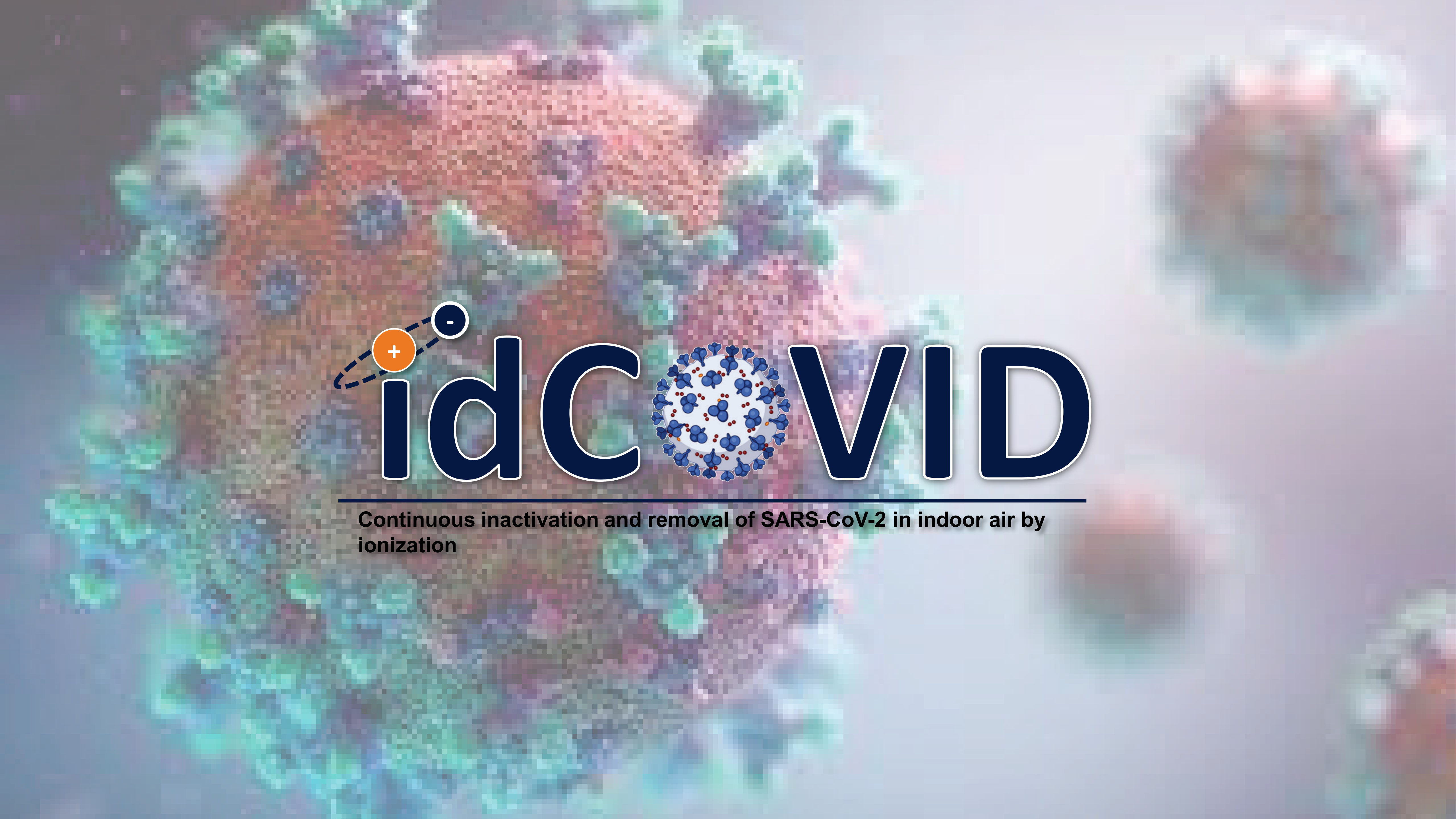
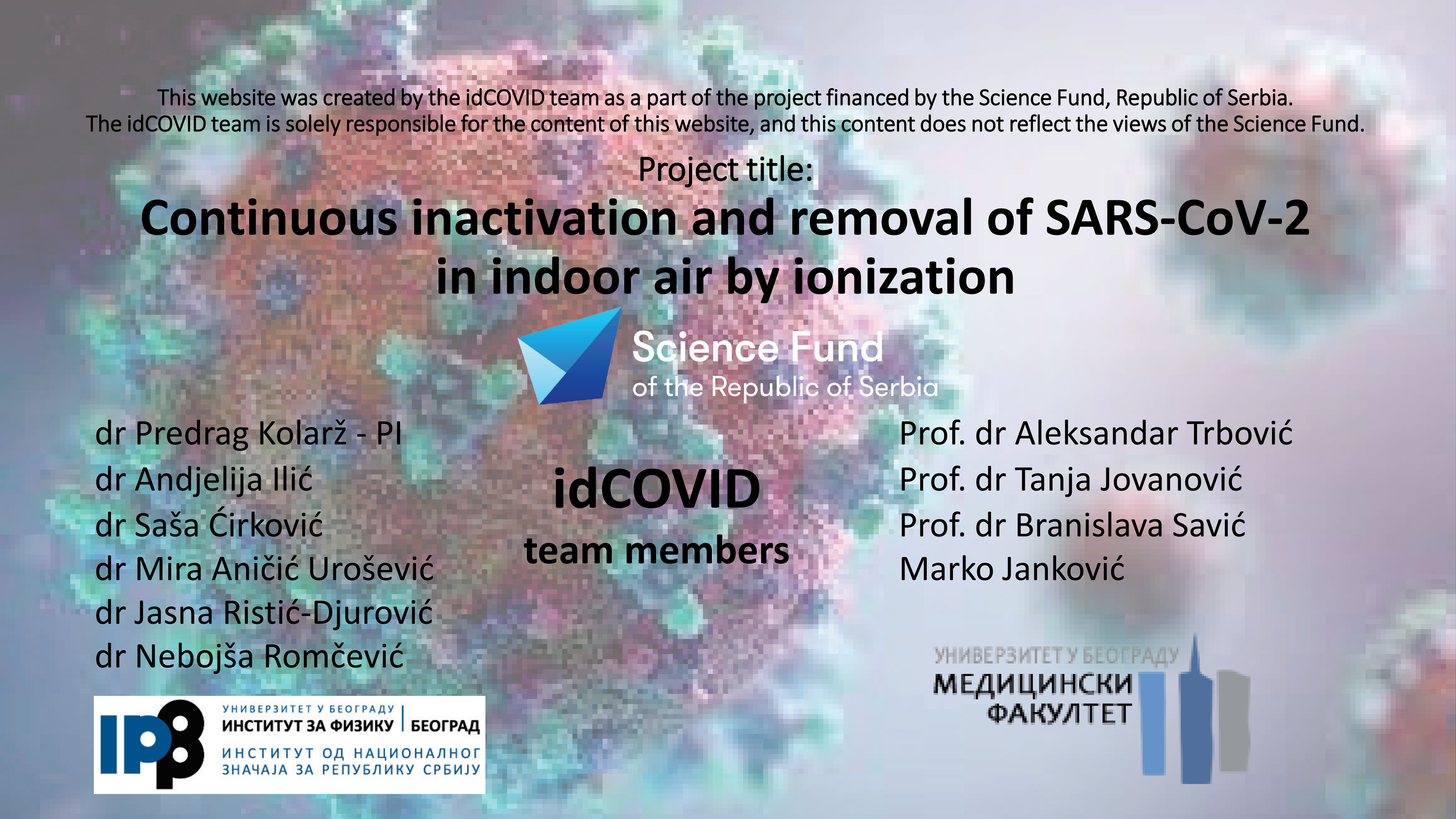


idCOVID

Continuous inactivation and removal of SARS-CoV-2 in indoor air by ionization



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Project title:

Continuous inactivation and removal of SARS-CoV-2 in indoor air by ionization

Science Fund
of the Republic of Serbia

idCOVID

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IPB
УНИВЕРЗИТЕТ У БЕОГРАДУ
ИНСТИТУТ ЗА ФИЗИКУ | БЕОГРАД
ИНСТИТУТ ОД НАЦИОНАЛНОГ ЗНАЧАЈА ЗА РЕПУБЛИКУ СРБИЈУ

