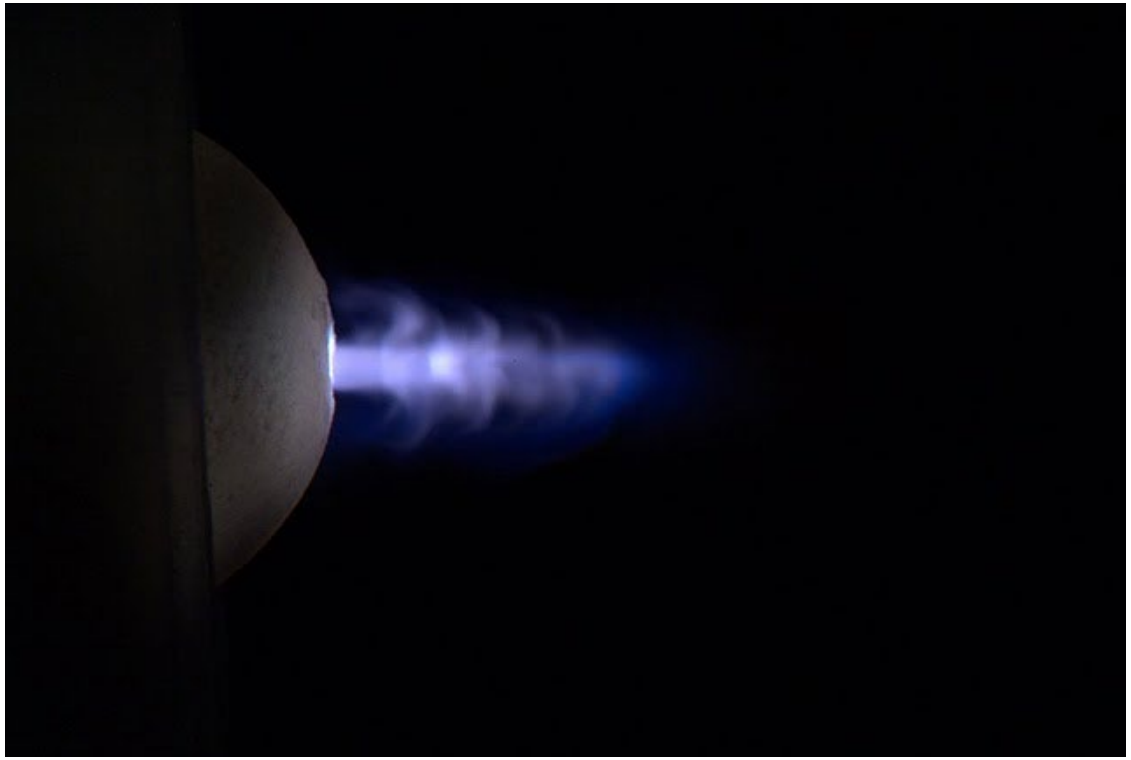
NATIONAL ACADEMIES
Sciences
Engineering
Medicine

Plasma sterilization

Danil Dobrynin

Tokyo Electron America inc., Austin, TX



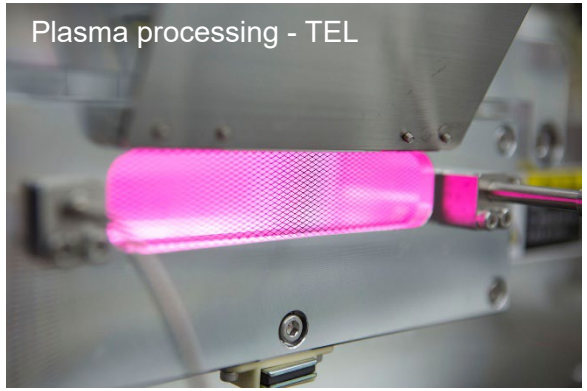
What are plasmas

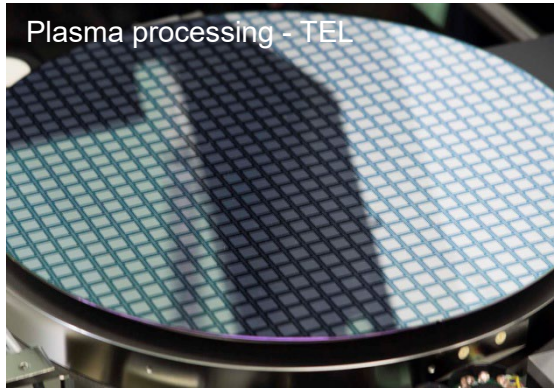
- *Low temperature plasmas* are ionized gases that are created by application of electric fields to accelerate electrons and ionize gas







