distance R and polar coordinates in azimuth and height (φ-θ) for the radiation emission of the sterilizer machine. (b) Spectral analysis of the emitted radiation (c) Analysis of results and determination of sterilization conditions according to the international standards in the near field (R<50cm) and the far field (R~50cm-500cm).
3. **Sterilization study** by use of (a) e-coli and staphylococcus cultures (more than 15 samples each) (b) UVC exposure of samples at a range of radiation doses [J/m^2] at spatially distributed points in laboratory environment (c) cultivation and cell population growth – no growth estimation.
4. **Analysis of Results- Technical Reporting**

Radiation measurements show very high irradiance levels in the range of 200nm-300nm recorded mainly at Hg Line λ=253.7nm emitted by the low-pressure mercury lamps. Biological experiments proved the strong sterilization effect of the UVC radiation on staphylococcus aureus and e-coli cultures even at distances greater than 6m from the source. It is noted that the tolerance of viruses (e.g. SARS, Covid-19, hepatitis, etc.) is negligible as compared to the bacteria used here. According to the international standards the estimated survival probability at the irradiance levels recorded is zero.

1 Description of the sterilizer

The machine UVC WeMax-CK1000 Zhuzhou Wavelane Technology Co.LTD, comprises two rows of 8 and 7 units 900X19mm Hg lamps mounted vertically in stainless steel trolley. One manual timer and one ON/OFF switch are in operation.

2 Emission spectra

The emitted radiation spectra was recorded by a Theta-metrisis / Ocean optics spectrum analyzer and presented in Fig. 1. The spectrum was recorded at several operation time intervals. Strong emission at UVC Hg-line λ=253.7nm (~254nm) was evidenced with minute power levels found between 254 and 300nm. Emission stability of the hot lamp is evidenced with insignificant power variation.

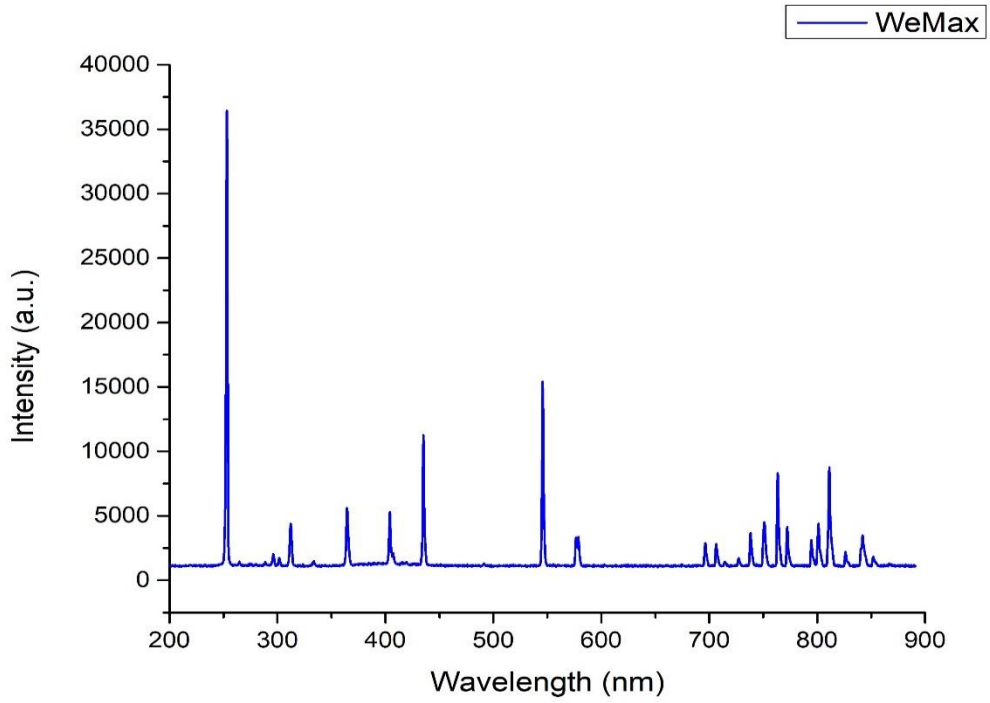


Fig. 1 Emission spectrum of WeMax-CK1000 sterilizer.

The recorded spectrum fully agrees with the typical emission spectra of low-pressure Hg lamps. Emission at 270nm is negligible. However, radiation at 270nm shows higher sterilization due to higher penetration in the cells. Radiation 254nm has ~50% the efficiency of radiation at 270nm but it is safer for the user.

3 Irradiance measurements

Irradiance levels were recorded using Newport 2832C NIST validated power meter having a two detector heads recording from the ultraviolet to the near infrared (200nm-1100nm) A bolometric Gentec power meter was used for cross reference. Total radiation (200nm-1100nm) and NUV-NIR (300nm-1100nm) radiation measurements were performed and the respective Irradiance levels I [mW/cm^2] were recorded and presented in the following sections.

3.1 Exit window and near-field irradiance

Fig. 2 presents the relevant cartesian coordinates used.

Fig. 3 tabulates the irradiance over the area of the exit window as described by the respective coordinates

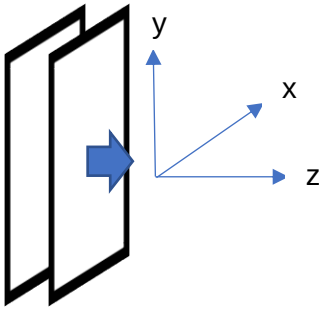


Fig. 2 Coordinate diagram.

UVC IRRADIANCE [mW/cm^2]			
x(cm)	.-30	0	.+30
y(cm)	UVC IRRADIANCE 200nm-300nm at z=10cm		
120		**1.284**	
60	**1.35**	**1.989**	**1.398**
30		**2.026**	

NUV-NIR IRRADIANCE [mW/cm^2]			
x(cm)	.-30	0	.+30
y(cm)	NUV-NIR IRRADIANCE 300nm-1100nm at z=10cm		
120		**0.605**	
60	**0.882**	**0.776**	**0.498**
30		**0.814**	

Fig. 3. Irradiance at z=10cm from the exit window at reference points x-y. Upper of UVC 200nm-300nm lower of NUV-NIR 300nm-1100nm.

3.2 Far field irradiance

Measurements were performed along the central z-axis of propagation and are presented in Fig. 4 with their respective fitting functions.