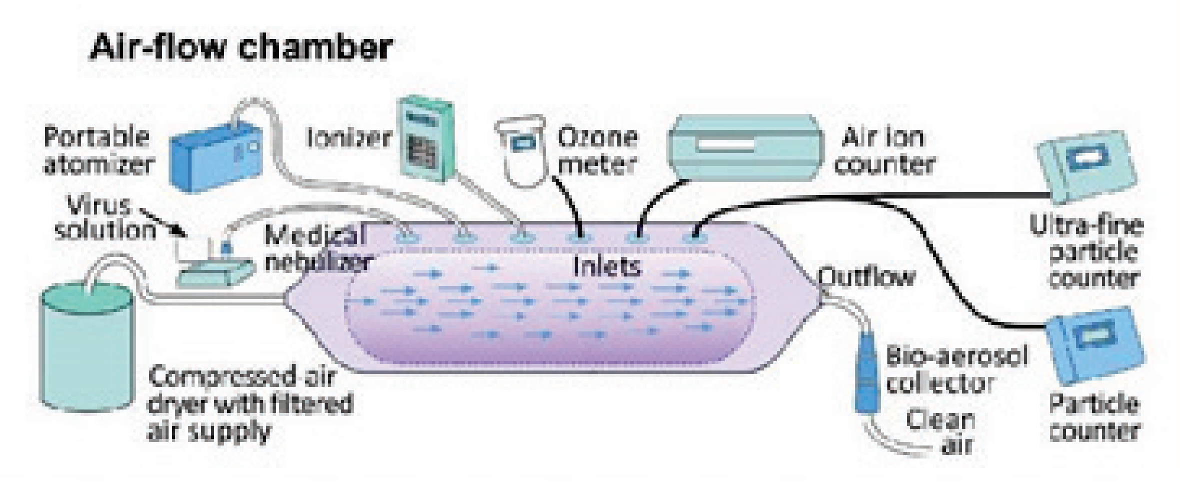
УНИВЕРЗИТЕТ У БЕОГРАДУ
МЕДИЦИНСКИ ФАКУЛТЕТ

Background of the problem

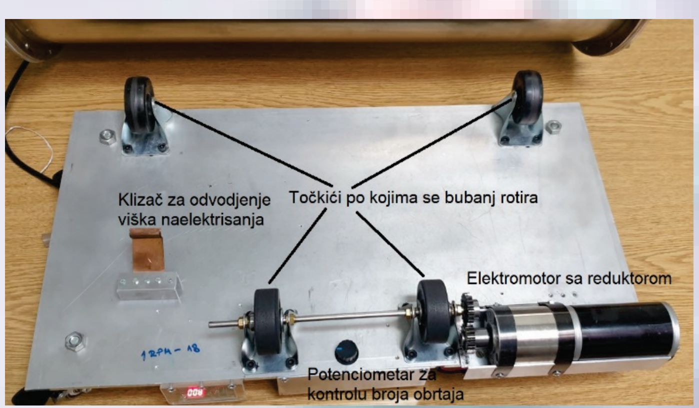
Diseases transferred through the air (airborne diseases) are carried via larger expelled particles named droplets that quickly settle to the ground and/or smaller exhaled aerosol particles that stay in the air for a prolonged period. Airborne pathogens, such as SARS-CoV-2, are usually treated upon the onset of illness in humans. If vaccination is not available, the prevention of infection is generally based on wearing facemasks, which is never fully implemented and avoiding social gatherings and public spaces. Since such behavior may bring a severe economic burden on society, the solution is to inactivate airborne pathogens in closed spaces such as public transportation and workspaces. The most common sterilizers of ambient indoor air are ozone and UV radiation. These methods are effective but harmful to humans and can operate only in the absence of people. We propose ionization to continuously inactivate airborne pathogens in the breathing zone of closed spaces in the presence of people. Air ionization is not harmful and brings additional health benefits to humans. Moreover, it has been shown that ions can inactivate viruses; therefore, it can be expected that our method for inactivating SARS-CoV-2 in the air of closed spaces will yield results.

Experiments with airborne pathogens in the air are not common due to numerous safety measures that must be undertaken. We will design special experimental chambers that will overcome this obstacle. We intend to experimentally determine the ion polarity, types of ion sources, concentration, composition, and spreading that will be the most efficient in reducing the transmission of viruses in the indoor air. Distribution of droplets and aerosols generated by coughing and breathing indoors have been numerically modeled to study its dependence on various parameters of the considered closed spaces. We will use numerical models of ion and virus dynamics adjusted to experimentally obtained data to define conditions that typical air-conditioning systems have to provide to achieve the most efficient virus inactivation.

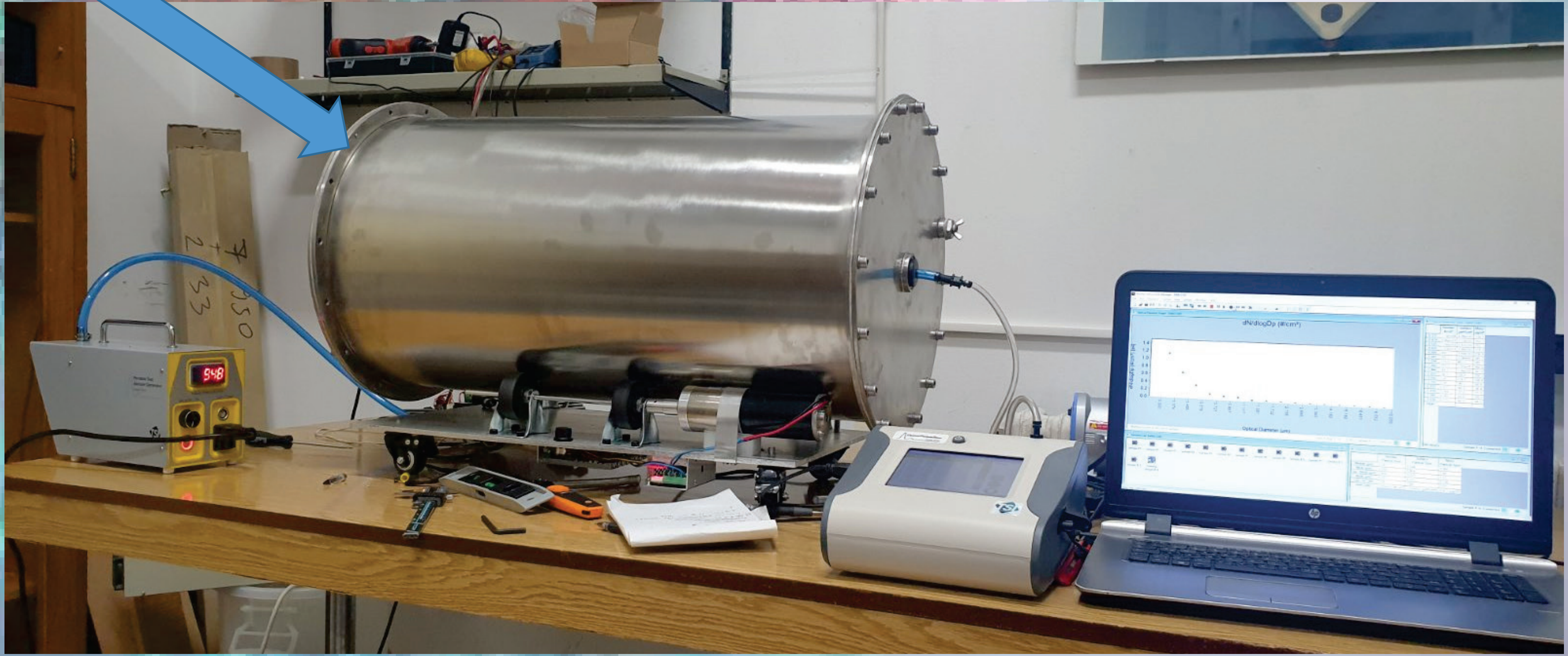
The chamber originally intended



Rotating chamber stand

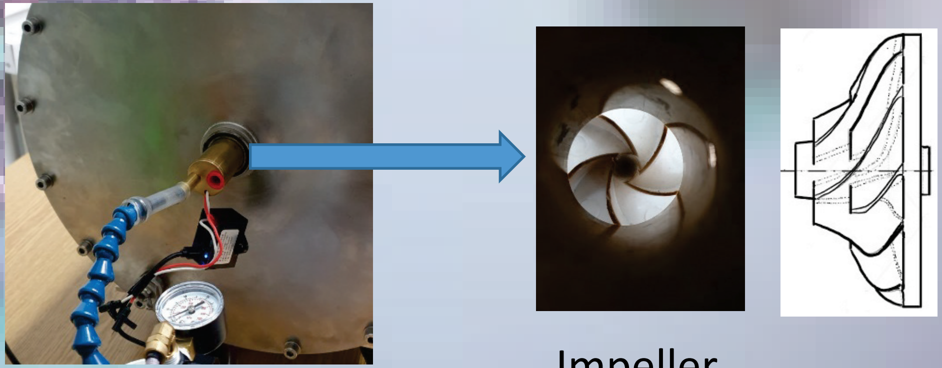


Finally realized rotating Golberg chamber



Patent application: ROTATING DRUM CHAMBER WITH INNER PASSIVE IMPELLER FOR THE IMPROVED PARTICLE DISPERSION AND PROLONGED EXPOSURE TIME

Precise control of experimental conditions in biophysical investigations of interaction of ionized gasses with bio-aerosols is highly important for reducing the variability of results and facilitating the study of results and drawing reliable conclusions. Experimental chambers are used to provide controlled interaction volume, whereas the rotating drum chambers are used to prolong the maximal exposure time which is necessary for many types of experiments. The uneven distribution of aerosols, as well as ions, across the cross-section of the chamber and the additional time and amounts of particles and ions that would be necessary for better homogeneity of such distribution significantly complicate experiments and making reliable conclusions. Therefore, additional scattering of particle beams immediately after introduction into the chamber is desirable. Also, the particles in the chamber are deposited on the surface of the walls when, under the influence of the surface of the chamber wall and gravity, they reach the same angular velocity as the chamber wall. To prevent that it is necessary to direct the particles in the direction opposite to the direction of rotation of the chamber. For that purpose we used passively mounted impeller on the stationary inlet pipe of the chamber passing through its axis. The impeller is positioned so that it disperses incoming particles in the direction opposite to the direction of rotation of the chamber.



