Low-temperature plasma technology for inactivation of pathogenic microbial aerosol

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Content

1

Hazards of Pathogenic Microbial Aerosols

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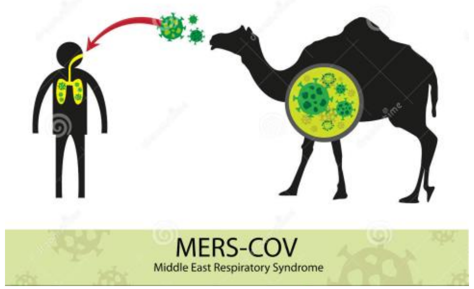
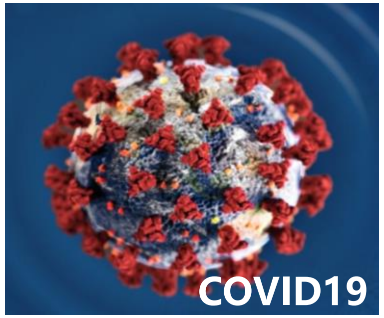
1.1 The world has entered a period of high incidence of infectious diseases

HUST SEEE

In the short 20 years of the 21st century, there have been many major global plagues such as SARS, MERS, Ebola, and the current epidemic of COVID-19





2000 → **2022**

Potential threat: 1. **highly pathogenic avian influenza**

2. **Global warming, resuscitation of ancient viruses in permafrost.**

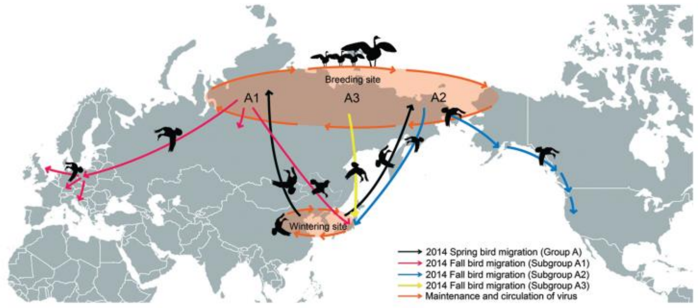
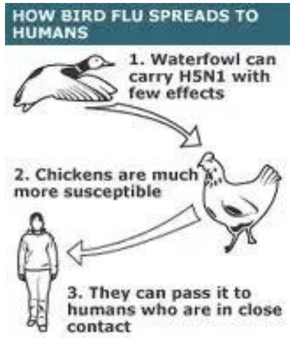


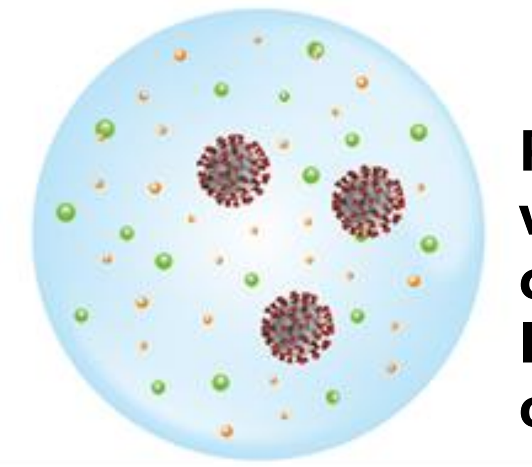
FIG 2 Geographic map showing the movement of H5N8 HPAIV in Asia, Europe, and North America in relation to regional waterfowl migration routes. The map, by Dmthoth, is from Wikipedia Commons (http://commons.wikimedia.org/wiki/File:Blank_Map_Pacific_World.svg).



Global Migration of Migratory Birds and Transmission of Avian Influenza

30,000-year-old broadmouth virus revived in Siberian permafrost

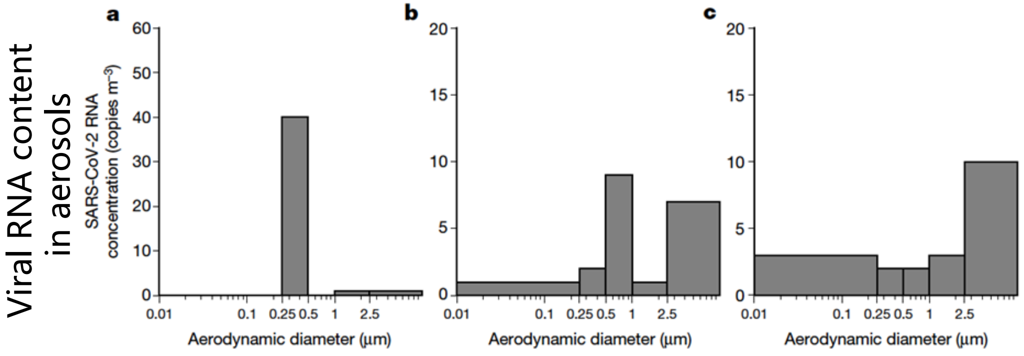
2. Aerosols are one of the transmission routes of the new coronavirus



Structure of PMA

PMA is a droplet with a virus or bacteria as the condensation nucleus. Its diameter is in the order of micrometers.

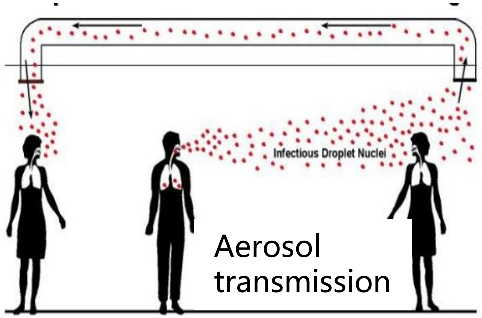
Many hospitals have detected PMAs of different particle sizes containing corona virus through aerosol sampling



Isolation ward shelter Doctor's office

A Covid-19 supers spreading incident caused by PMA transmission in a church (45 out of 60 singers in the choir were diagnosed with Covid-19, 2 died)

Lots of aerosols generated during choir practice



Indoor aerosol transmission routes

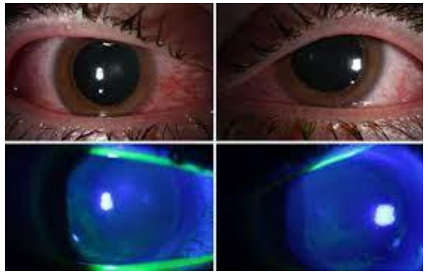
Masks have become a necessity

1.3 Limitations of traditional aerosol disinfection and filtration methods

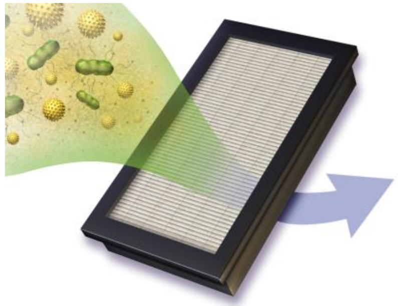
Traditional air purification methods such as UV, High Efficiency Particulate Air (HEPA) and other methods have shortcomings such as only working under unmanned conditions, and forming potential pollution sources.