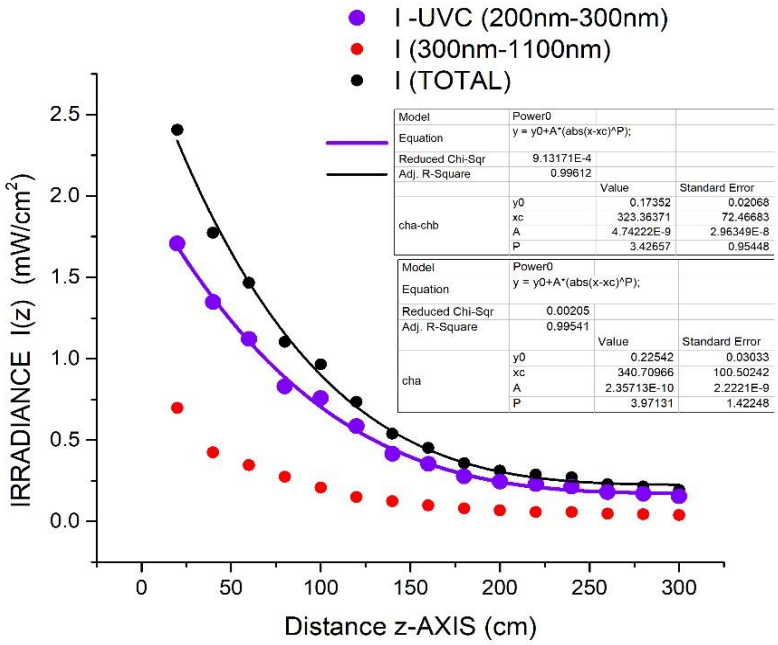


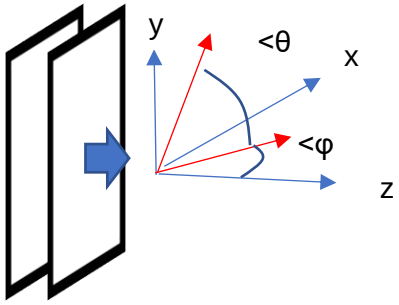
Fig. 4 Irradiance along the radiation propagation z-axis; (x,y,z)→ (0,0,z).

The fitting function beyond z= 300cm is found as

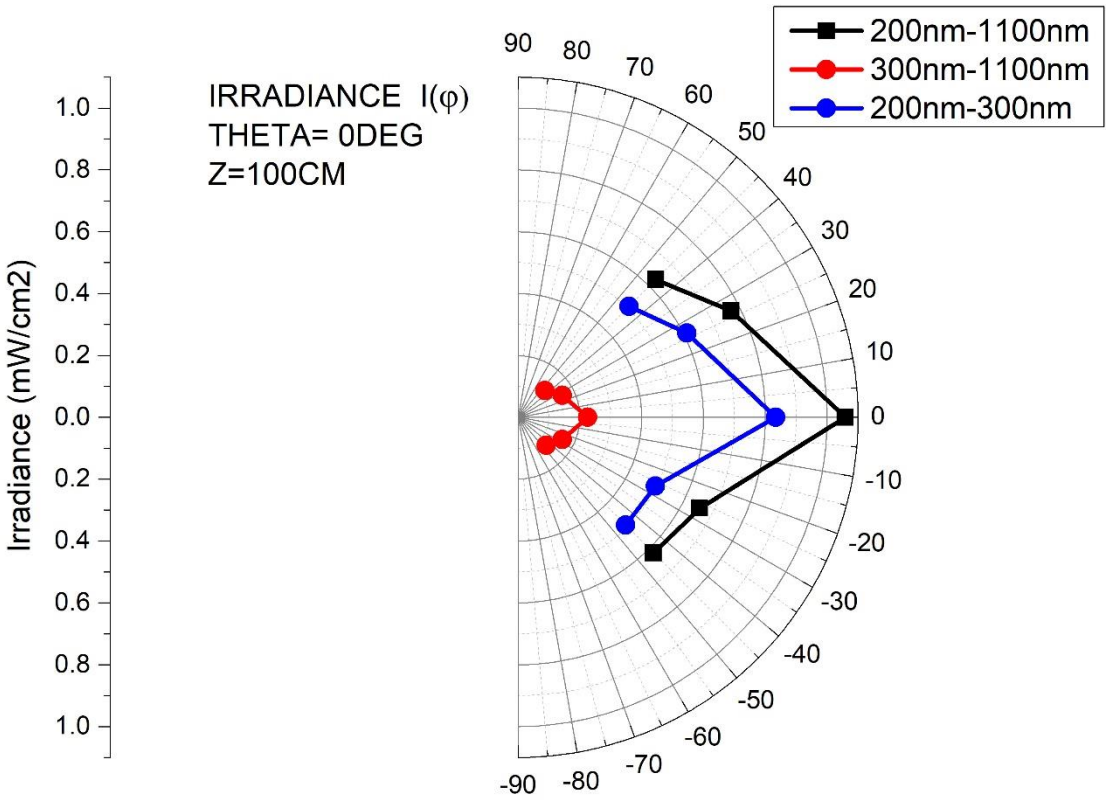
$$I\ [mW/cm^2]=522\ z^{-1.427}$$

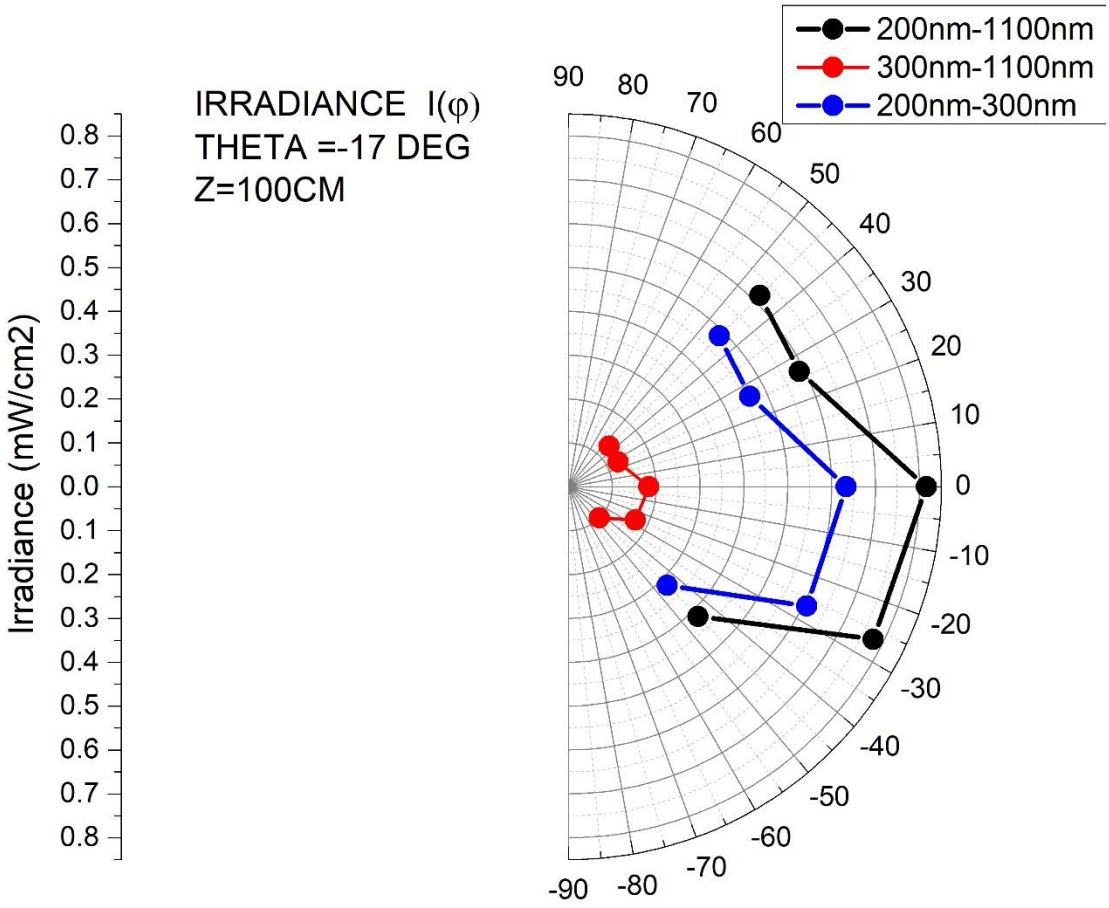
It is underlined the very high radiation intensity which at a distance of 2m from the sources doubles the total solar radiation intensity of a clear summer midday.