Impeller

An additional result of the project – bipolar air ion counter

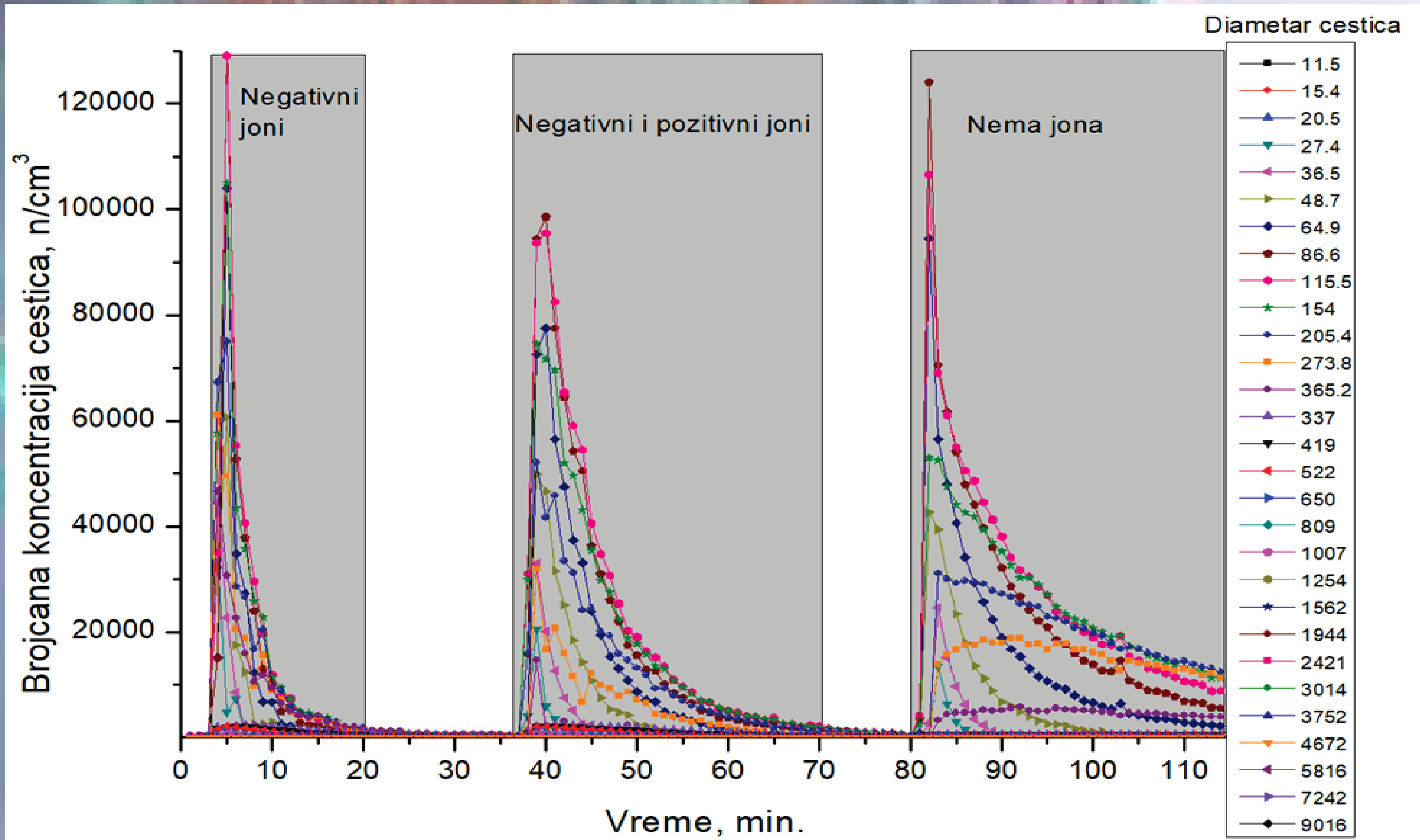
For the needs of the project, we designed and built a air ion concentration meter. It continuously and simultaneously measures the concentration of +, - ions, RH, T and pressure. It has autonomous power supply and data acquisition, bluetooth communication with PC which allows it to measure and display ion concentrations while in the chamber. The instrument performs stable measurements and is resistant to interference and elevated RH.

Experiments

Experiments with aerosols and ions in the chamber were designed and performed. Carbon fibre corona ionizers were inserted into the chamber on the one side and tubes for aerosol size distribution and concentration were inserted on the other side of the chamber. Difference of aerosol number concertation with and without ionization enabled us to determine electrified deposition rate. In order to prolong aerosol lifetime and reduce the measurement uncertainty, specially for larger particles, we rotated the chamber at a speed of 1 RPM. Before the measurements, bipolar ion counter and corona ionizer was inserted into the chamber and ion concentration was measured and tuned at reasonable level. During the measurements, air ion counter was taken out due to rotation of the chamber and increased humidity.

Chamber aerosol deposition results

Experiments with aerosol deposition on the walls of the chamber were designed and performed. Inserting the brushes into the chamber and sampling them and measuring the size distribution, deposition rate, charge distribution...To begin with, the longer life of larger particles during chamber rotation (1 RPM) was measured. Measured deposition coefficients in the chamber and in "real life" conditions.

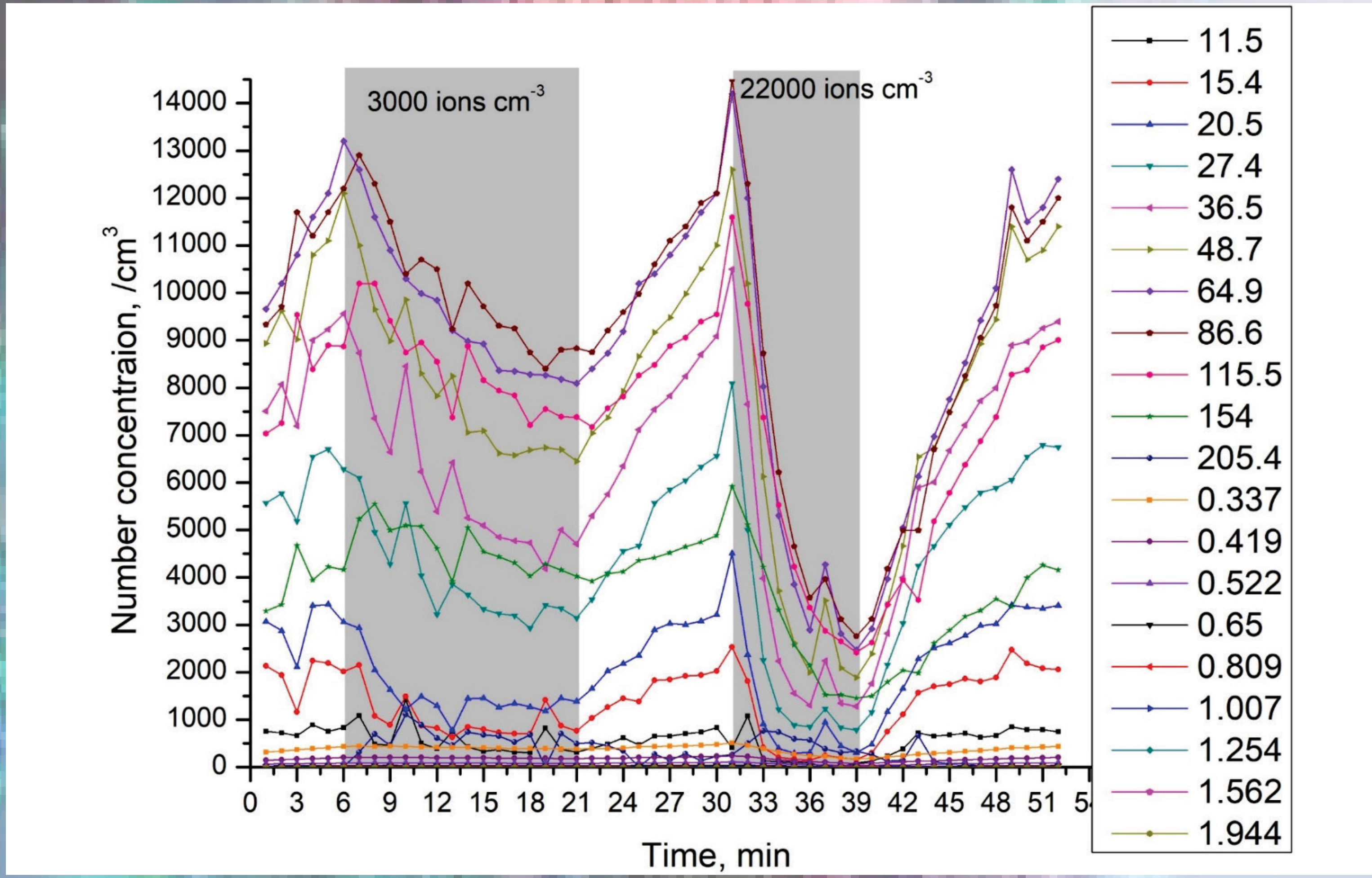


Change in the numerical concentration of particles with sizes of 10 nm - 10 μm with unipolar, bipolar and without ionization.

Example of real space experiment of aerosol deposition on surfaces induced by ionization in the office. Solution of NaCl and cigarette smoke was used as aerosol sources.

Ions of both polarities were generated using GPS-FC48™-AC.

Real space ionization results



- Electrostatic deposition coefficients have been shown to be highest for particles up to 200 nm, which is the upper limit of the SARS-CoV-2 virus diameter.
- Deposition of particles 150 nm in diameter is about 3 times faster during unipolar ionization than without it.

Real space experiments concerning particle deposition rates during ionization

Conclusions drawn during experimental work:

- The half-life of the ion is approximately 0.3 seconds. The speed of ion transport from the site of generation to the breathing zone is of crucial importance.
- Aerosol deposition on surfaces in indoor space occurs only if ions are directed into that space by air flow.
- The result – a very effective deposition of unipolar ions on the deposition of particles on surfaces
- Problem – unipolar ionization causes charge agglomeration and possible discharge (especially when RH is low). It can be uncomfortable for inhabitants.
- Bipolar ionization has very little effect on deposition. On the other hand, excessive charge accumulation can lead to sudden discharges and cause discomfort and problems.
- A large unipolarity coefficient may be the solution. In this way, the accumulated unipolar charge on the surfaces attracts the opposite polarity and lowers its potential.