UV

Impaired vision



Hazardous to the skin



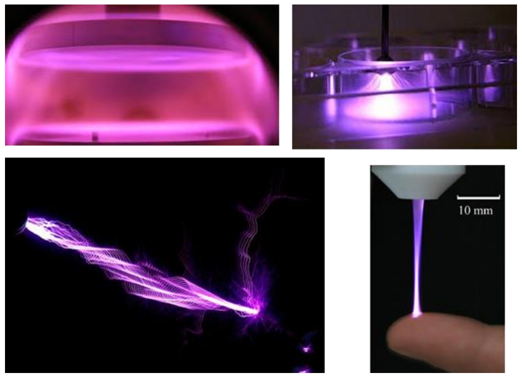
Microbial long-term survival
A potential source of pollution

病原微生物种类	存活时间	
	空气中	无机材料表面
新冠病毒	≤3小时	≤3天
流感病毒	≤21天	≤11天
大肠杆菌	≤1小时	≤16月
葡萄球菌	≤3天	≤7月
链球菌	≤2天	≤6.5月
曲霉和青霉分生孢子	≤22年	≤22年

A large number of live viruses and bacteria were detected in HEPA used for more than a month

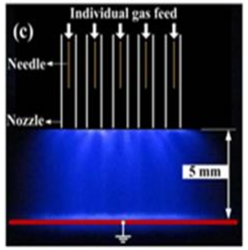
1.4 Plasma kills a variety of PMAs

➢ **Plasma is the fourth state of matter, which is created when a gas is heated sufficiently or exposed to a strong electromagnetic field.**



Different Discharge Forms

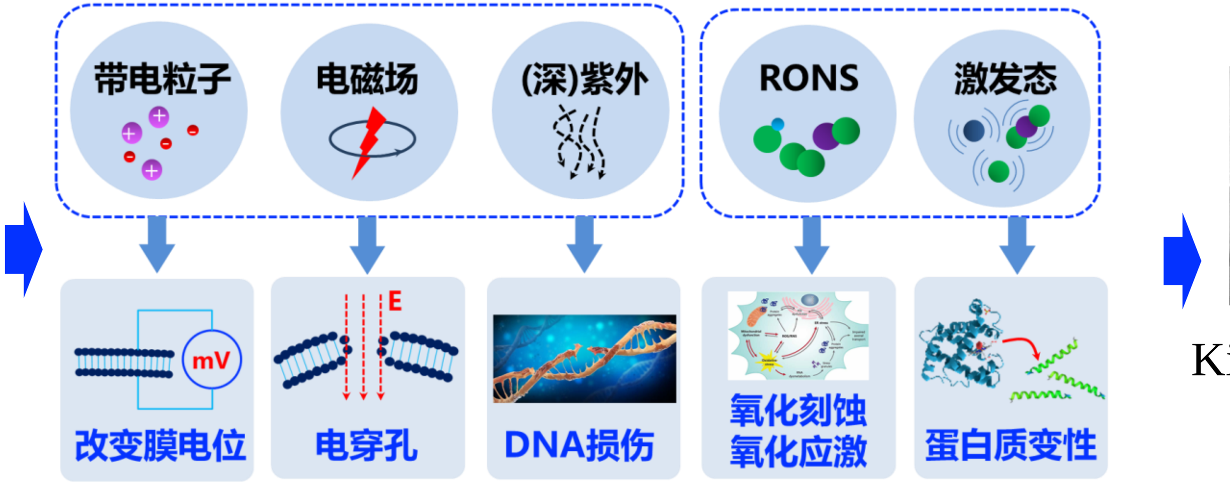
➢ **Plasma contains high-density charged particles, a variety of highly active components, and a strong electric field, which can effectively eliminate PMA.**

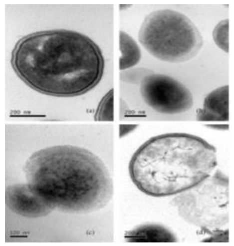


Plasma

Physics

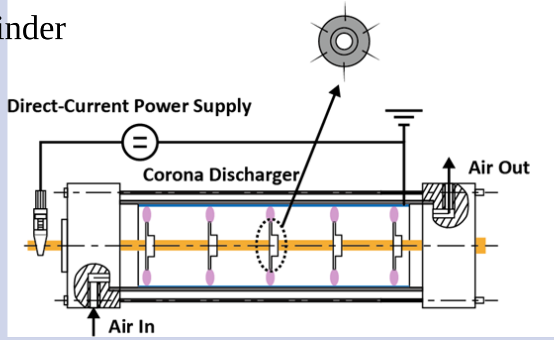
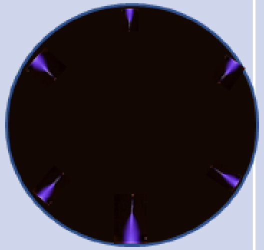
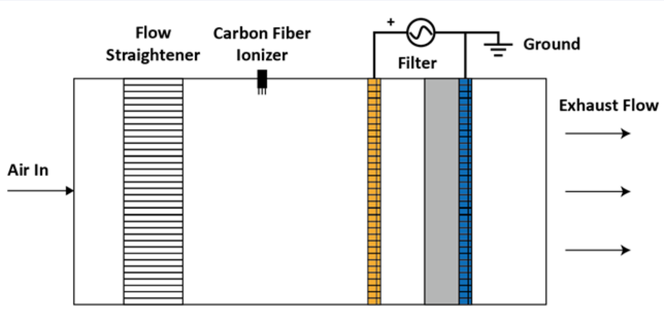
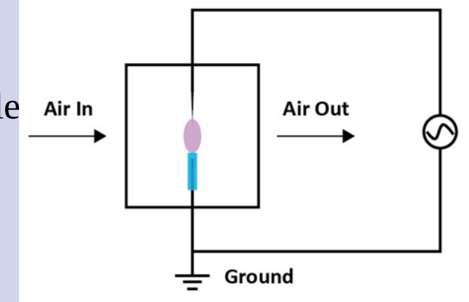
Chemistry



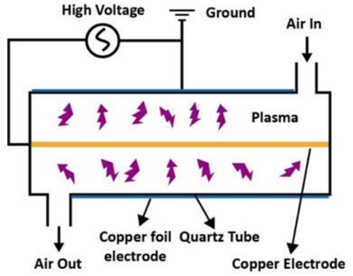
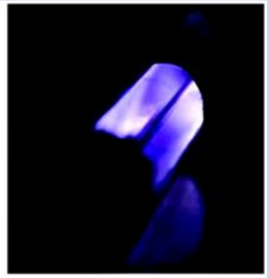
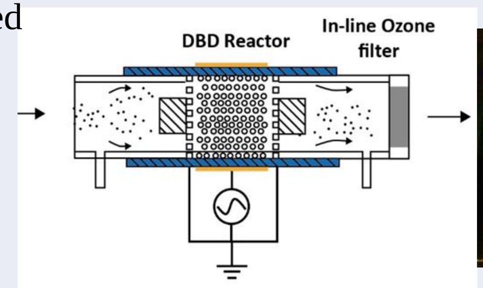
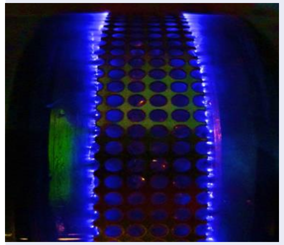