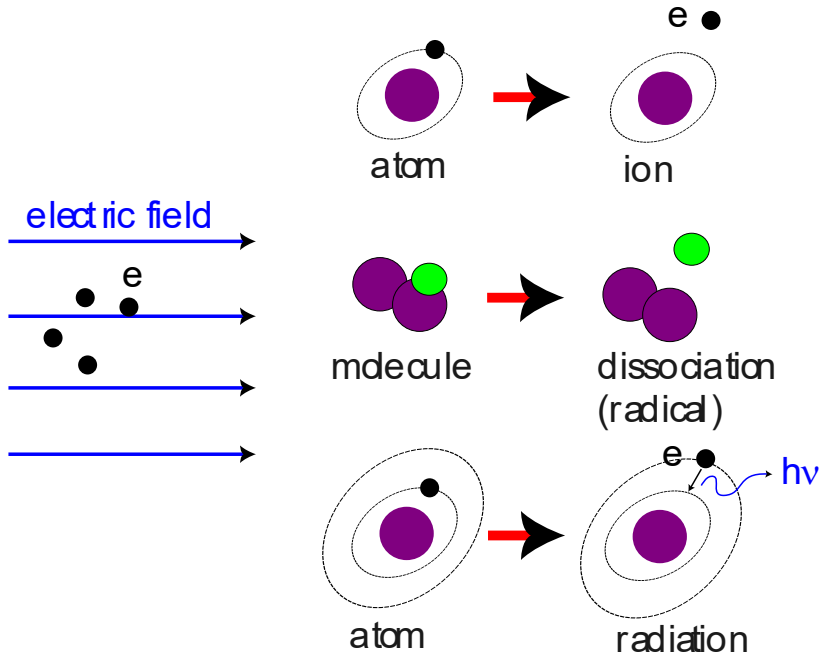


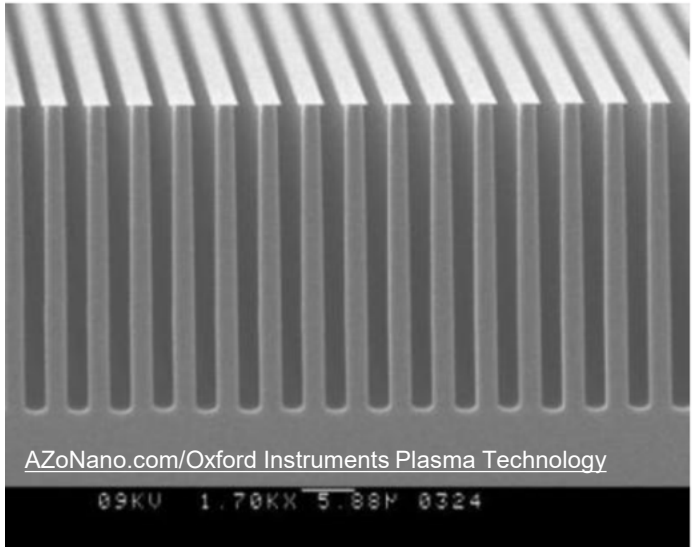


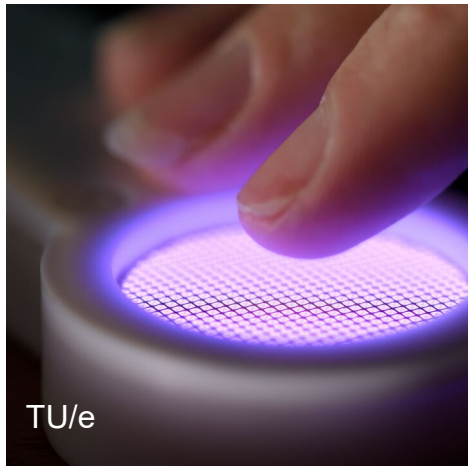


Low temperature plasma physical and chemical uses

- Low temperature plasmas are employed for ionization (e.g., production of fast ions for etching), reactivity (e.g., production of reactive species for treatment), radiation, and heat