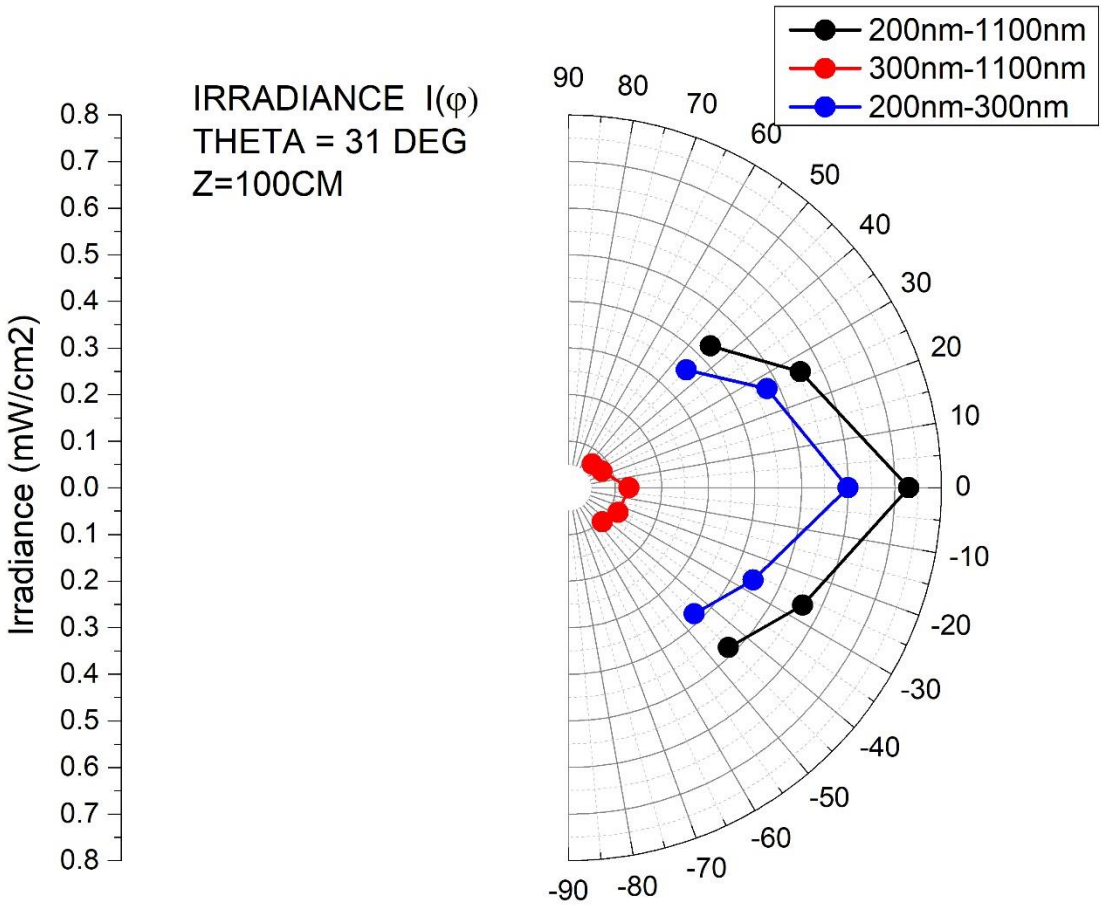
Polar diagrams of measured irradiance are presented in Fig. 5 and describe the spatial distribution of radiation in free-space. Fig. 5(a) references the testing geometry. Fig. 5(b) presents the polar radiation distribution at the referenced z-φ-θ.