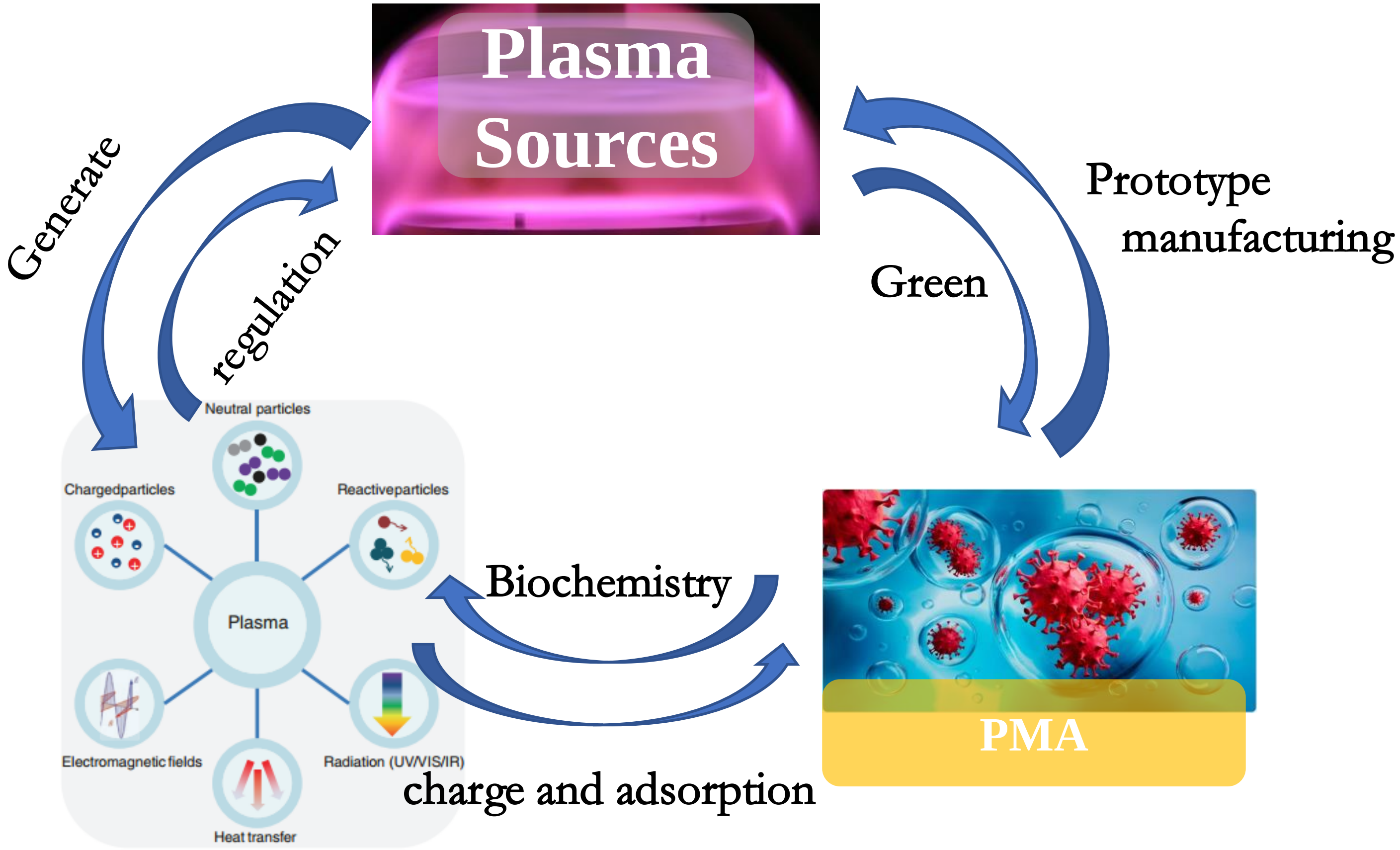
Kill different PMA

1.5 Typical Plasma disinfecting PMAs Device

R&D University	Plasma Device Structure	Processing objects and efficiency	Limitations
South China Agricultural University **Journal of Aerosol Science 54 103–12 2012**	Needle-Cylinder DC Corona Discharge  	➢ Penicillium aerosol ➢ Discharge power 1.6w ➢ Inactivation efficiency 99.9% ➢ Works normally in low temperature and high humidity environment	➢ **Big size** ➢ **complex structure** ➢ **Low discharge power and low air flow**
Yonsei University, Korea. **Journal of Aerosol Science 107 31–40 2017**	carbon fiber discharge 	➢ Bacteriophage virus aerosol ➢ Air velocity 0.1-1m/s ➢ Improve HEPA filtration efficiency by 20% ➢ The virus inactivation efficiency 97.4%	➢ **Requires HEPA-enhanced filtration** ➢ **Limited service life**
University of Toulouse, France **PLOS ONE 12 e0171434 2017**	Double-needle electrode AC discharge  	➢ Escherichia coli Aerosol ➢ Discharge power 18.2W ➢ Bacterial inactivation efficiency of 99.9%	➢ **small device** ➢ **low air flow** ➢ **Processing is limited**

1.5 Typical Plasma disinfecting PMAs Device

R&D University	Plasma Device Structure	Processing objects and efficiency	Limitations
Beijing University **Plasma Environ. Sci. Technol. 46 3360–8 2012**	DBD  	➢ Bacillus subtilis is 98% inactivated ➢ Complete inactivation of Pseudomonas fluorescens	➢ **limited air flow** ➢ **The device needs to be amplified in parallel**
University of Michigan **J. Phys. D: Appl. Phys. 52 255201 2019**	Packed bed discharge  	➢ Phage MS2 virus aerosol ➢ Discharge power 2W ➢ Virus inactivation efficiency is over 99%	➢ **complex structure** ➢ **greater wind resistance** ➢ **Need to increase airflow**



1. Biochemical mechanism of plasma disinfecting PMAs
2. Physical process of plasma charged and adsorption of PMAs
3. Development of a Plasma Air Purifier

2 Research progress on the elimination of PMAs by plasma

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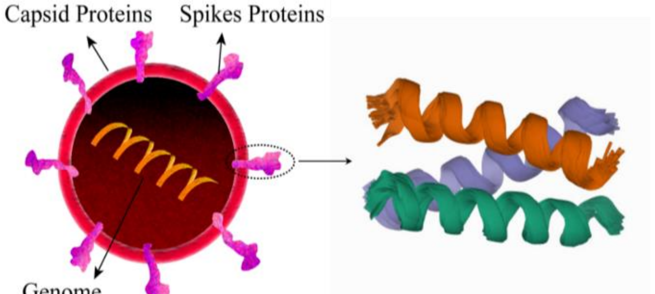
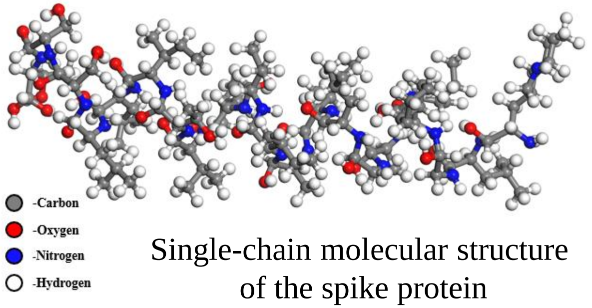
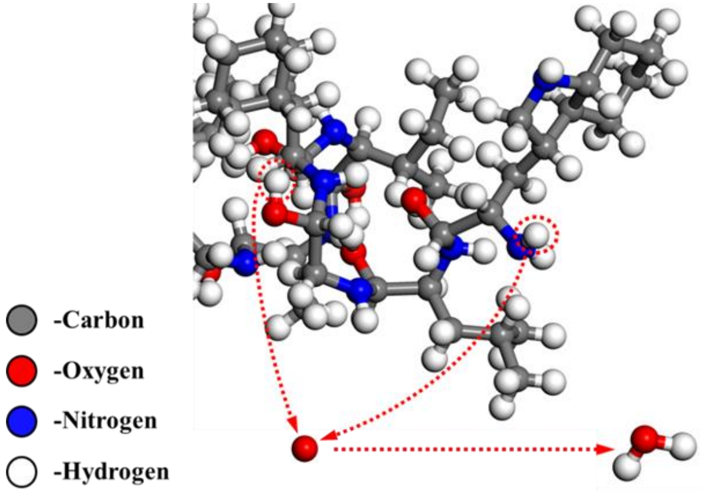
- **Molecular dynamics simulation research on the interaction between plasma active components and the new coronavirus spike protein.**
- **The O atom of plasma deprives H of the close atoms (one H atom is deprived from the O atom, and the other H atom is deprived from the N atom). The breaking of hydrogen bonds leads to a significant reduction in the steric stability of the entire macromolecule.**
- **The chain reactions in the whole molecule further exacerbate the destruction of the molecular structure.**