SARS-CoV-2-size particle removal from the breathing zone: the effects of different ionization types

MOTIVATION

- Virus removal by electrostatic deposition on surfaces via continuous ion emission
- Flu & coronaviruses 80–200 nm
- Droplets: 1–10 µm in diameter
    - Evaporate rapidly (<1 min) if <100 µm
    - Less than 1 s for 10 µm particles
    - The particle deposition is slow, making the virus core size relevant (Fig. 1, Fig. 2)

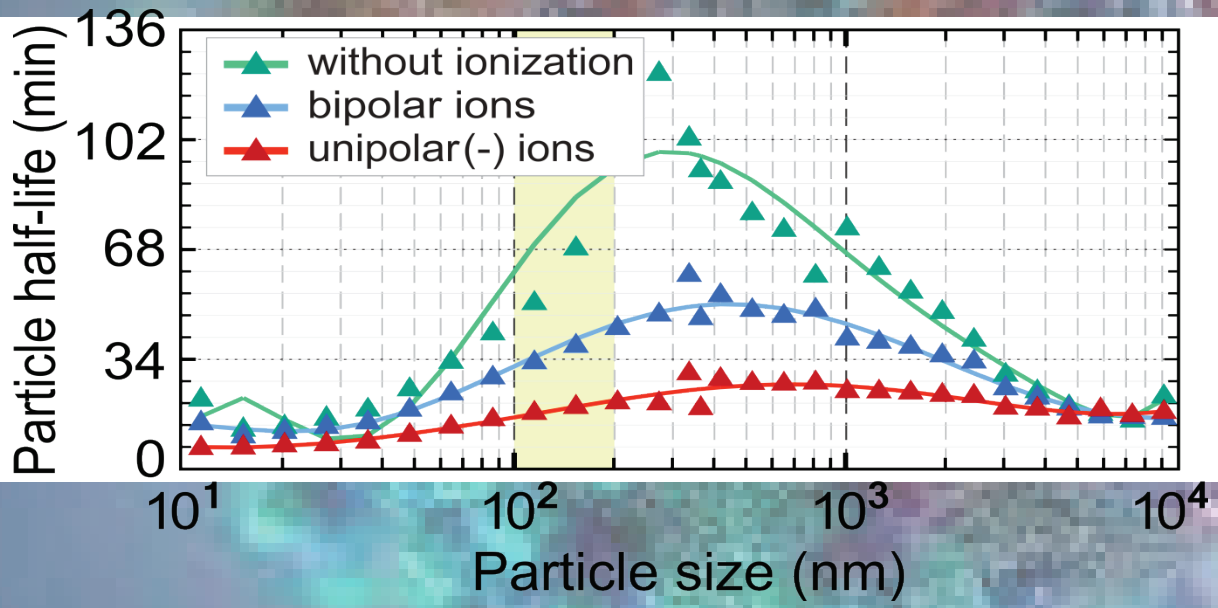


Figure 1. Particle half-life decrease resulting from the bipolar (≈$4 \cdot 10^4$, +/-) and unipolar ionization (≈$1.6 \cdot 10^5$, neg)

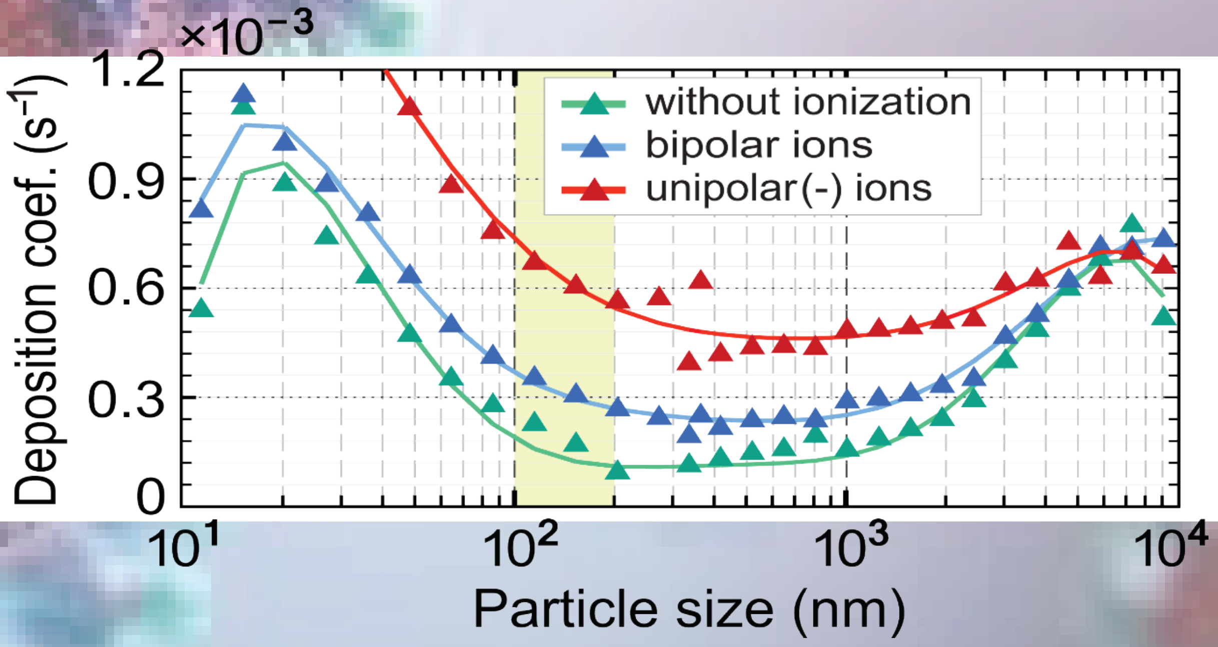


Figure 2. Comparison of particle deposition rates.

EXPERIMENTS

- Moderately sized office (5 m x 3 m) with 4 plastic coated desks and wooden parquet
- Instrumentation: portable Test Aerosol Gen. (TSI 3037, USA). Particle concentration: Nanoscan SMPS & OPS (TSI, USA), 10 nm–10 µm range, Bipolar air ion counter (Institute of Physics, Belgrade, Serbia)
- GPS-FC48™-AC (GPS ltd, USA) ionizer, 2.5 m away from measuring equipment including ion conc. meas. instrument made in the IPB, Serbia
- Aerosol dispersion: 10 cm diameter fan until the total ultrafine particle conc. ~1x10^5 cm^{-3}

Table 1. Percentage of particle half-life shortening by air ionization for typical virus-sized particles.

Size (nm)	Bipolar ions (%)	Unipolar ions (%)
86.60	45.18	70.05
115.50	52.27	74.77
154.00	54.49	76.93
205.40	53.35	77.81

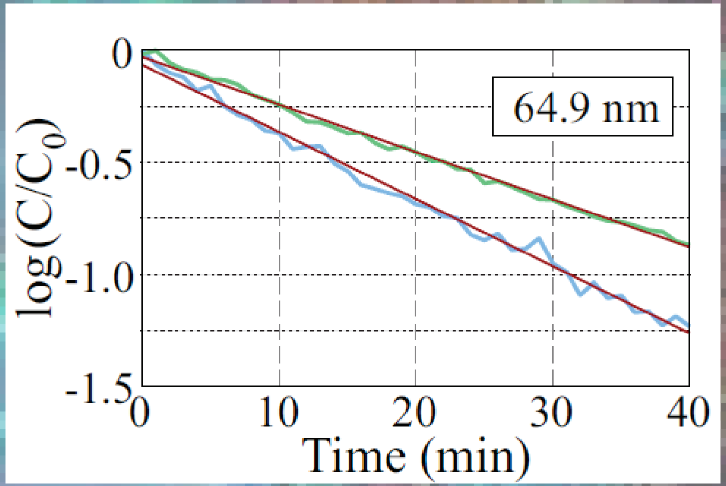
CONCLUSIONS

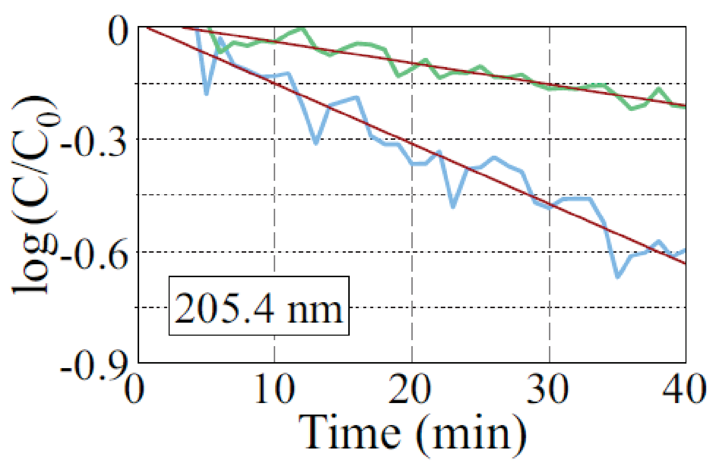
- Bipolar ionization showed promise and unipolar was highly successful in decreasing aerosol lifetimes (Table 1)
- Unipolar ionization is very useful in lowering the virus concentration in breathing zone in the public spaces

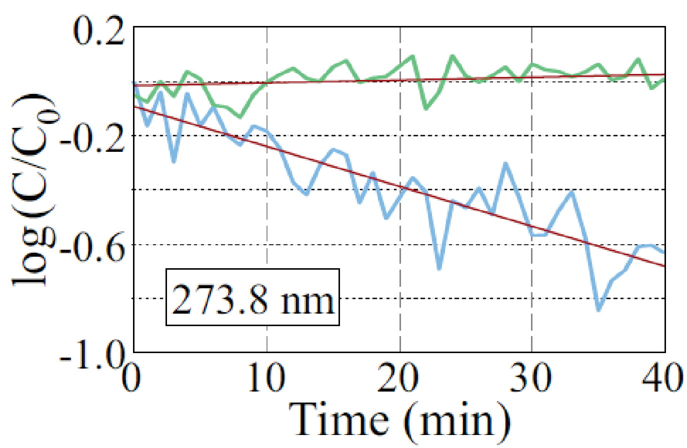
DATA ANALYSIS

Obtaining the deposition rate coefficients from measured particle concentrations

- Exponential particle concentration decrease curves
- Straight line fit minimizing the root mean square deviation
- Slope determination errors most critical at low particle concentrations
- Large variation of measured data for particle size limits of instruments







$$\ln\left(\frac{C}{C_p}\right) = -(\alpha + \kappa)t$$

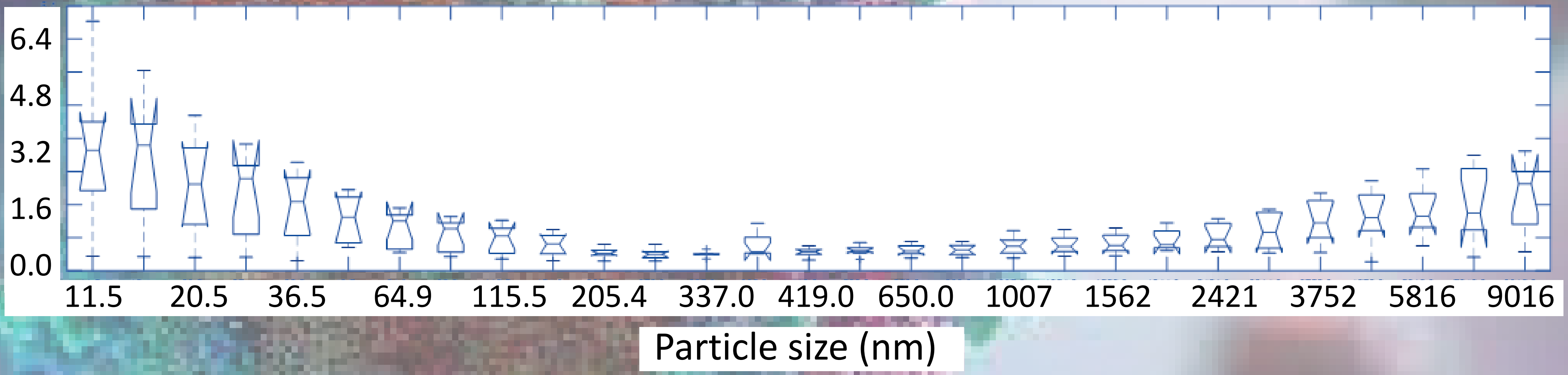
κ – deposition rate coefficient

α – ventilation rate

DATA ANALYSIS

Obtaining the deposition rate coefficients from measured particle concentrations

- Deposition rate coefficients without applied ionization (from our experiments)