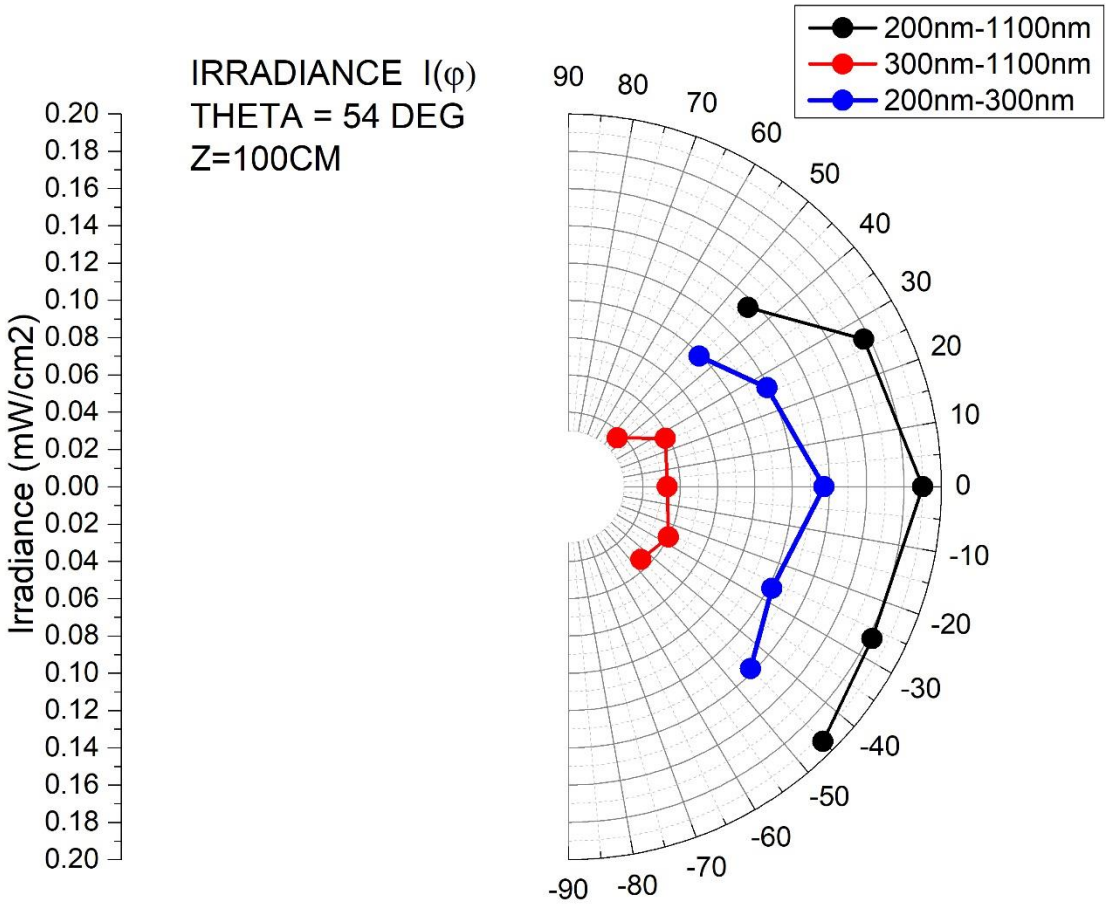


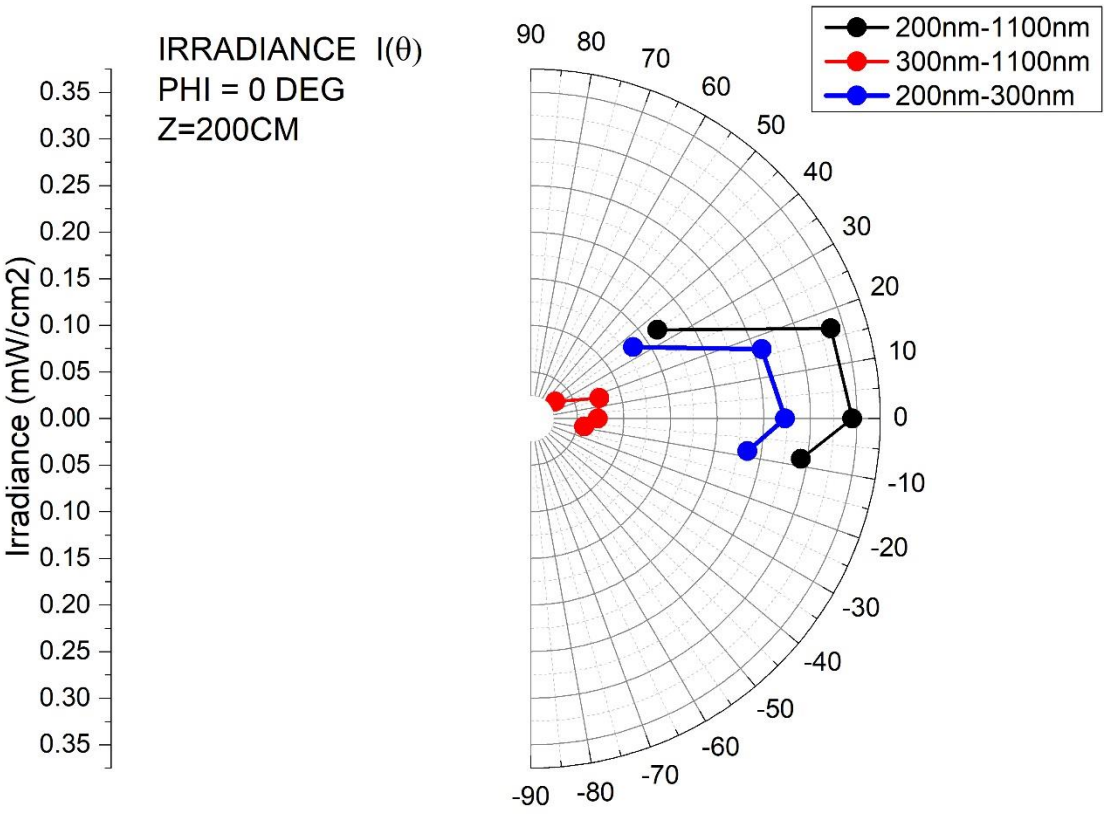
Εικ. 5(a) Geometry and Polar coordinates.

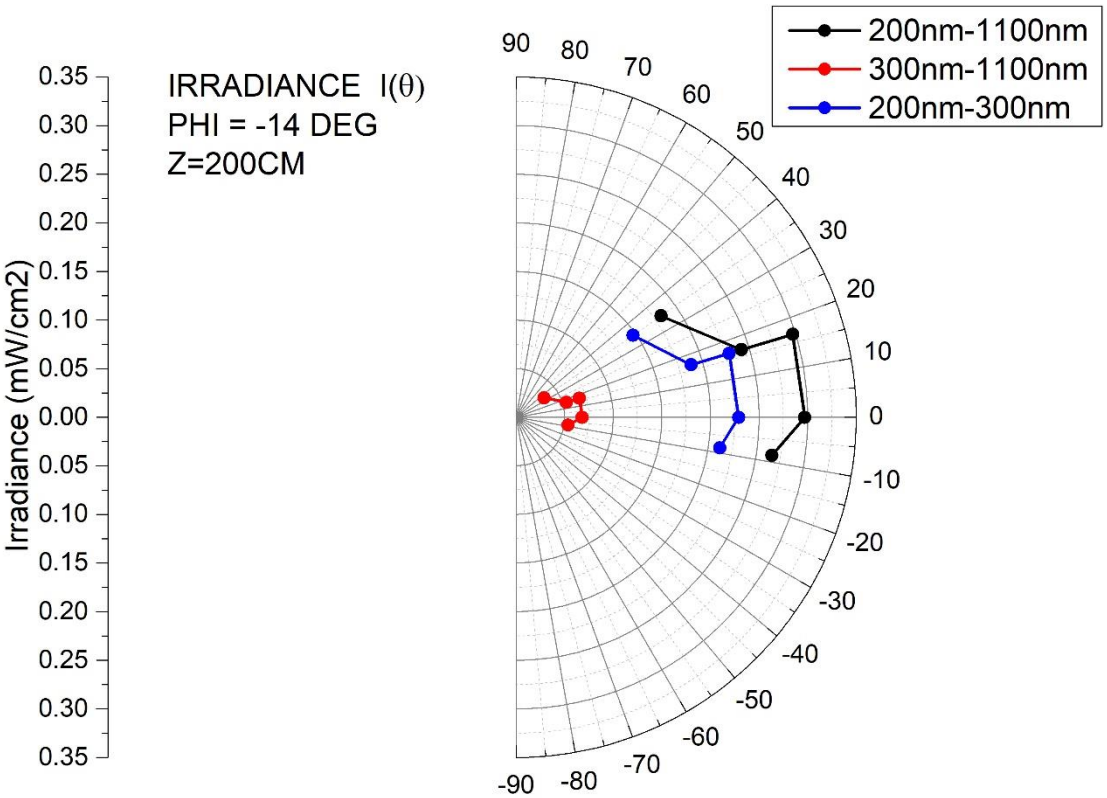

IRRADIANCE I(φ)
THETA= 0DEG
Z=100CM
Irradiance (mW/cm2)
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
200nm-1100nm
300nm-1100nm
200nm-300nm