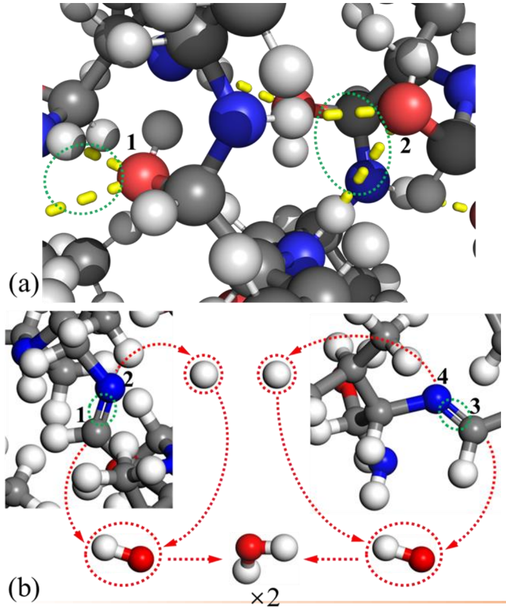
Structure of SARS-CoV-2



Single-chain molecular structure of the spike protein



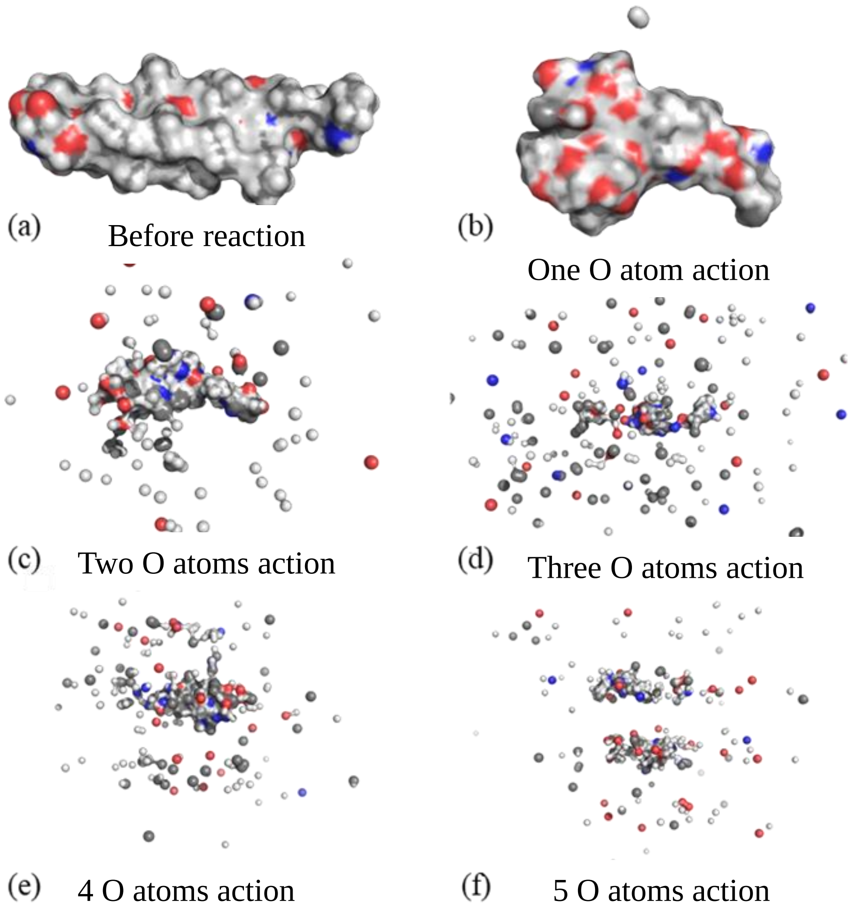
one H atom is deprived from the O atom, and the other H atom is deprived from the N atom



Two OH groups are exfoliated from the C1 and C3 atoms.

The free two OH radicals deprive one H atom of the N2 and N4 atom and generate H_2O.

C1 and N2 atom, C3 and N4, generate double bounds



Surface structures of SARS-CoV-2 spike protein molecules before and after the reaction with different numbers of O atoms.

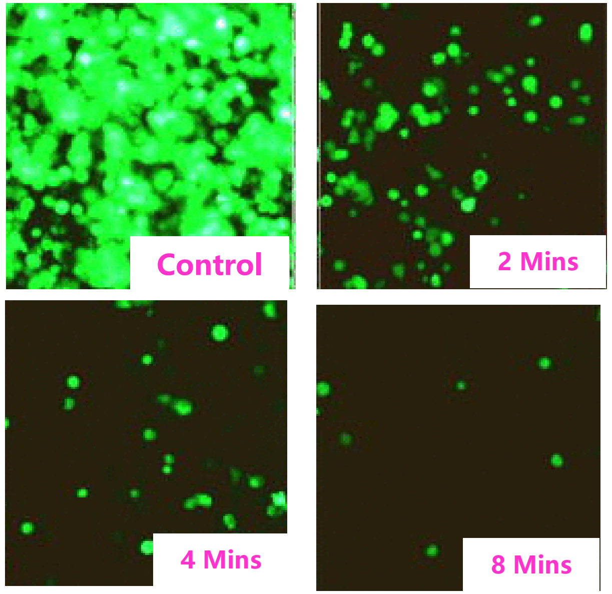
- **One O atom causes changes in amino acid sequence and spatial configuration, which reduces the activity of the spike protein**
- **Two or more O atoms cause protein disintegration. The main chain integrity decreases from 84.1% (1 O atom action) to 68.2% (3 O atoms) and 64.1% (5 O atoms action). 3 O atoms disintegrate the spike protein and finally inactivate the new coronavirus efficiently.**

Plasma Processes and Polymers, to be published.

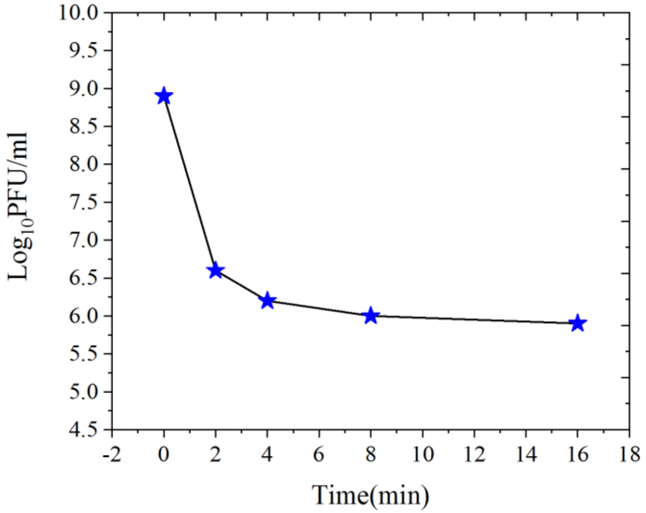
2.2 Air plasma Inactivation of adenovirus by plasma

- Air plasma treatment can effectively reduce the infectivity of adenovirus (AdV). The gene expression of AdV in HEK 293A primary human embryonic kidney cells was quantified mainly by green fluorescent protein imaging.
- The RONS generated by the plasma first oxidized and destroyed the capsid protein of AdV, then directly acted on the adenovirus DNA, and finally inactivated AdV.