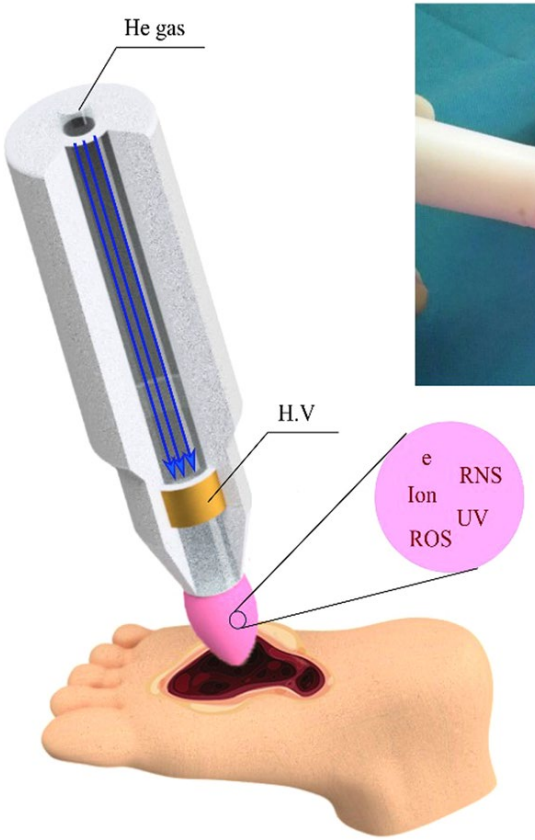






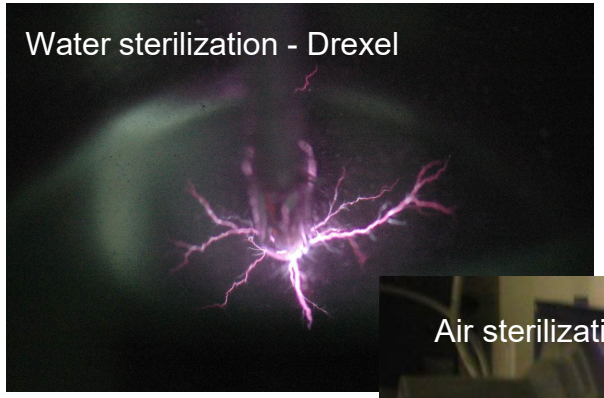
Selectivity of plasma treatment

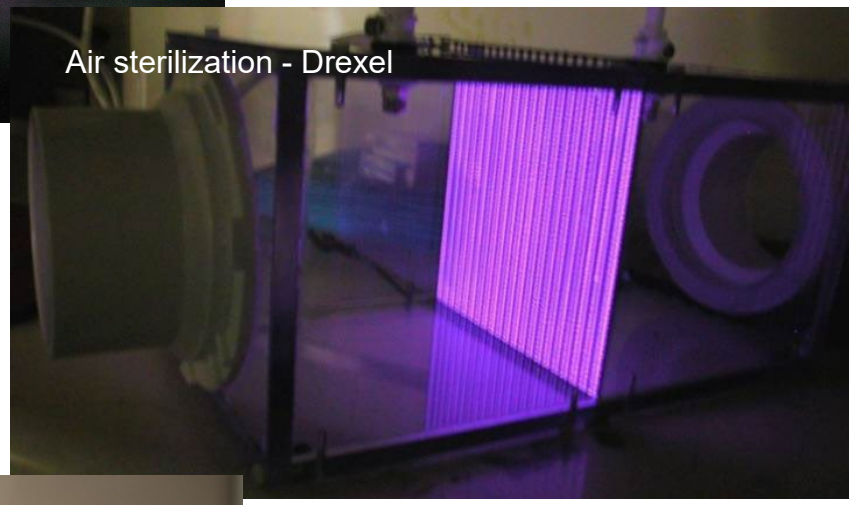
- Plasma medicine

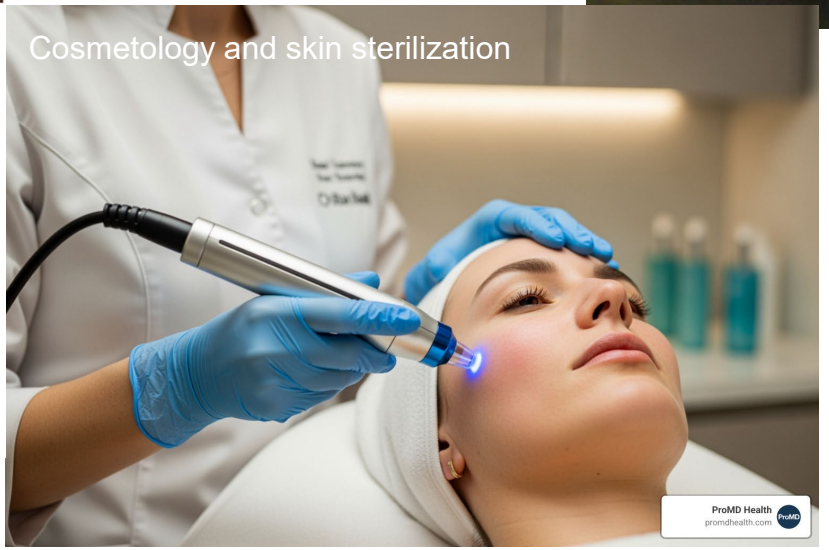




Wound healing: Mirpour, S. et al. Sci Rep 10, 10440 (2020)

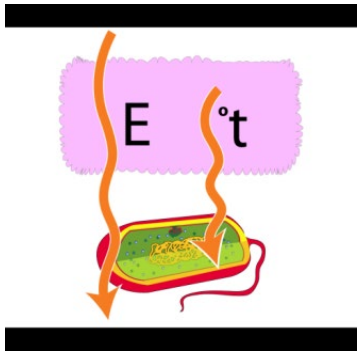




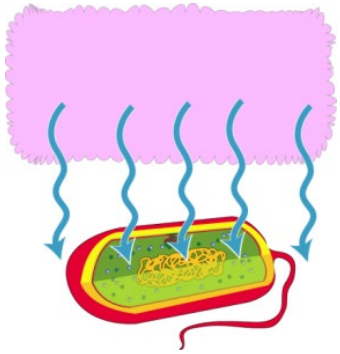


How Can Sterilization Be Achieved?

Sterilization Classification	Traditional Method	Mechanism
Physical	Dry Heat	Denaturing of proteins, lipids, nucleic acids, etc. through oxidation
	Moist Heat	denaturing and damaging of enzymes, proteins.