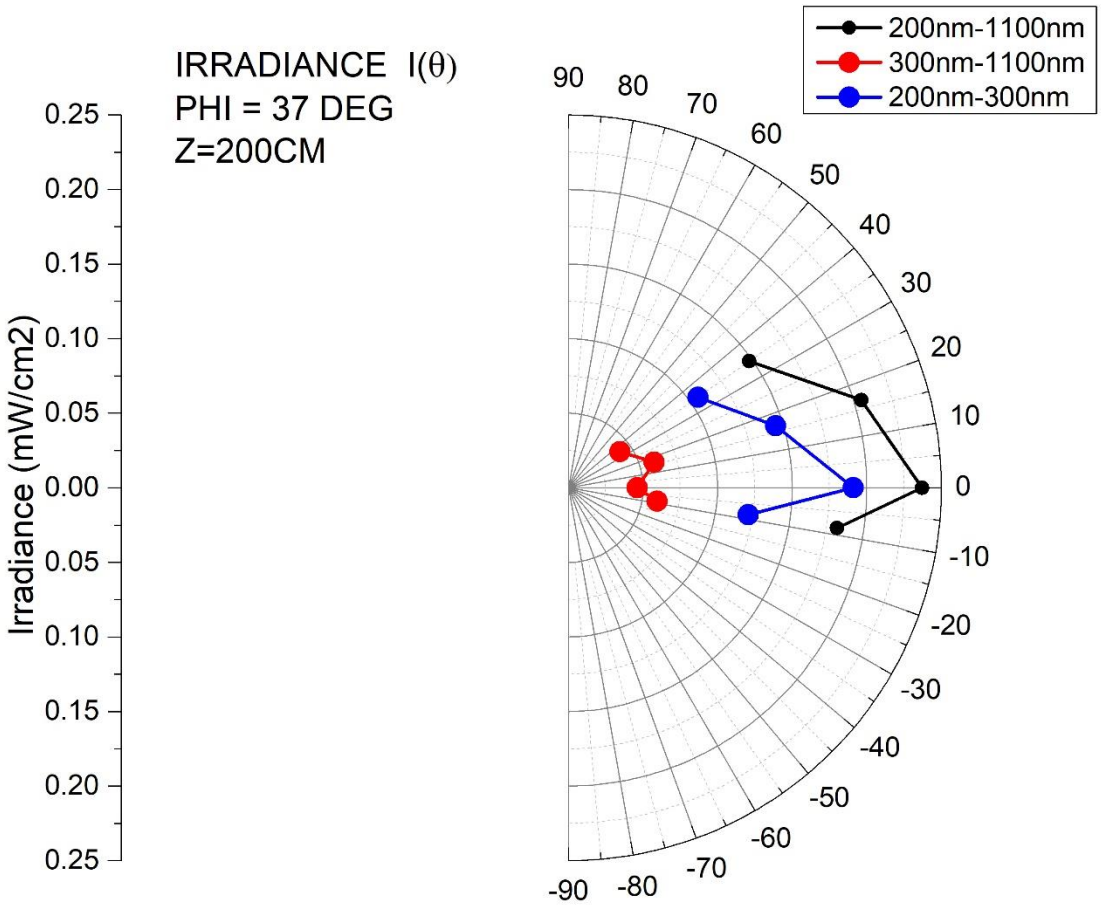

IRRADIANCE I(φ)
THETA =-17 DEG
Z=100CM
Irradiance (mW/cm2)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
200nm-1100nm
300nm-1100nm
200nm-300nm

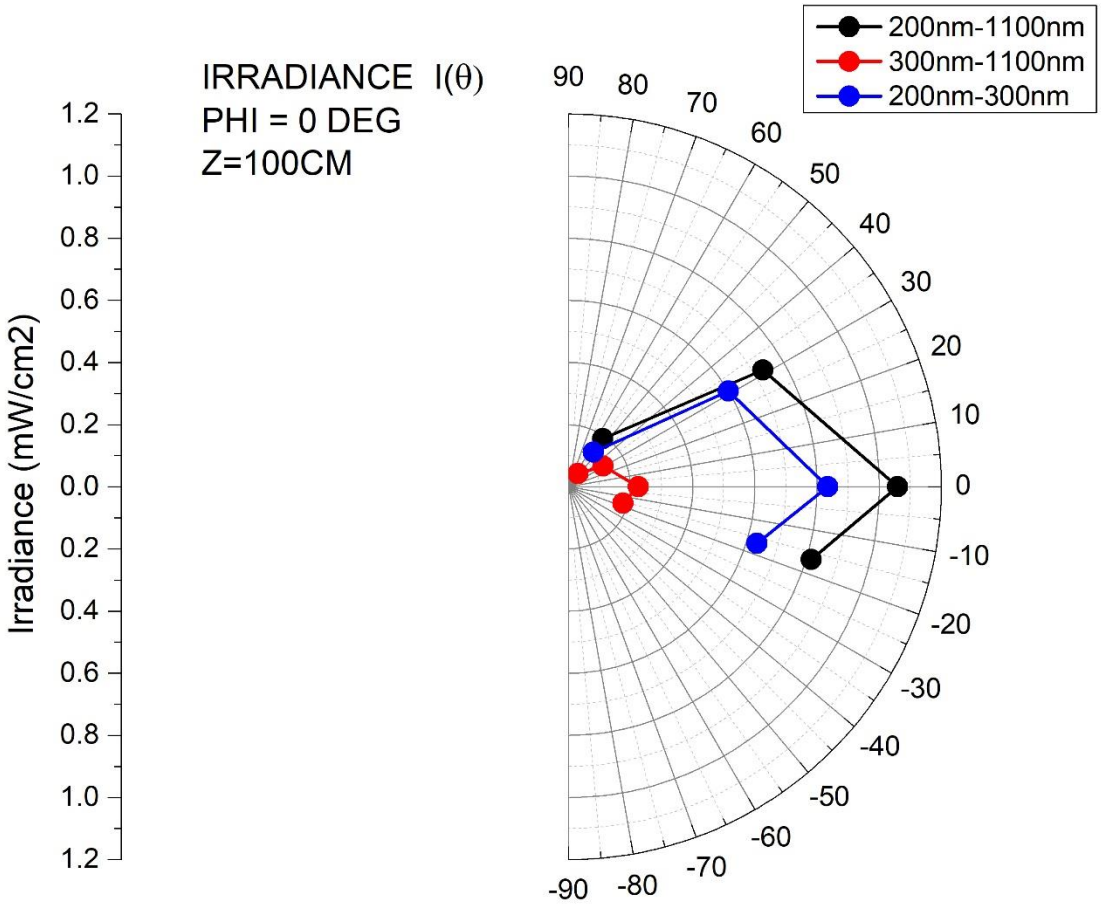

IRRADIANCE I(φ)
THETA = 31 DEG
Z=100CM
Irradiance (mW/cm2)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
200nm-1100nm
300nm-1100nm
200nm-300nm
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90