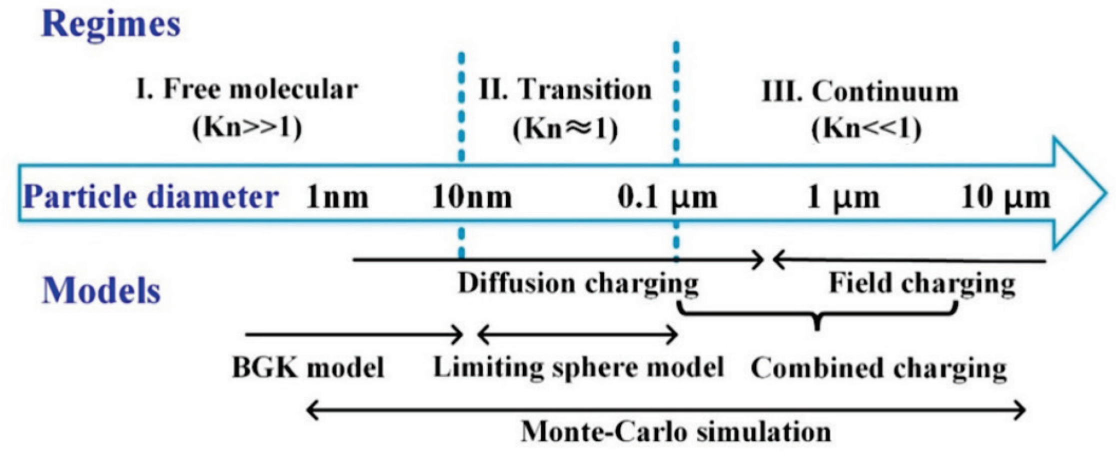


- Deposition rate coefficients without applied ionization (and also with ionization) are typically the lowest for the particle size range **0.1 μm – 1 μm**
- Percentage increase in deposition due to ionization in this size range is the highest (several times)
- ***Implications for the airborne virus particles transport***

Ion attachment (to the viral particles) probability and average attachment time constants

DATA ANALYSIS

- Models of particle charging (Zheng, C., et al. (2016) *Aerosol and Air Quality Research*, 16: 3037–3054)



$Kn = 2\lambda/d_p$ – Knudsen number

ratio of the mean free path of gaseous charging ions to the particle diameter

10 nm – 500 nm: *Diffusion charging*

Fuchs, 1963: *Limiting sphere model*

Typical virus sizes

Particle radius (nm)	Ion concentration (1/cm^3) 2000	4000	6000	8000	10000	12000	14000
160	62.1699	31.0849	20.7233	15.5425	12.4340	10.3616	8.8814
180	55.2621	27.6311	18.4207	13.8155	11.0524	9.2104	7.8946
200	49.7359	24.8680	16.5786	12.4340	9.9472	8.2893	7.1051
220	45.2145	22.6072	15.0715	11.3036	9.0429	7.5357	6.4592
240	41.4466	20.7233	13.8155	10.3616	8.2893	6.9078	5.9209

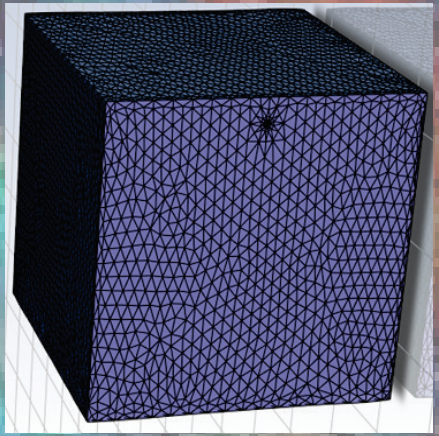
Required minimal time estimates for chamber exposures (seconds)

- Fuchs, N.A. (1963). On the stationary charge distribution on aerosol particles in a bipolar ionic atmosphere. *Geofis. Pura Appl*. 56: 185–193.

Three-dimensional volume (indoor spaces) modeling

COMPUTER MODELING

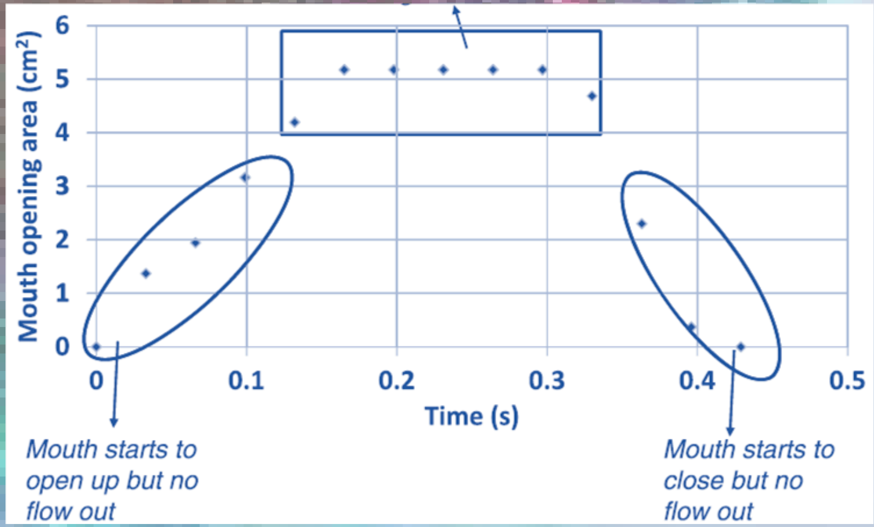
- Models are inherently **multiscale.**



Small room size
2.6m×2.6m×2.6m

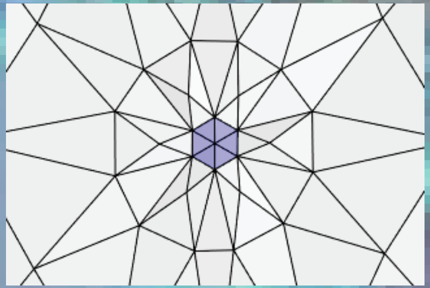
- Modular approaches to 3D computational mesh generation.