	Ionizing Radiation	Single and double strand breaks from direct interaction or indirect effects of free OH radicals, H radicals, and H2O2
Chemical	Ethylene oxide	alkylation of proteins vital to the cell reproduction process
	Hydrogen Peroxide	oxidation of DNA, proteins and membrane lipids
Mechanical	Filtration	a barrier permits small molecules and particles to pass while retaining larger particles

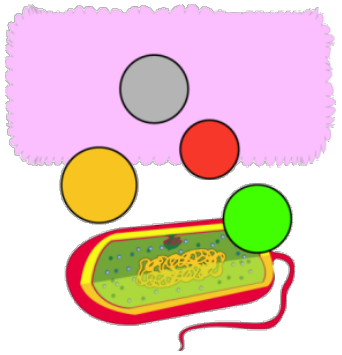


Global effects:
1. E-field
2. Temperature
Electroporation
Surface heating (cooking)

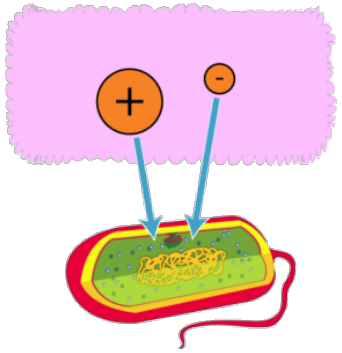


UV (180-340 nm)
VUV (110-180 nm)