Air plasma treatment device for adenovirus



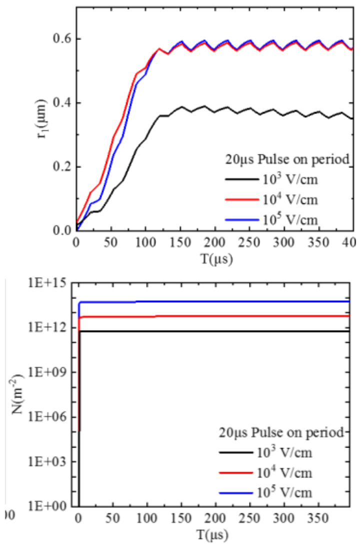
Fluorescence images of adenovirus-infected HEK 293A cells after plasma needle treatment



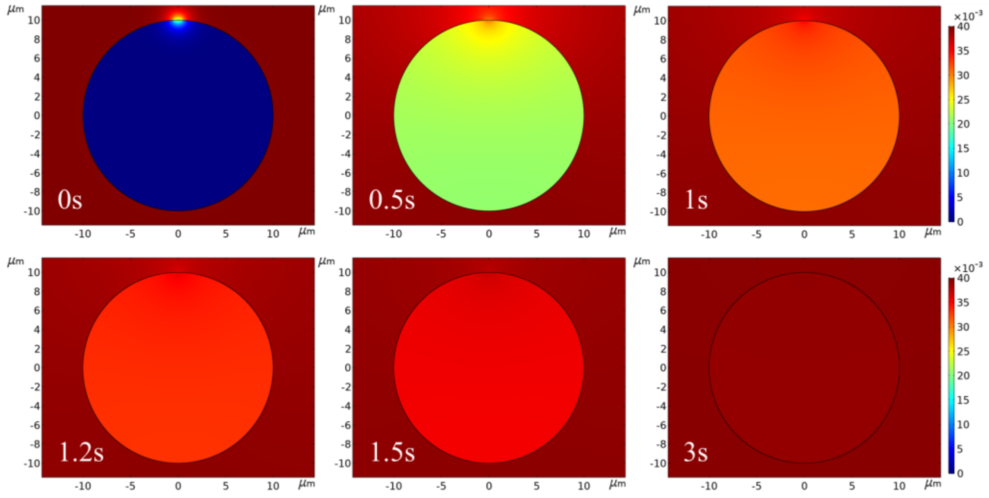
Air plasma treatment significantly reduces adenovirus survival

2.3 Plasma kills bacteria aerosol

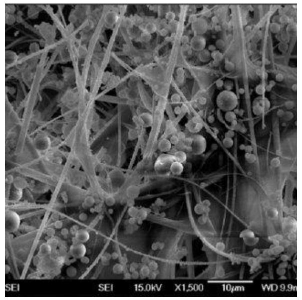
- The electric field strength generated by the plasma on the surface of PMA is >10^5 V/cm, and the internal E-field reaches 10^4 V/cm, which causes the bacterial cell (the condensation nucleus)membrane to perforate, and promotes the rapid entry of RONS into the bacteria, thereby inactivating bacterial aerosol.
- PMAs are charged and adsorbed on the discharge electrode, plasma penetrate deep into the submicron irregular structure of the aerosol deposits and quickly kill the PMAs intercepted by the system.



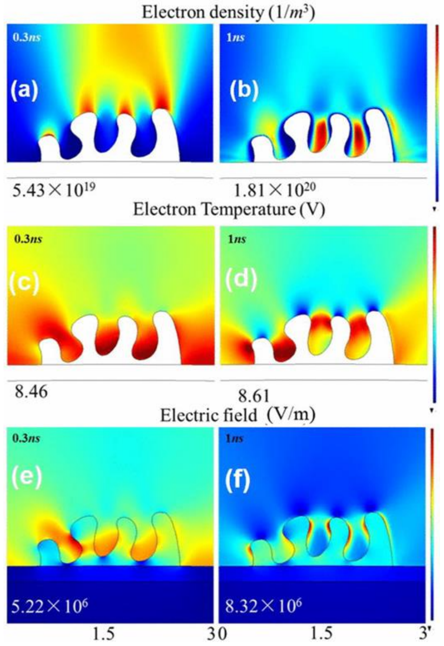
Plasma increases cell membrane perforation radius and number of perforations



H_2O_2 diffuses into cells (within 3 seconds)



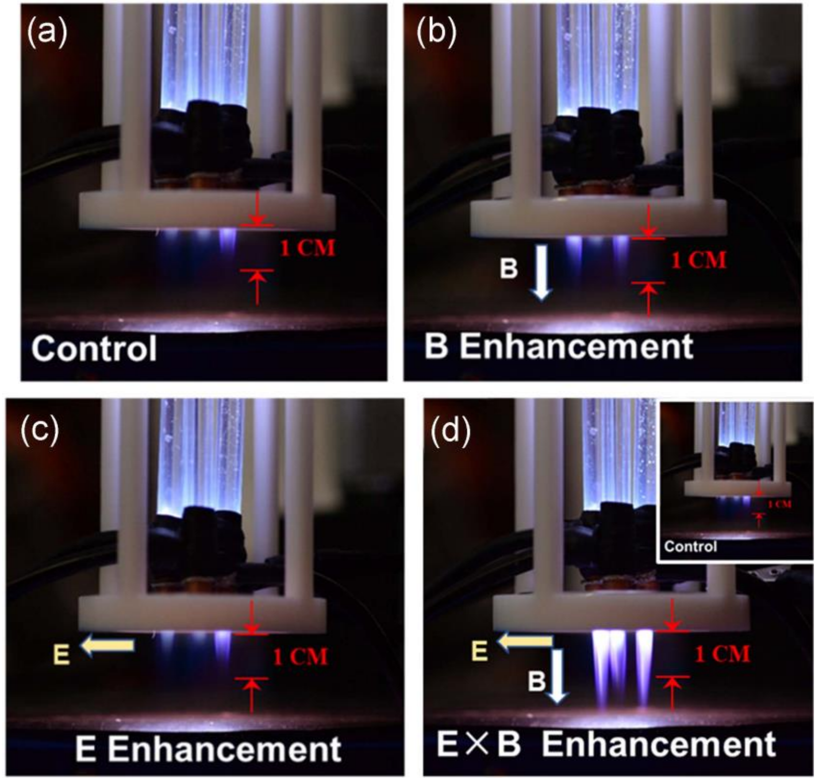
aerosols deposited on the metal foam electrodes



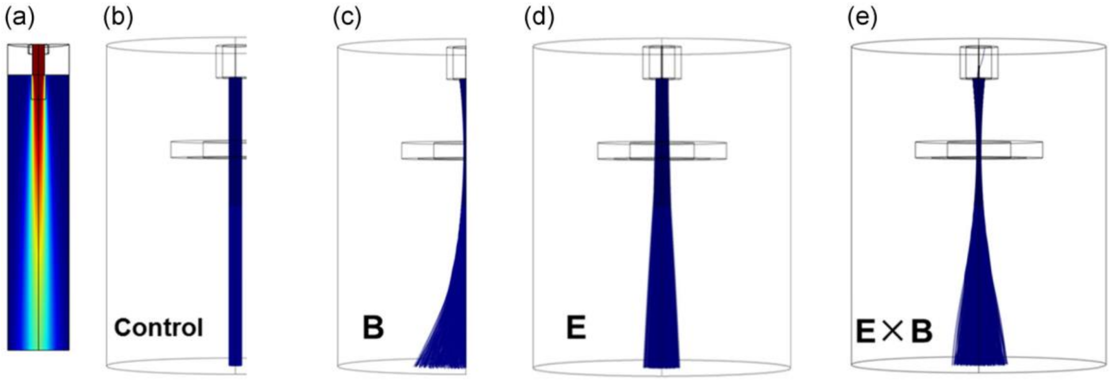
Plasma penetrates deep into submicron spaces inside sediments