Gupta, J.K., Lin, C.-H., Chen, Q. (2009) *Indoor Air*

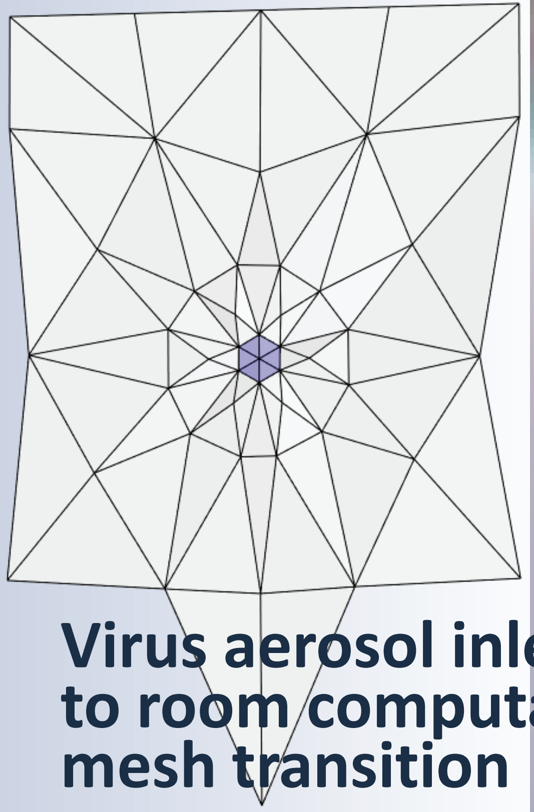


Mouth starts to open up but no flow out

Mouth starts to close but no flow out



Inlet diameter
~2.85 cm

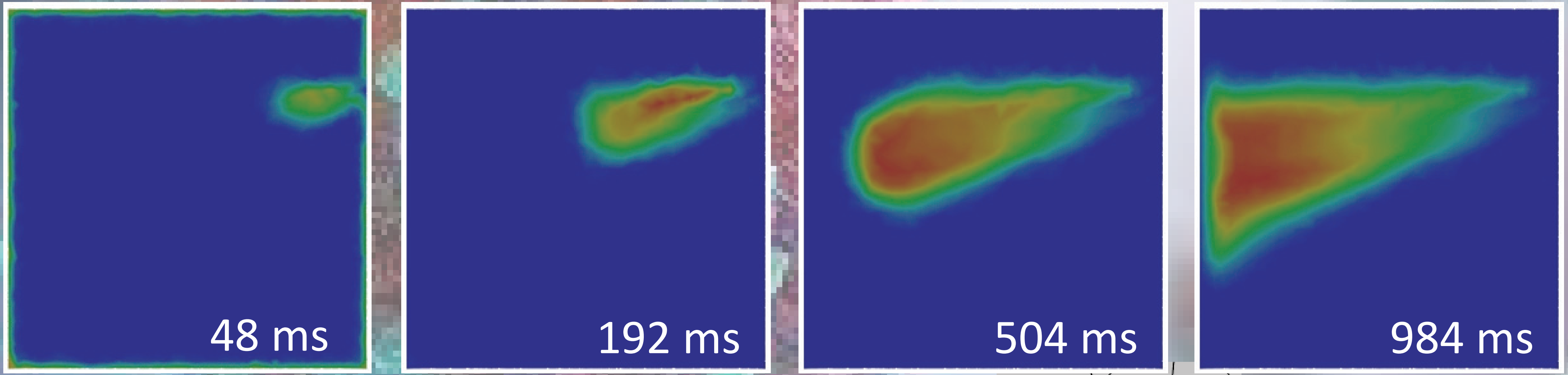


Virus aerosol inlet to room computational mesh transition

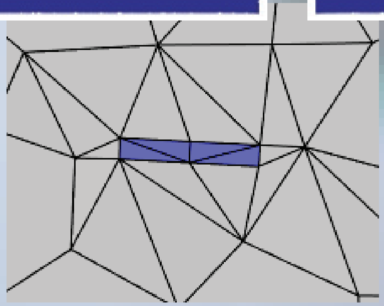
Transient simulations of ion streaming

COMPUTER MODELING

- Data written to the files at computational nodes and the predefined indoor space cross-sections.
- Variable ion inlet size, streaming velocity, initial velocity angle, continuous ion streaming with limited half-life times.



Plots above: 12 cm × 2 cm inlet size (right),
10 m/s init.velocity, 12° streaming angle (w.r.t. horiz.dir.)
Turbulent viscosity



Ion inlet transition to the room size

Cough and breathing dynamics

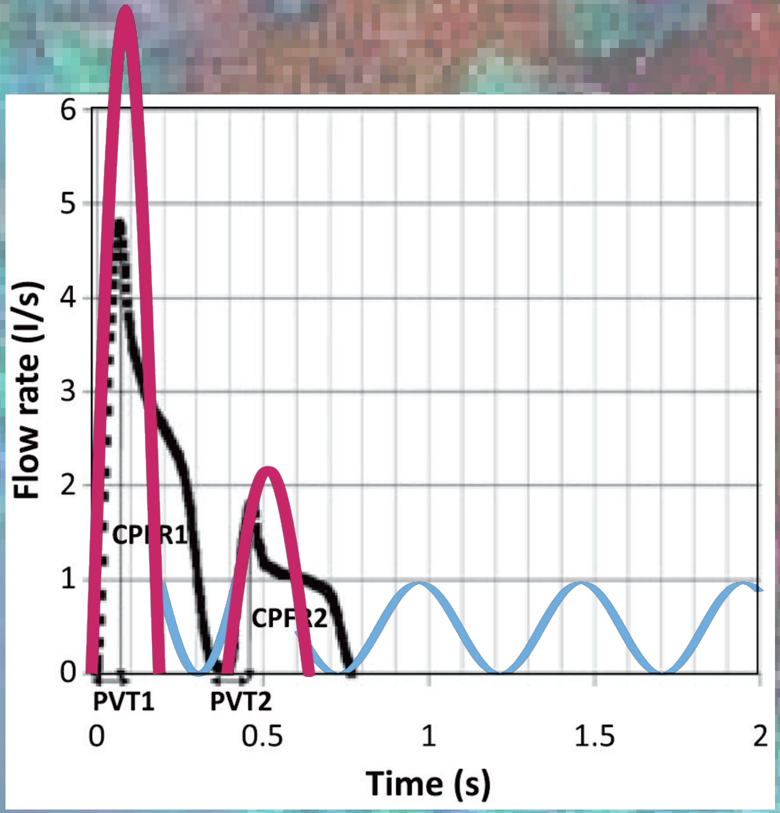
COMPUTER MODELING

- Simple models based on literature data.

Gupta, J.K., Lin, C.-H., Chen, Q. (2009) *Indoor Air* vol 19: 517–525.

- Example: simple sinusoidal fit $11.2\ \text{m/s}*\sin(5.0\ \text{Hz}*\pi*time)$ for $time<0.2$ s

  0 m/s, otherwise



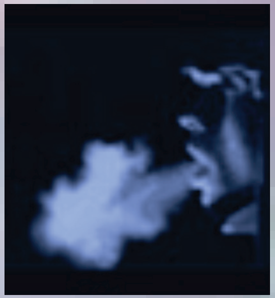
CPFR --- *Cough Peak Flow Rate*

Peak cough velocity: 6 to 22 m/s Average cough velocity: **11.2** m/s

Mean angles: $\theta_1 = 15° \pm 5°$

$\theta_2 = 40° \pm 4°$

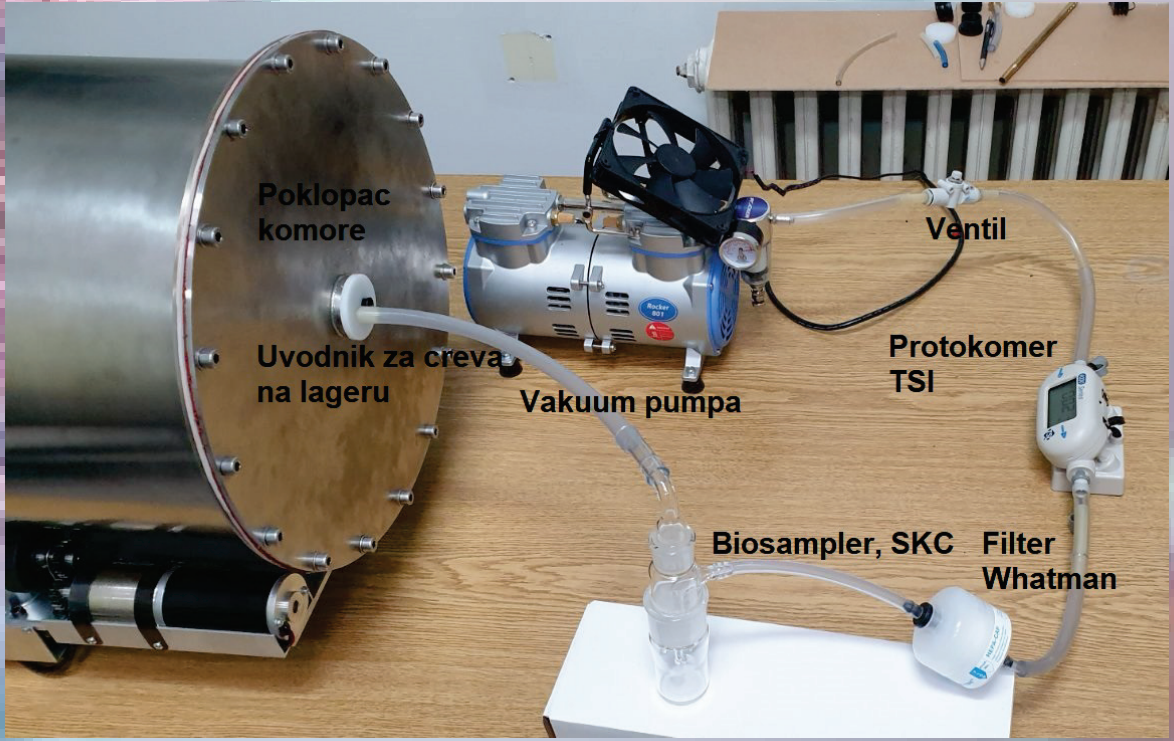
Mean angle: 28°



Experiments: Virus exposure to ionization

VIRAL EXPERIMENTATION

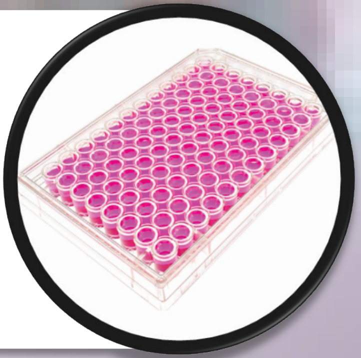
Chamber can be used as an air-flow or a still air chamber.



VIRAL EXPERIMENTATION

The ***Vero cells*** were initially cultivated within plastic flasks. After the cultivation, ***the virus*** was inoculated into the flasks, allowing for it to multiply within the cells. This is how the ***stock amounts*** of the pathogen were obtained.

After the virus was allowed to multiply, the ***virus concentration*** was determined via a ***TCID$_{50}$ test*** in 96 well plates. This step was a requirement in order to determine the pathogen concentration in working viral solutions.