• DNA damage



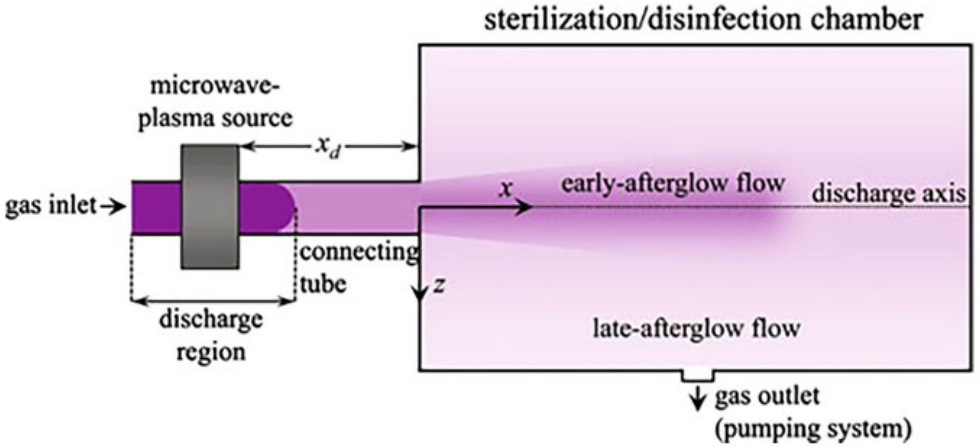
Radicals
1. Long-living (O3, NO, HO2,..)
2. Short-living (OH, O,…)
Lead to erosion w/o reaching DNA

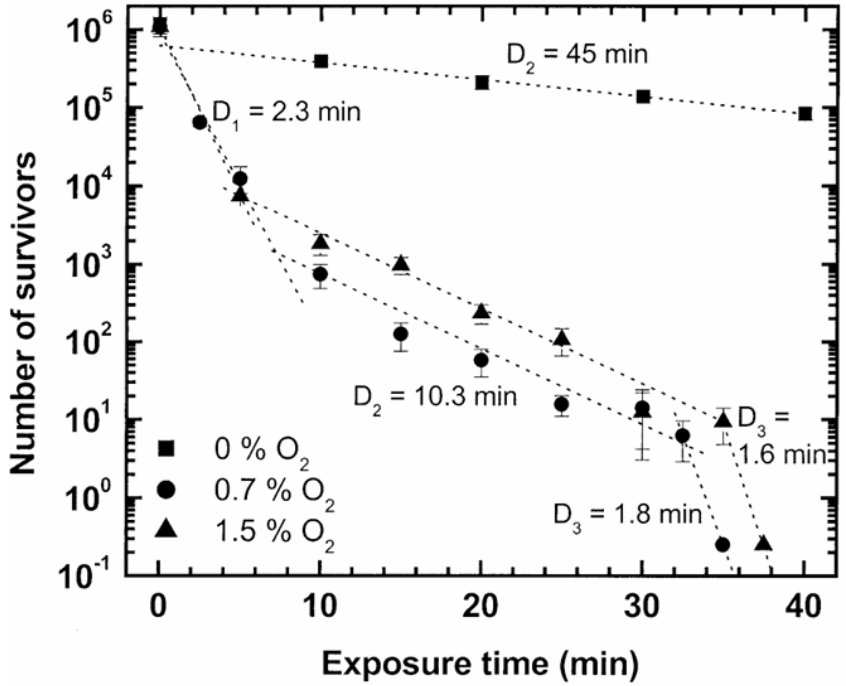


Charged Species
(ions and electrons)
Ion Bombardment
Etching

Low pressure plasma sterilization

- Considered for decontamination of interplanetary space probes and the sterilization of medical tools – 1960s and renewed early 2000s
- Low pressures ~Torrs (10^2-10^3 Pa) $Ar/O_2/N_2$ RF or MW plasmas with power of ~0.1-1 kW
- Sterilization typically achieved in tens of min (afterglow) or seconds (direct) for spores (e.g., *Bacillus subtilis*)