2.4 Charged particles accelerate aerosol collisions

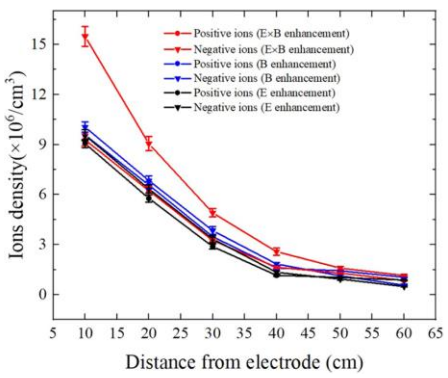
- **E×B can enhance the discharge intensity of the jet array and provide a large number of unipolar charged particles to the open space.**
- **E×B compresses electrons in the high argon concentration region and intensifies the discharge.**
- **The aerosol is charged through the diffusion charging mechanism. The charged aerosol has a higher aerosol collision rate.**



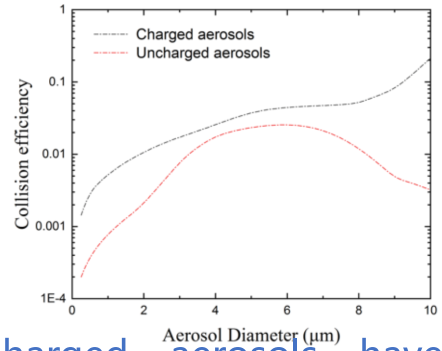
E×B improves the length and strength of plasma jet



E×B compress electrons in the high argon concentration region

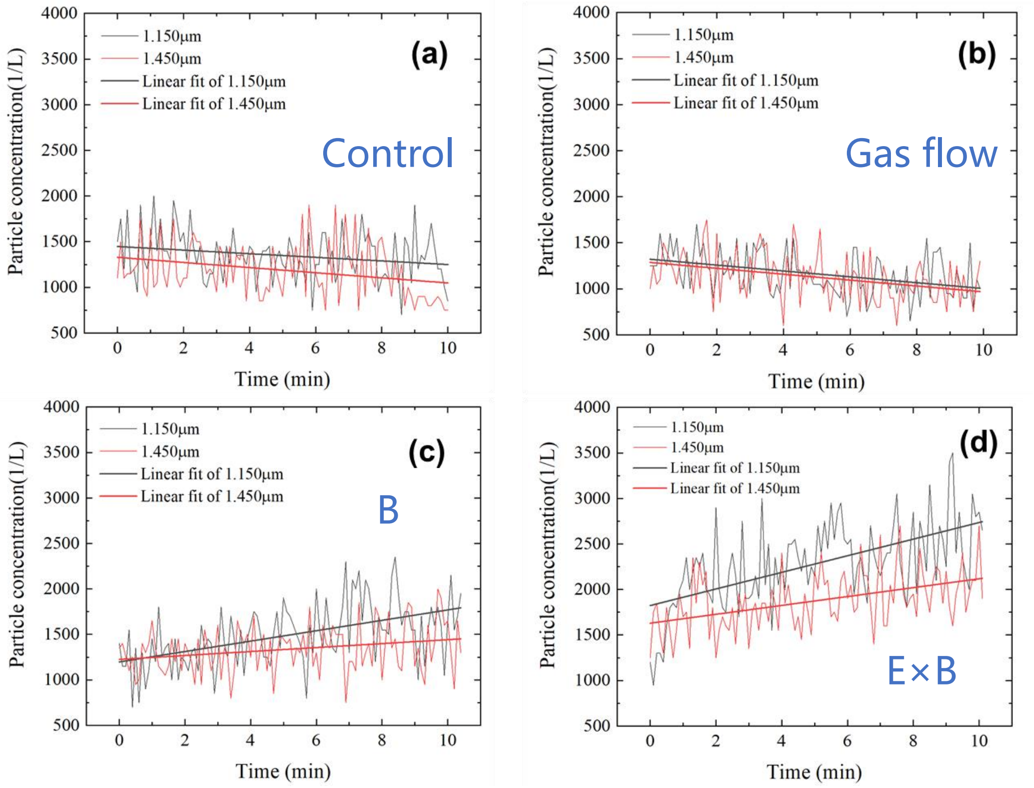


E×B provides $10^7/cm^3$ negative ions

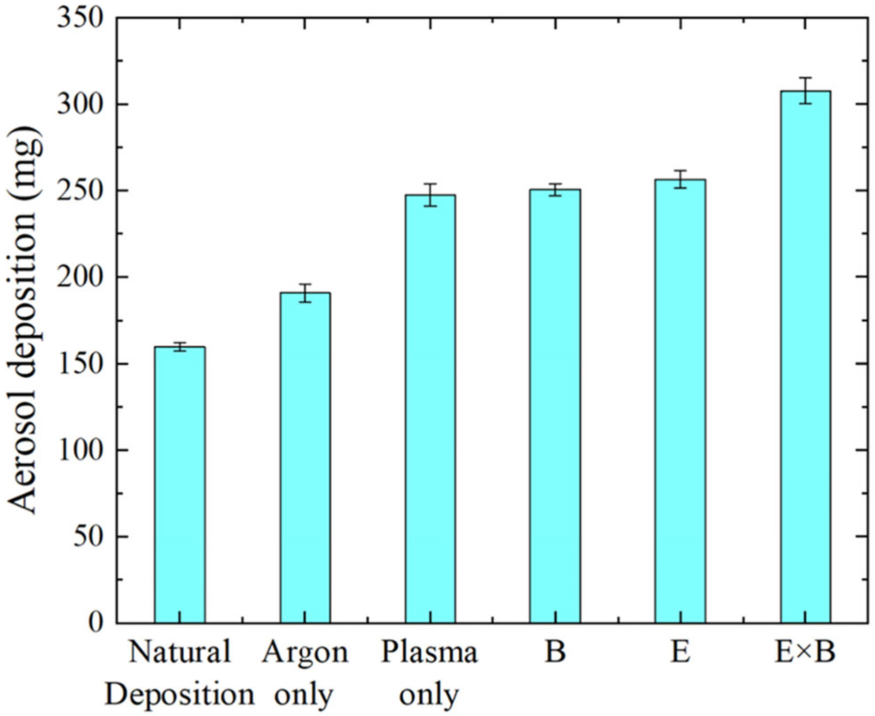


Charged aerosols have higher aerosol collision rates

2.4 Charged particles accelerate aerosol collisions



E×B promote the generation of larger aerosols

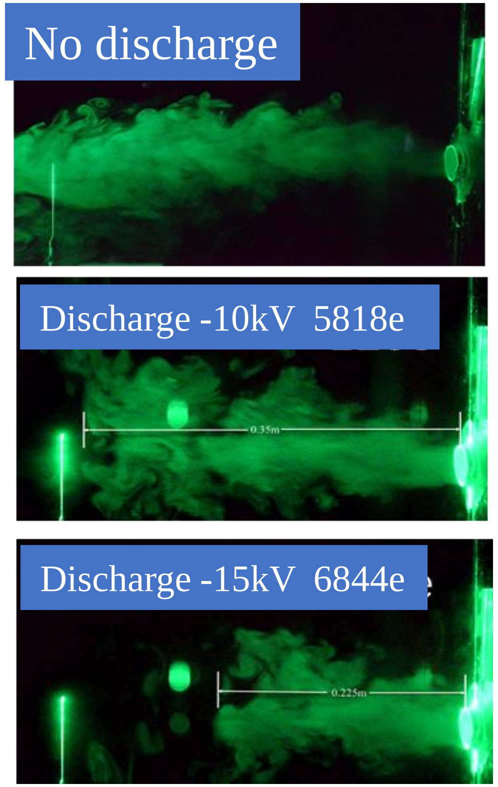


E×B promote the deposition of aerosols

E×B generates more aerosols with larger particle sizes, thereby accelerating the sedimentation of aerosols.