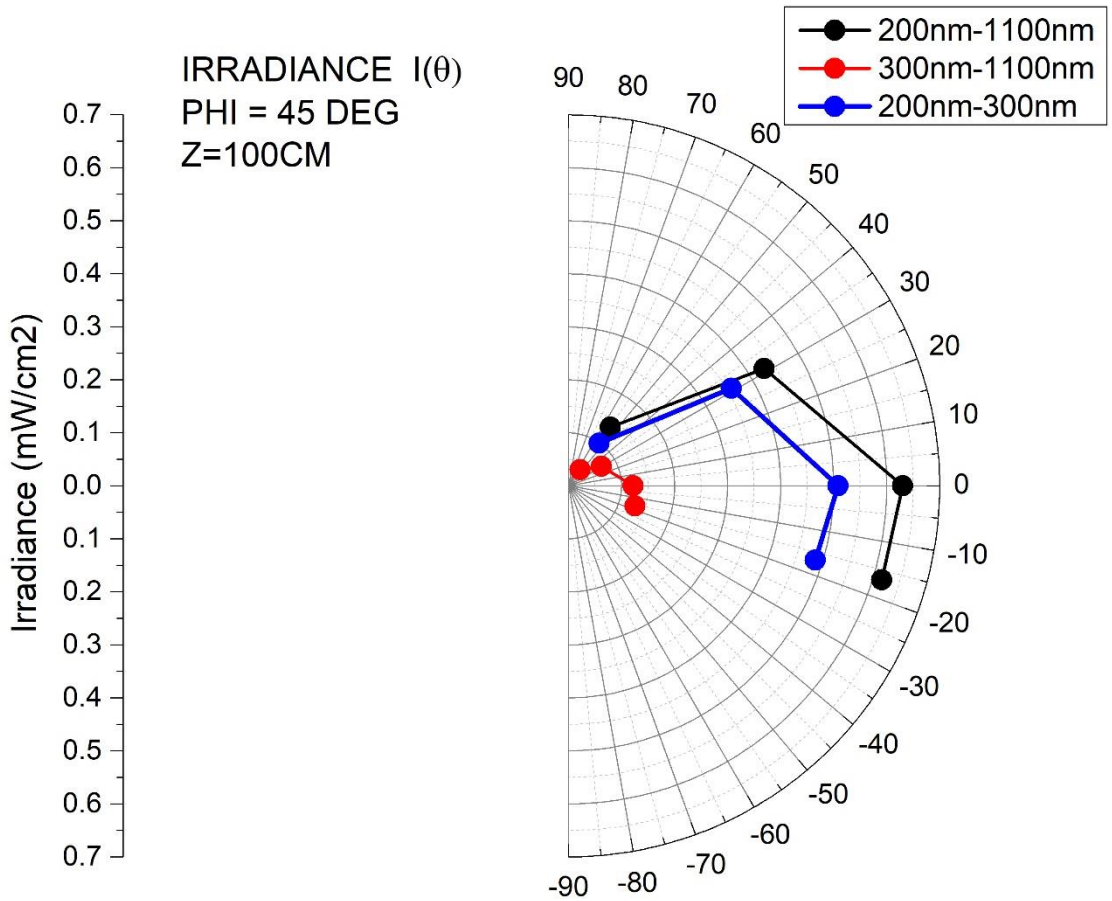

IRRADIANCE I(φ)
THETA = 54 DEG
Z=100CM
Irradiance (mW/cm2)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
200nm-1100nm
300nm-1100nm
200nm-300nm
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90


IRRADIANCE I(θ)
PHI = 0 DEG
Z=200CM
Irradiance (mW/cm2)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
200nm-1100nm
300nm-1100nm
200nm-300nm
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90


IRRADIANCE I(θ)
PHI = -14 DEG
Z=200CM
Irradiance (mW/cm2)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
200nm-1100nm
300nm-1100nm
200nm-300nm
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90


IRRADIANCE I(θ)
PHI = 37 DEG
Z=200CM
Irradiance (mW/cm2)
0.25
0.20
0.15
0.10
0.05
0.00
0.05
0.10
0.15
0.20
0.25
200nm-1100nm
300nm-1100nm
200nm-300nm
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90


IRRADIANCE I(θ)
PHI = 0 DEG
Z=100CM
Irradiance (mW/cm2)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
200nm-1100nm
300nm-1100nm
200nm-300nm
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90



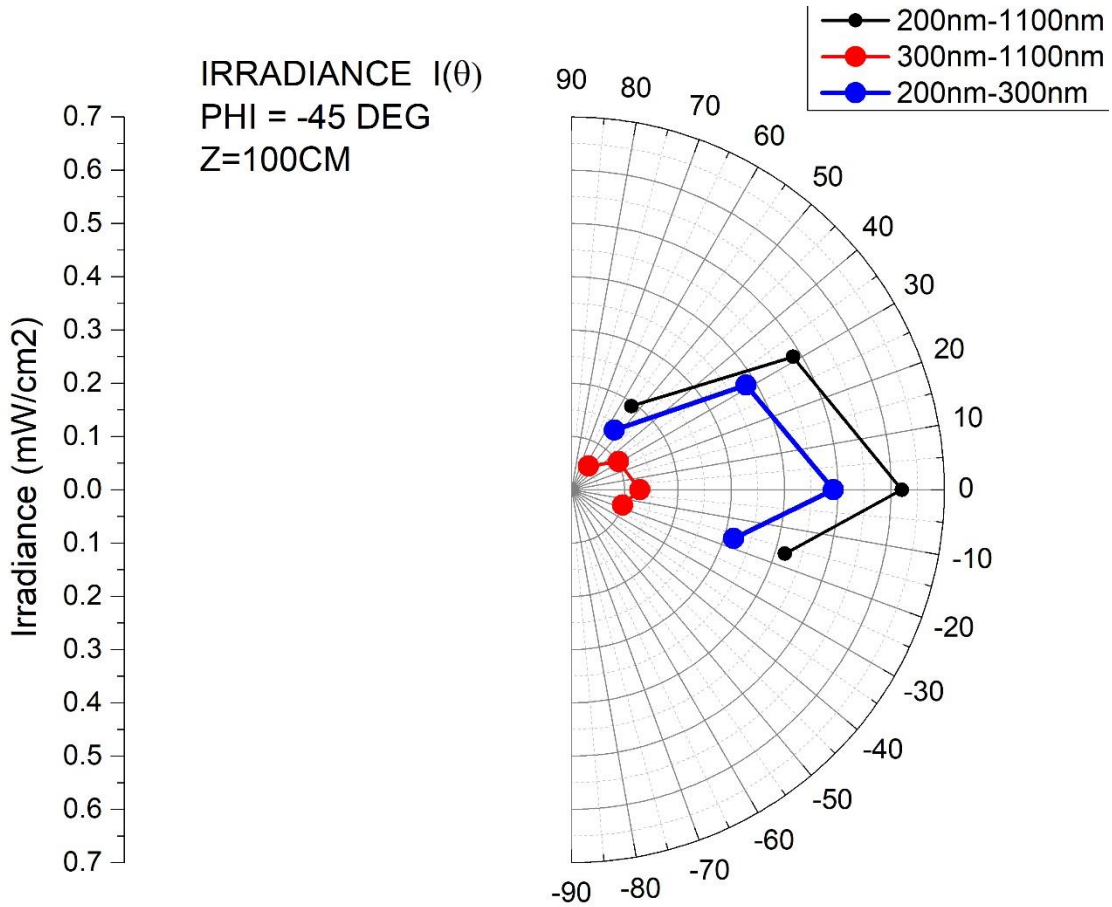


Fig. 5(b) Radiation emission in space I(z)-φ-θ [mW/cm^2]

4 Sterilization experiments

Sterilization experiments were performed to assess the effectiveness of the machine. Staphylococcus aureus and e-coli cultures in Petri dishes were exposed to UVC radiation produced by the machine respectively for (a) various intensity levels I[mW/cm^2] and (b) various exposure times [sec] and respective Exposure Dose levels [mJ/cm^2].