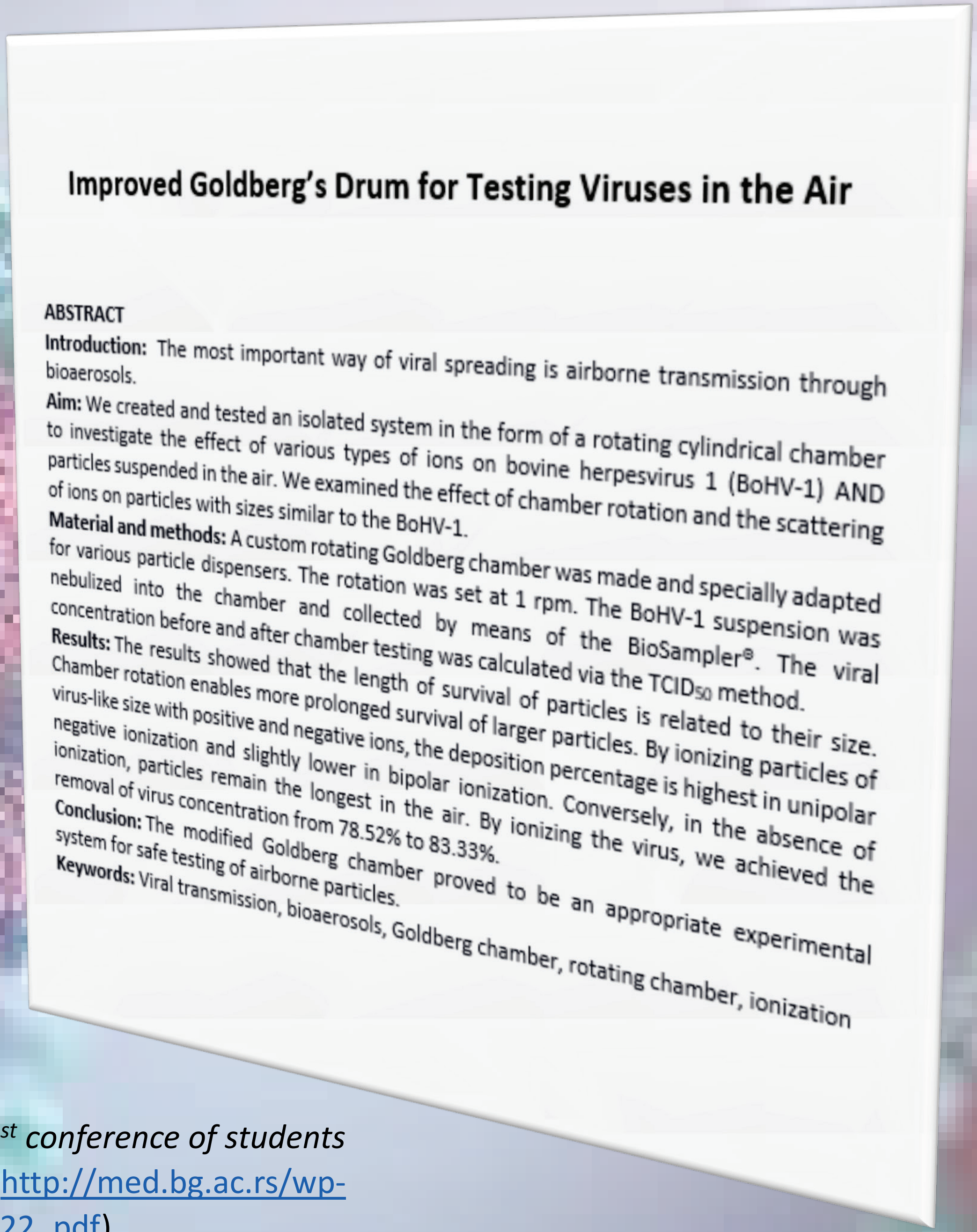
The viral solutions with determined concentrations were placed in 50 ml tubes. ***Aliquots*** of pathogens were divided into equal volumes of 20 ml. This volume was used in the nebulizer and the ***experimental chamber part of the experiment***.

Inside the chamber, the viruses were ***dispersed*** using different nebulzers and exposed to ions. After a certain amount of time, the air within the chamber was sucked out by a pump and through a ***bio-aerosol collector***. The concentration of viruses collected thusly was again determined by the ***TCID$_{50}$ test*** and compared to the initial concentration.

Dissemination:
STUDENT SCIENTIFIC PAPER

The results showed that the length of survival of particles is related to their size. Chamber rotation enables more prolonged survival of larger particles. By ionizing particles of virus-like size with positive and negative ions, the deposition percentage is highest in unipolar negative ionization and slightly lower in bipolar ionization. Conversely, in the absence of ionization, particles remain the longest in the air. By ionizing the virus, we achieved the ***removal of virus concentration from 78.52% to 83.33%.***

We concluded that ***the modified Goldberg chamber proved to be an appropriate experimental system for safe testing of airborne particles***.



Improved Goldberg's Drum for Testing Viruses in the Air

ABSTRACT

Introduction: The most important way of viral spreading is airborne transmission through bioaerosols.

Aim: We created and tested an isolated system in the form of a rotating cylindrical chamber to investigate the effect of various types of ions on bovine herpesvirus 1 (BoHV-1) AND particles suspended in the air. We examined the effect of chamber rotation and the scattering of ions on particles with sizes similar to the BoHV-1.

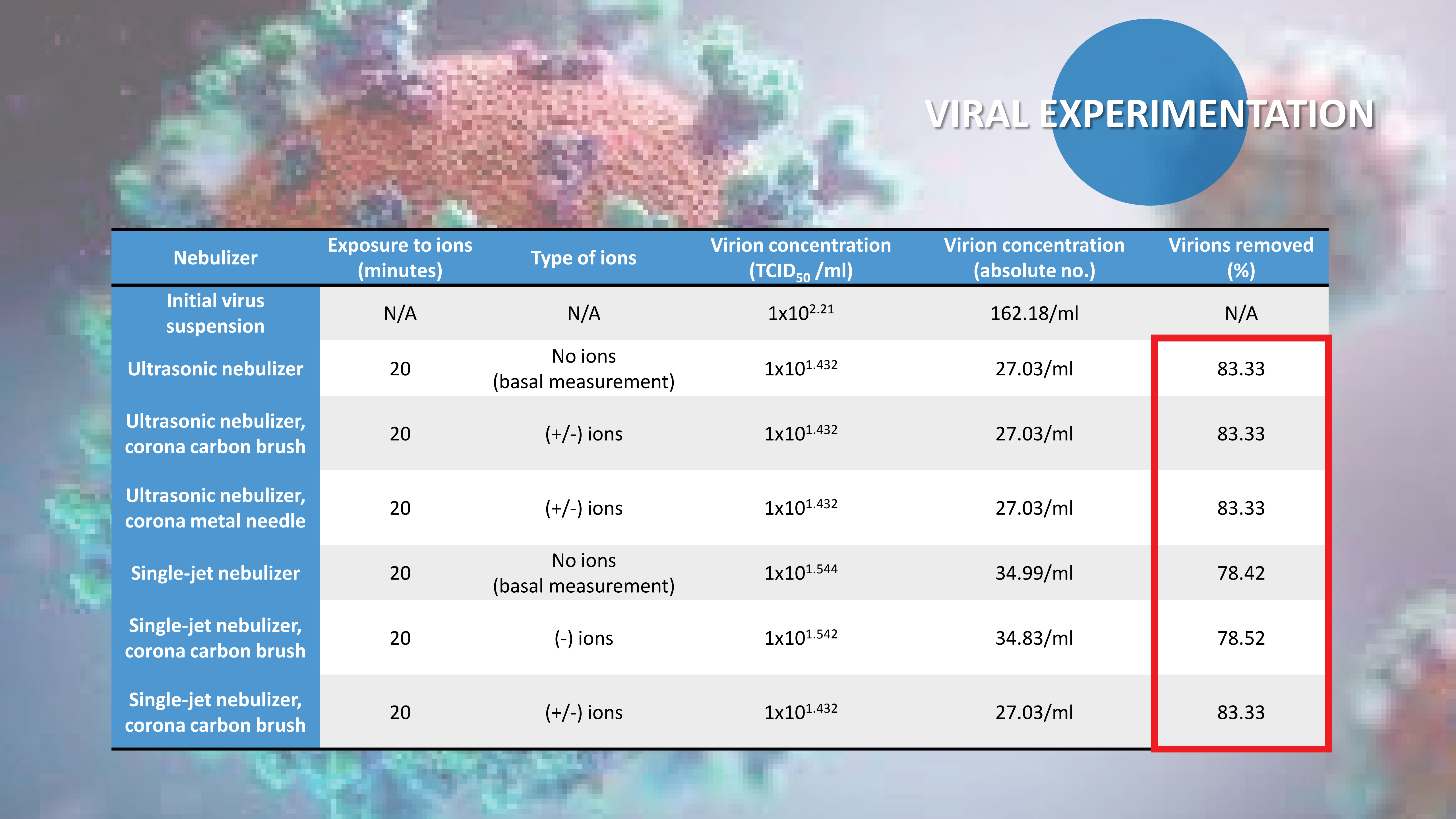
Material and methods: A custom rotating Goldberg chamber was made and specially adapted for various particle dispensers. The rotation was set at 1 rpm. The BoHV-1 suspension was nebulized into the chamber and collected by means of the BioSampler®. The viral concentration before and after chamber testing was calculated via the $TCID_{50}$ method.

Results: The results showed that the length of survival of particles is related to their size. Chamber rotation enables more prolonged survival of larger particles. By ionizing particles of virus-like size with positive and negative ions, the deposition percentage is highest in unipolar negative ionization and slightly lower in bipolar ionization. Conversely, in the absence of ionization, particles remain the longest in the air. By ionizing the virus, we achieved the removal of virus concentration from 78.52% to 83.33%.

Conclusion: The modified Goldberg chamber proved to be an appropriate experimental system for safe testing of airborne particles.