2.5 Aerosol's charge measurement

- **Develop an aerosol charge measurement system under high humidity conditions. When the discharge voltages were -10kV and -15kV, the aerosols (2 μm , 4 m/s) were directly charged by field charging mechanism, and the charges were 5818 e and 6844 e, respectively.**
- **The charged aerosol collides and condenses through the mirror electric force, which is more easily intercepted by filtering.**



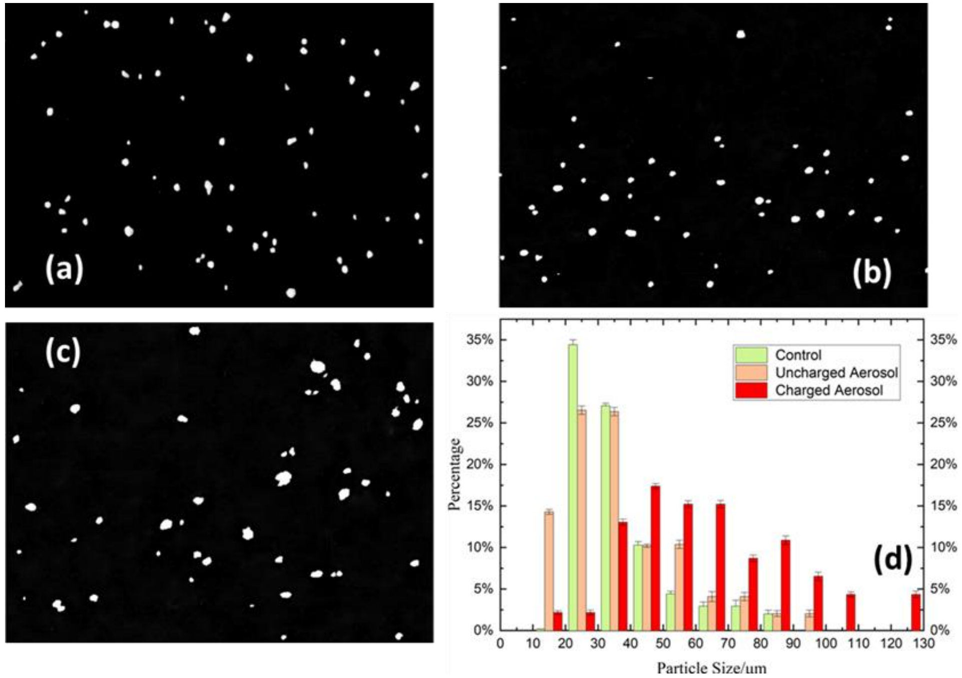
$$C_e >> C_{Th}, C_{Dif}$$

$$C_e = \frac{1}{4\pi\varepsilon_0}\left[Qq - \frac{q^2 A}{a}\left\{\frac{1}{\left(1-A^2/b^2\right)^2} - 1\right\}\right]$$

$$C_{Dif} = -6\pi\eta_a r \frac{0.74\,\mathrm{D_a M}_a(\rho_{v,\infty} - \rho_{a,\infty})\,\overline{f}_v}{(1+aN_{Kn})\,\mathrm{M}_\varpi\,\rho_a}$$

$$C_{Th} = -\frac{12\pi\eta_a r(k_a + 2.5k_p N_{Kn})k_a a(T_\infty - T_a)\,\overline{f}_h}{5(1+3N_{Kn})(k_p + 2k_a + 5k_p N_{Kn})\,p}$$

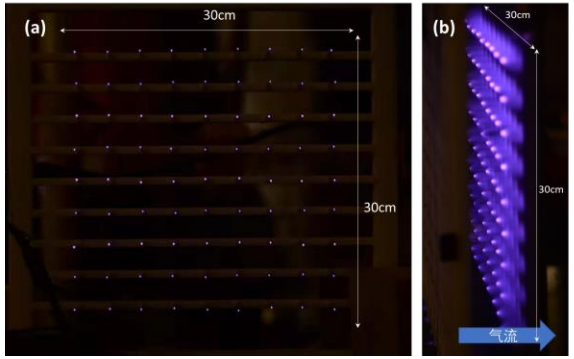
Calculation of electric field force, thermophoresis force and diffusophoresis force



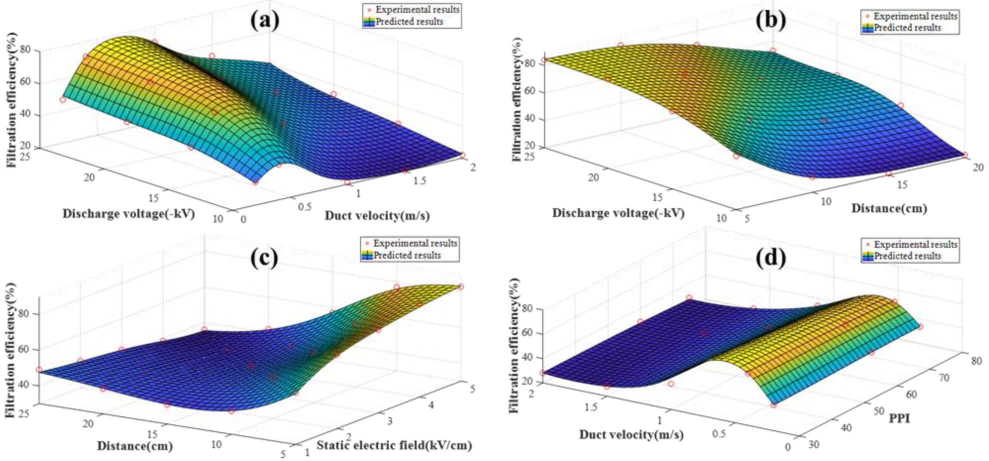
Charge-accelerated collision and condensation of aerosols

2.7 PAP Prototype development

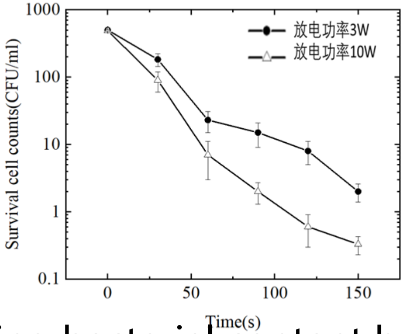
- **Develop a low wind resistance plasma charging and disinfecting device covering the entire air duct and optimize the operating parameters through AI.**
- **The first-generation PAP was developed and tested in a 12 m³ aerosol test environment. The bacterial aerosol content was reduced by more than 2 orders of magnitude in 2 minutes. The plasma can completely kill the bacterial aerosol intercepted by the system, breaking through the traditional HEPA's intercepting without killing limits.**