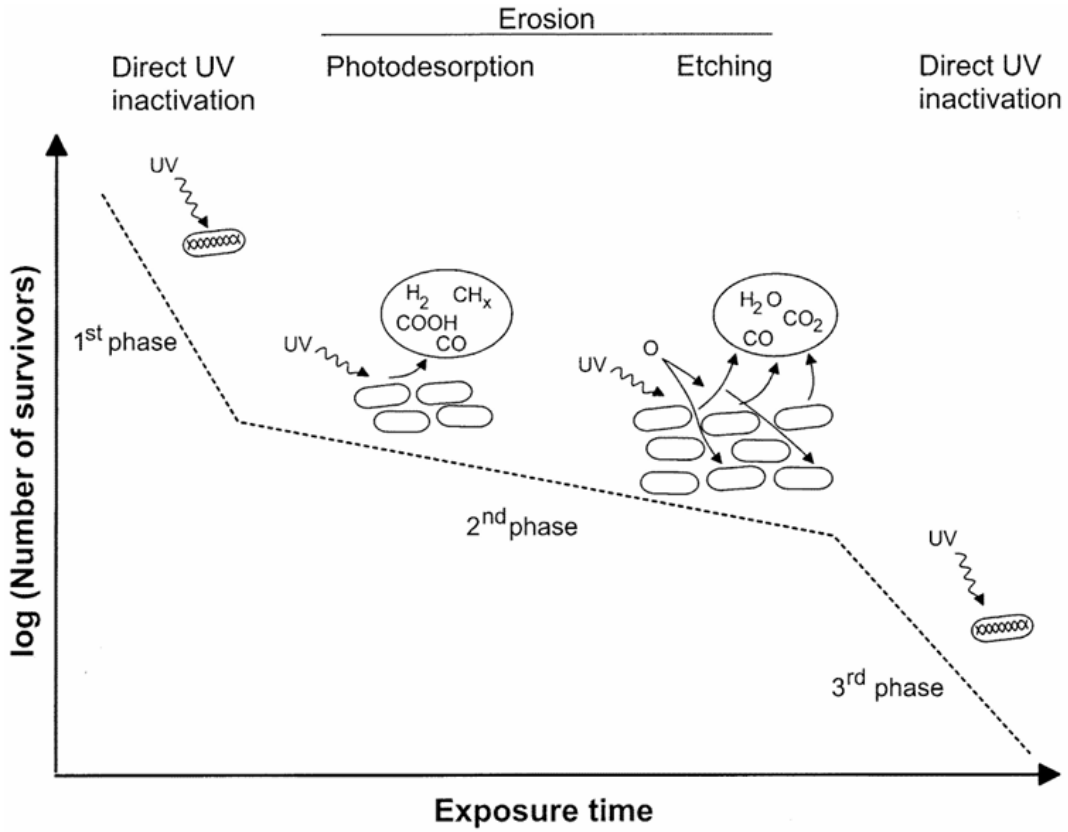




N. Philip et al, IEEE Trans. Plasma Sci. 2002, 30, 1429
M. Laroussi, Plasma Process. Polym. 2005, 2, 391–400
M. Moisan et al, Eur Phys J Appl Phys 2013, 63, 10001.

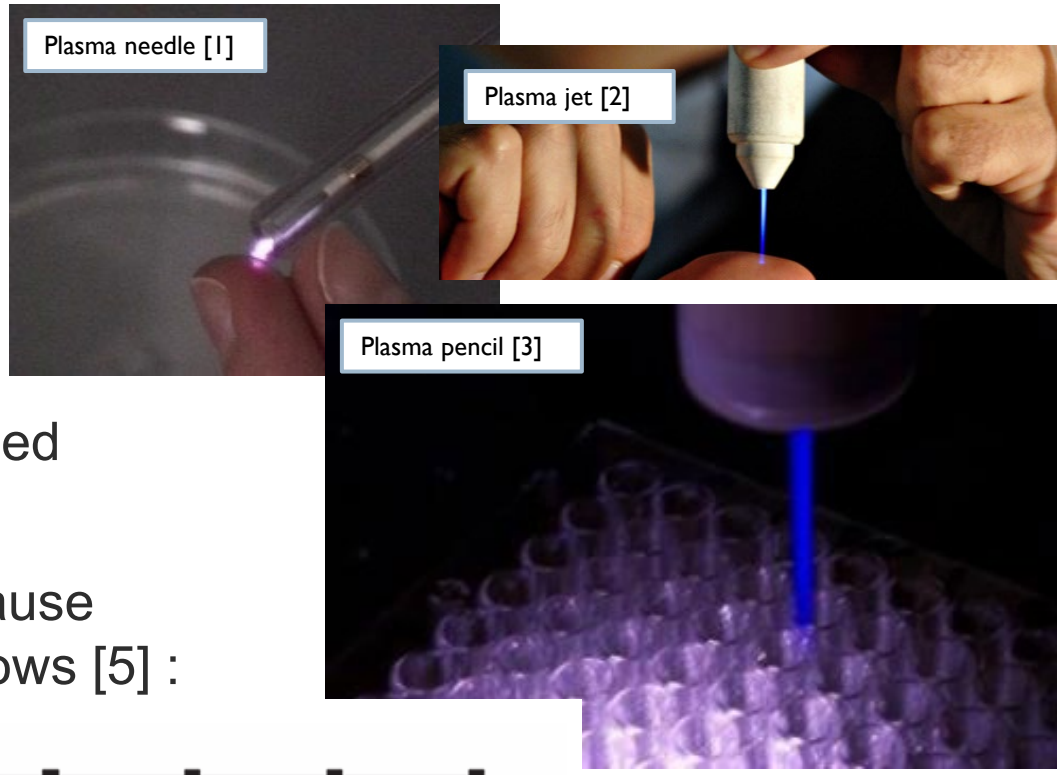
Low pressure plasma sterilization - mechanisms