For the measurement of the degree of bacteria survival there was performed a comparative assessment of optical density (OD) of the exposed and not exposed cultures by means of laser scattering using a HeNe laser beam at 633nm.

The original culture has cell density of

- Staphylococcus : 2.4x10^9 cell/ml
- e-coli: 1.76x10^9 cell/ml

and they were disposed on Petri dishes on suspension at thickness for

- Staphylococcus: 220 μm
- e-coli: 70μm

Laser power was measured at 11mW.

The mean value of non-scattered power over the laser aperture was of the order of ~7mW for all samples. This value corresponds to OD~0.2 and relates to the total loss caused by microbial population, gel suspension and dish surfaces.

It is noted that Staphylococcus produces larger scattering and variable response among samples.

It is underlined that the measurements of optical density were performed here in the cultures disposed in Petri dishes as described above and not as usually in liquid cultures disposed in cuvette of 10mm optical path.

The tables and graphs below present the microbial survival results in reference to the O.D. of exposed vs. unexposed samples.

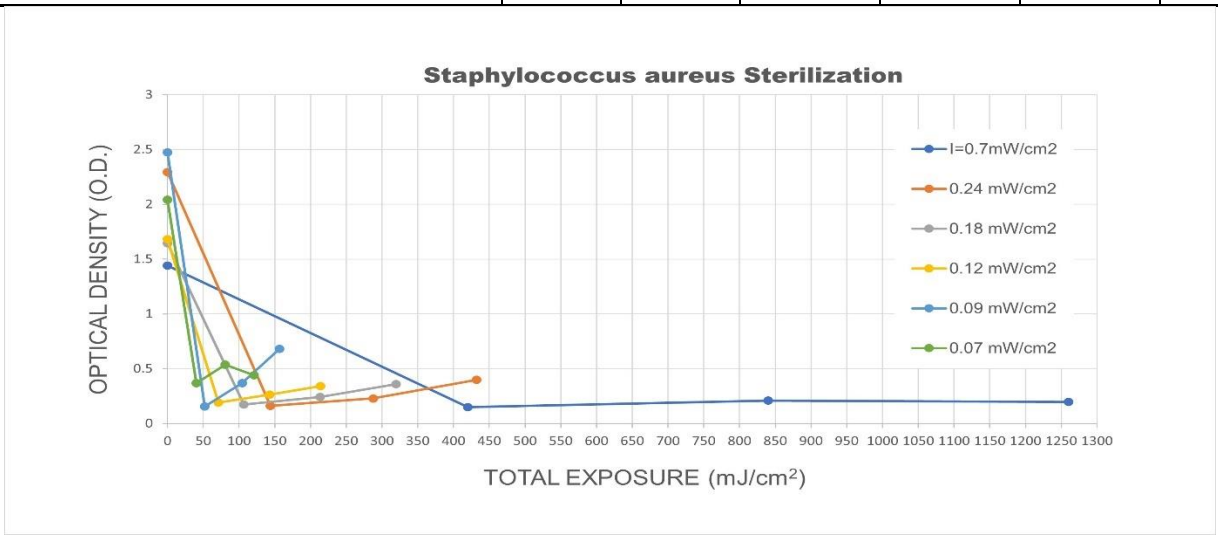
High sterilization efficiency is found even at distances over 6m from the source.

4.1 TABLE 1 - Staphylococcus aureus

CULTURE EXPOSURE LEVEL	Z-DISTANCE TO TARGET (cm)	100	200	300	400	500	600
	IRRADIANCE (mW/cm2)	0.7000	0.2400	0.1777	0.1188	0.0869	0.0673
		Total UVC energy exposure levels (mJ/cm^2)					
EXPOSURE TIME (sec)	0	0	0	0	0	0	0
	600	420	144	106.6233	71.27509	52.15113	40.40266
	1200	840	288	213.2465	142.5502	104.3023	80.80533
	1800	1260	432	319.8698	213.8253	156.4534	121.208

Test Subject:	Staphylococcus STERILIZATION	HeNe Laser 633nm Scattering Power Level - P (mW)					
	Z-DISTANCE TO TARGET (cm)	100	200	300	400	500	600
	IRRADIANCE (mW/cm2)	0.7000	0.2400	0.1777	0.1188	0.0869	0.0673
EXPOSURE TIME (sec)	0	0.40	0.06	0.25	0.23	0.04	0.10
	600	7.80	7.60	7.40	7.10	7.70	4.70
	1200	6.80	6.50	6.30	6.00	4.70	3.20
	1800	7.00	4.40	4.80	5.00	2.30	4.00

Test Subject:	Staphylococcus STERILIZATION	CELL SURVIVAL - OPTICAL DENSITY (O.D.)					
	Z-DISTANCE TO TARGET (cm)	100	200	300	400	500	600
	IRRADIANCE (mW/cm2)	0.7000	0.2400	0.1777	0.1188	0.0869	0.0673
EXPOSURE TIME (sec)	0	1.4	2.3	1.6	1.7	2.5	2.0
	600	0.1	0.2	0.2	0.2	0.2	0.4
	1200	0.2	0.2	0.2	0.3	0.4	0.5
	1800	0.2	0.4	0.4	0.3	0.7	0.4