Keywords: Viral transmission, bioaerosols, Goldberg chamber, rotating chamber, ionization

* Krulj I, Krća N. IMPROVED GOLDBERG'S DRUM FOR TESTING VIRUSES IN THE AIR. *61st conference of students of biomedical sciences*. Kopaonik, 25-29 April 2022. (abstract book link: http://med.bg.ac.rs/wp-content/uploads/2019/10/61.-Kongres-studenata-biomedicinskih-nauka-Kopaonik-2022..pdf)



VIRAL EXPERIMENTATION

Nebulizer	Exposure to ions (minutes)	Type of ions	Virion concentration ($TCID_{50}$ /ml)	Virion concentration (absolute no.)	Virions removed (%)
Initial virus suspension	N/A	N/A	$1x10^{2.21}$	162.18/ml	N/A
Ultrasonic nebulizer	20	No ions (basal measurement)	$1x10^{1.432}$	27.03/ml	83.33
Ultrasonic nebulizer, corona carbon brush	20	(+/-) ions	$1x10^{1.432}$	27.03/ml	83.33
Ultrasonic nebulizer, corona metal needle	20	(+/-) ions	$1x10^{1.432}$	27.03/ml	83.33
Single-jet nebulizer	20	No ions (basal measurement)	$1x10^{1.544}$	34.99/ml	78.42
Single-jet nebulizer, corona carbon brush	20	(-) ions	$1x10^{1.542}$	34.83/ml	78.52
Single-jet nebulizer, corona carbon brush	20	(+/-) ions	$1x10^{1.432}$	27.03/ml	83.33

VIRAL EXPERIMENTATION

Nebulizer	Exposure to ions (minutes)	Type of ions	Virion concentration ($TCID_{50}$ /ml)	Virion concentration (absolute no.)	Virions removed (%)
Initial virus suspension	N/A	N/A	**$1x10^{2.5}$**	316.22	N/A
Single jet nebulizer, corona	Appx. 30	bipolar	**$1x10^{0.946}$**	8.83	35.8; -1.554 log10/ml
Single jet nebulizer, corona	/	unipolar	**$1x10^{0.835}$**	6.83	46.24; -1.665 log10/ml
Single jet nebulizer, needlepin	Appx. 30	bipolar	**$1x10^{0.835}$**	6.83	46.24; -1.665 log10/ml
Control measurement	N/A	No ionization	**$1x10^{0.723}$**	5.28	59.8; 1.777 log10/ml
Single jet nebulizer	/	negative	**$1x10^{0.723}$**	5.28	59.8; 1.777 log10/ml

VIRAL EXPERIMENTATION

Nebulizer	Exposure to ions (minutes)	Type of ions	Virion concentration ($TCID_{50}$ /ml)	Virion concentration (absolute no.)	Virions removed (x; log)
Initial virus suspension	N/A	N/A	$1x10^{4.625}$	42169	N/A
Ultrasonic nebulizer, corona carbon brush	45	bipolar	$1x10^{2.875}$	749	56,3; -1.75 log10/ml
Single jet atomizer, corona carbon brush	45	bipolar	$1x10^{1.0}$	10	4216.96; -3.625 log10/ml
Single jet atomizer	45	No ionization	$1x10^{2.25}$	177	237.13; -2.375 log10/ml

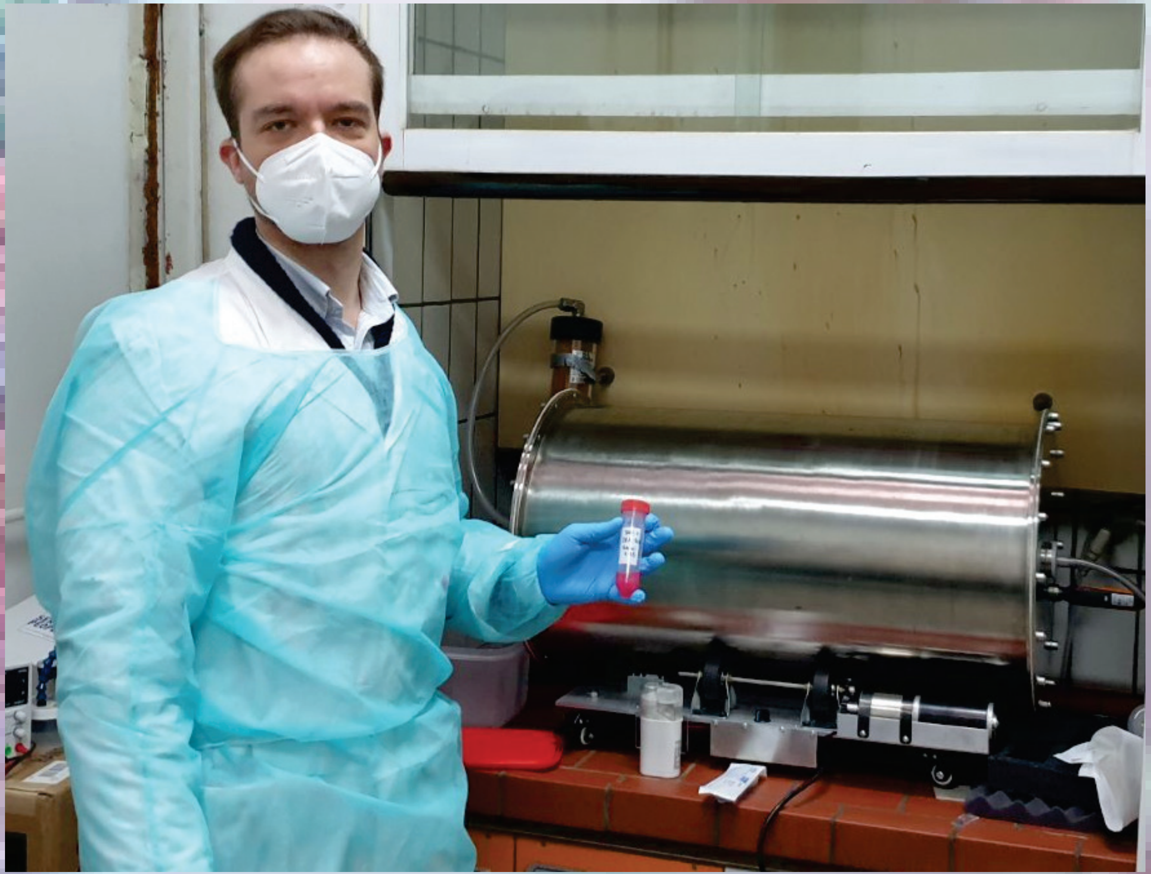
Experiments concerning virus inactivation by ionization in rotating chamber in standard humidity and temperature conditions were performed. ***18 sets of measurements*** were carried out.

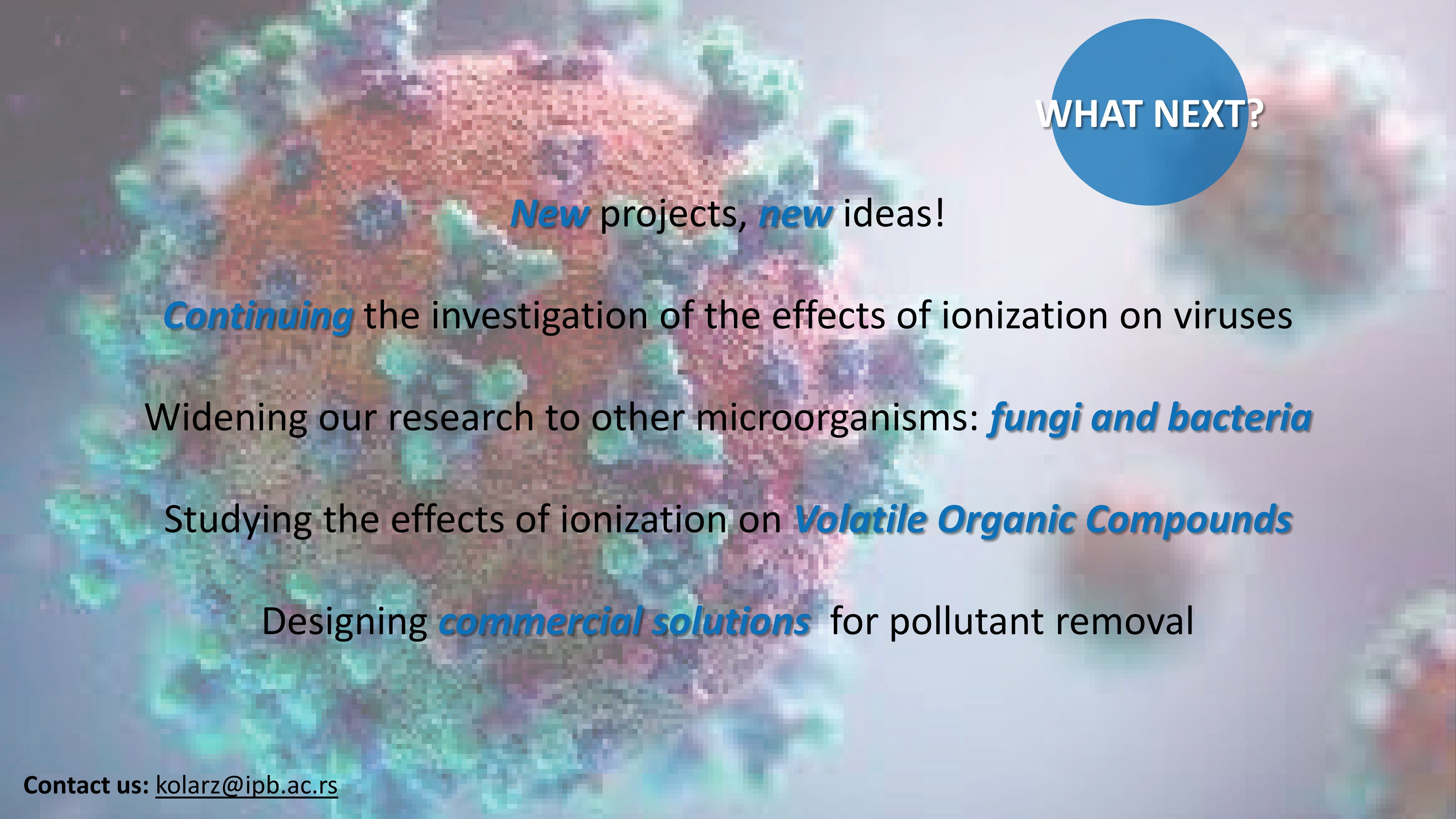
The experimental data regarding the ***BoHV1 virus*** (surrogate of SARS-CoV-2) indicated that the most remarkable effect on viral infectivity titers was in the experiment where particles were nebulized via single jet atomizer and ions were generated using bipolar coronal discharge on carbon fibre brushes.

Decrease of viral concentrations with and without ionization were noted after 45 min of exposition.

However, additional repetitions of these experiments need to be performed in order to establish the most favourable conditions for the inactivation process and results reproducibility. Also, for practicality of usage, we posit that the ***time of 45 minutes of exposure to ions in the breathing zone should be reduced***.

We are looking into possible solutions for shortening this timeframe.





WHAT NEXT?

New projects, ***new*** ideas!

Continuing the investigation of the effects of ionization on viruses

Widening our research to other microorganisms: ***fungi and bacteria***

Studying the effects of ionization on ***Volatile Organic Compounds***

Designing ***commercial solutions*** for pollutant removal

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