Low wind resistance, plasma charging and disinfecting device



AI optimization

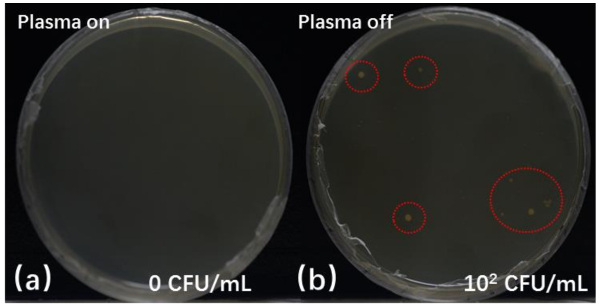


Reducing bacterial content by more than 2 orders of magnitude in 2 mins

First generation
Plasma Air Purifier (PAP)

CADR 500 m^3/h

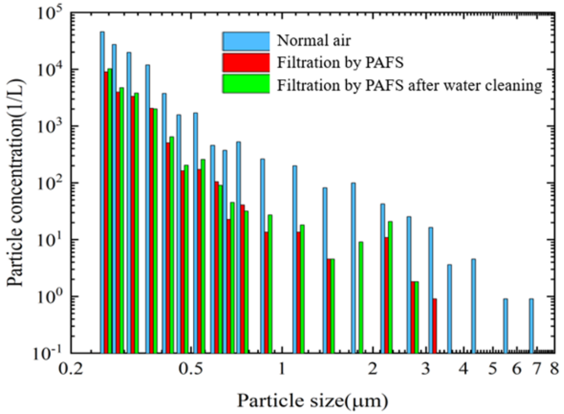
$12m^3$ aerosol test environment



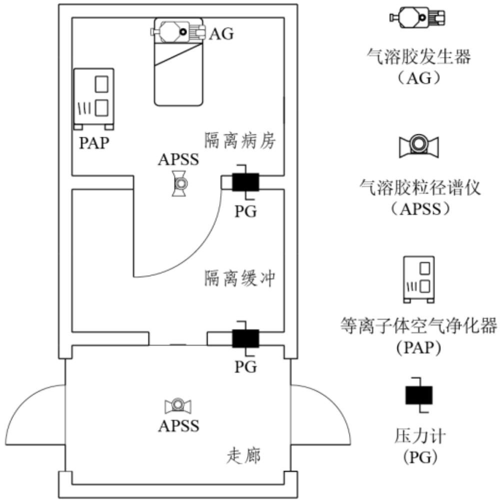
Plasma completely kills bacterial aerosols

2.8 Prototype test

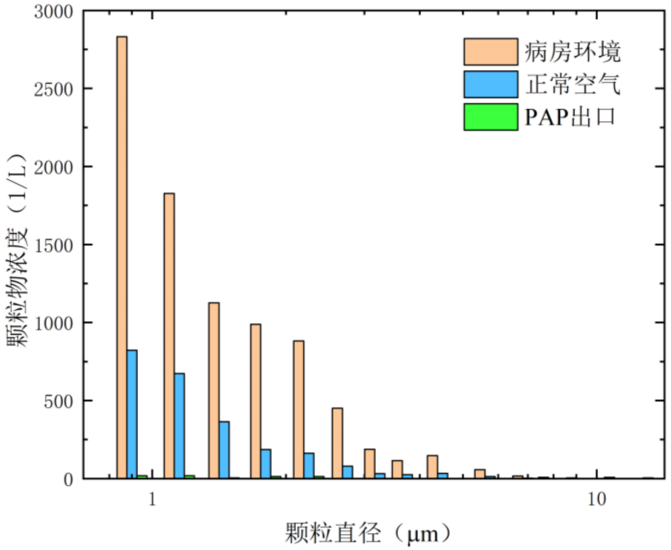
- **In cooperation with Union Hospital, a negative pressure environment is set up in a simulated isolation ward through a plasma air purifier to inhibit the spread of PMAs to public areas such as corridors.**
- **The aerosol generator is used to increase the aerosol concentration in the isolation ward by 5 times. After the plasma air purifier is turned on, it provides a negative pressure environment of -27Pa. The air outlet is directly discharged to the outside, and the aerosol concentration of the air outlet is 2% of the background air aerosol concentration.**
- **PAP works continuously for 500 hours. After cleaning and drying, it still maintains the same interception and disinfecting efficiency.**



PAP can be reused after multiple cleaning and drying



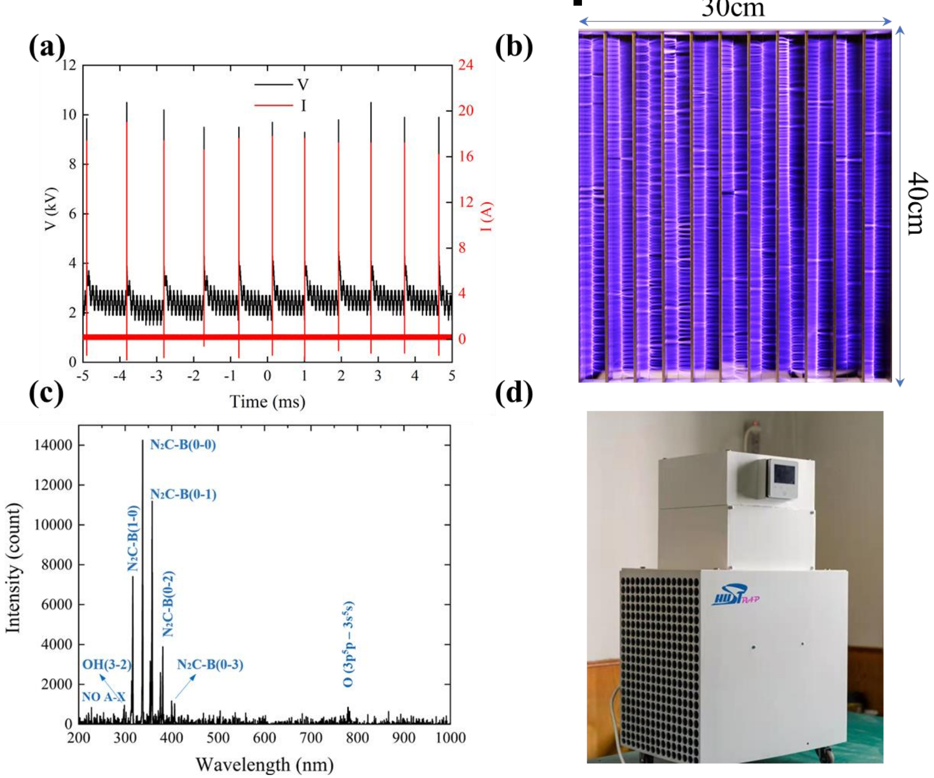
Schematic diagram of using PAP to realize negative pressure experimental ward



PAP outlet does not contain aerosols >1 μm

2.9 2nd generation of PAP

- We developed a nanosecond pulse power supply with a rising edge of 25ns, a peak voltage of 10±0.5kV, and a frequency of 1.1kHz to drive a uniform plasma array of 30 cm*40 cm to achieve efficient treatment of aerosols.
- The 2nd generation of PAP was developed based on this ns pulse power supply and uniform plasma array. **It kills 99.4% of the H1N1 virus in 1 hour in a 20m³ aerosol test environment** and has the potential to further improve the virus-killing efficiency.



2nd generation of PAP

Test report of killing H1N1 virus aerosol by PAP

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Summary and Outlook

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Summary and Outlook

Summary

1. Plasma can effectively disinfect a variety of bacterial aerosols
2. Plasma enables fast charging and interception of aerosols
3. Using AI to assist in optimizing the working parameters of PAP
4. PAP has the advantage of low-cost reuse

Outlook

1. Precise measurement of plasma active components
2. Microscopic mechanism of disinfecting PMA by plasma
3. Electromagnetic compatibility of high voltage power supplies, motors and air monitoring equipment in confined spaces
4. Research and development of small high-efficiency high-voltage power supply

Thank You

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