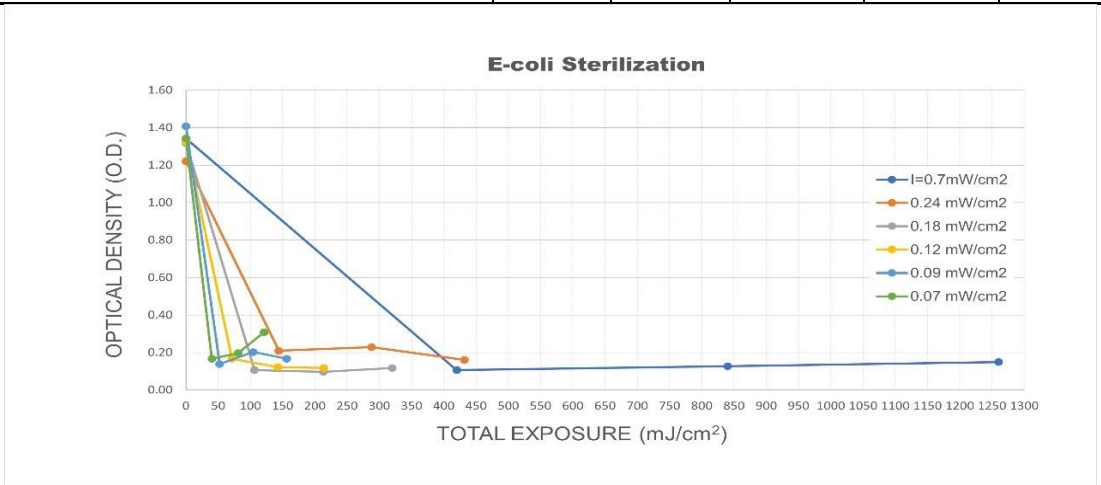


4.2 TABLE 2 - E-coli

CULTURE EXPOSURE LEVEL	Z-DISTANCE TO TARGET (cm)	100	200	300	400	500	600
	IRRADIANCE (mW/cm2)	0.7000	0.2400	0.1777	0.1188	0.0869	0.0673
		Total UVC energy exposure levels (mJ/cm^2)					
EXPOSURE TIME (sec)	0	0	0	0	0	0	0
	600	420	144	106.6233	71.27509	52.15113	40.40266
	1200	840	288	213.2465	142.5502	104.3023	80.80533
	1800	1260	432	319.8698	213.8253	156.4534	121.208

Test Subject:	e-coli STERILIZATION	HeNe Laser scattering power level -P (mW)					
	Z-DISTANCE TO TARGET (cm)	100	200	300	400	500	600
	IRRADIANCE (mW/cm2)	0.7000	0.2400	0.1777	0.1188	0.0869	0.0673
EXPOSURE TIME (sec)	0	0.50	0.66	0.53	0.52	0.43	0.50
	600	8.60	6.80	8.60	7.50	8.00	7.50
	1200	8.20	6.50	8.80	8.30	6.90	7.00
	1800	7.80	7.60	8.40	8.40	7.50	5.40

Test Subject:	e-coli STERILIZATION	CELL SURVIVAL - OPTICAL DENSITY (O.D.)					
	Z-DISTANCE TO TARGET (cm)	100	200	300	400	500	600
	IRRADIANCE (mW/cm2)	0.7000	0.2400	0.1777	0.1188	0.0869	0.0673
EXPOSURE TIME (sec)	0	1.34	1.22	1.32	1.33	1.41	1.34
	600	0.11	0.21	0.11	0.17	0.14	0.17
	1200	0.13	0.23	0.10	0.12	0.20	0.20
	1800	0.15	0.16	0.12	0.12	0.17	0.31



5 Concluding Remarks

This report presents the results of radiation intensity meaurements and sterilization experiments performed for testing the efficiency and good operation performance of the air and surface sterilization machine unit UVC Wemax - CK1000 of Zhuzhou Wavelane Technology Co.LTD.

The intensity of UVC radiation emitted was found at very high levels with microbe killing effectiveness at distances >6m and exposure time as low as 10min.

The polar distribution of radiation is very satisfactory, giving UVC intensity of 0.5mW/cm^2 5-fold greater than the total solar radiation intensity in a clear summer midday.

According to international literature* the percentage level of cell survival, S, exposed to UVC for one stage sterilization is given by:

$$S=\exp(-k\,D)$$

k=rate of exposure constant (cm^2/mJ)

D=exposure dose (mJ/cm^2)

TABLE 3 presents the survival results according to the bibliographical data by using specific experimental conditions and test data reported here for the minimum exposure time 10min (600sec) at the maximum z-axis site of 600cm corresponding to D=40mJ/cm^2.

TABLE 3 BACTERIA SURVIVAL

E-coli

k (cm^2/mJ)	D (mJ/cm^2)	Survival %	Medium (Water/Surface/Air)	Reference cited	Year
1.09	40	1.16081E-17	W	Zelle	1955
0.432	40	3.1289E-08	W	Tyrrell	1972
1.151	40	1.01177E-19	W	Oguma	2001
0.494	40	2.62024E-07	W	Kim	2002
0.53	40	6.20808E-08	W	Hofemeister	1975
1.8	40	5.38019E-30	W	Harris	1987
1.15	40	1.05306E-18	W	Harm	1968
0.96	40	2.10422E-15	W	David	1973
0.2832	40	1.20313E-03	W	Abshire	1981
0.9398	40	4.72065E-14	S	Sharp	1939
1.2	40	1.42516E-19	S	Rentschler	1942
1.93	40	2.96801E-32	S	Rentschler	1942

* W. Kowalski, Ultraviolet Germicidal Irradiation Handbook, Springer-Verlag Berlin Heidelberg 2009

Staphylococcus aureus

4.40E-01	40	2.27205E-06	W	Dolman	1989
8.53E-01	40	1.51403E-13	W	Chang	1985
4.13E-01	40	6.58425E-06	W	Abshire	1981
7.70E-01	40	4.20465E-12	S	Sturm	1932
4.65E-01	40	8.29179E-07	S	Hollaender	1955
3.50E-01	40	8.31529E-05	S	Gates	1934
8.86E-01	40	4.06072E-14	S	Sharp	1939
6.24E-01	40	1.44547E-09	S	Luckiesh	1949
1.18E+00	40	2.7028E-19	S	Gates	1929
1.13E+00	40	2.34363E-19	Air	Nakamura	1987
3.48E+00	40	4.12758E-57	Air	Sharp	1940
9.60E+00	40	1.571E-165	Air	Luckiesh	1949
9.62E+00	40	7.6469E-166	Air	Luckiesh	1946

The above estimations yield zero survival levels at the given conditions verifying the very strong sterilization efficiency of the Wemax- CK1000 machine. We may further underline that even at the lowest exposure rate constant k~0.3cm^2/mJ, 200sec exposure is enough to provide 99% sterilization. Alternatively, a 600sec exposure is capable to sterilize to 99% level at 30m distance.

SAFETY NOTE

The American Conference of Governmental Industrial Hygienists (ACGIHR)** references UVC radiation at 254 nm to have half the biological effects of radiation at 270 nm. The allowable eye-exposure at 254nm defined as the Threshold Limit Value (TLV) is 0.2μW/cm^2 for 8hr continuous irradiation to reach the total dose of 6.0mJ/cm^2.

It is recommended to use the machine with extreme care, wearing full protective clothing, gloves, and full-face mask with at least OD3 UV protective glasses. Presence of people and animals in space during irradiation is forbidden.

** Melvin W. First, Robert A. Weker, Shojiro Yasui, and Edward A. Nardell, Monitoring Human Exposures to Upper-Room Germici, dal Ultraviolet Irradiation, J Occup Environ Hyg, 2: 285–292(2005)

The Scientific Responsible

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