- Direct destruction of the genetic material of the spore by UV irradiation
- Erosion of the micro-organisms or material covering them, atom by atom, through etching
- The kinetics of phase 3 is again direct inactivation of the genetic material by UV. Phase 3 starts when the last few surviving spores have been sufficiently eroded for the UV photons to reach the genetic material.



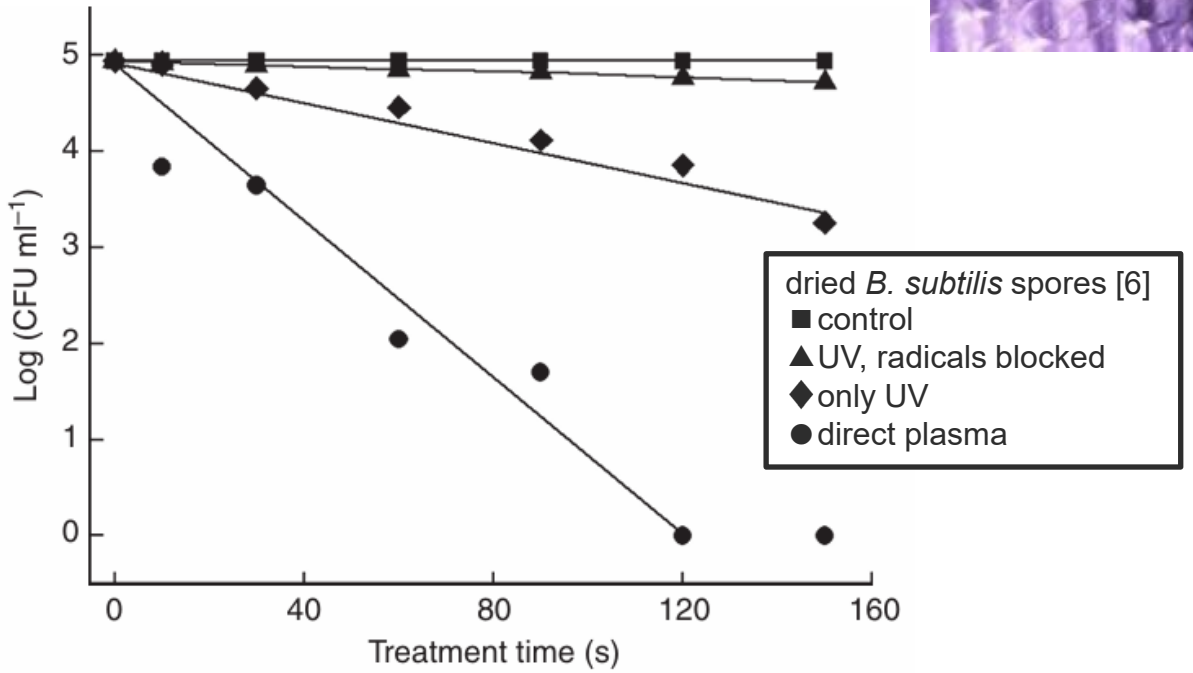
N.Philip et al., IEEE Trans. Plasma Sci. 2002, 30, 1429
M. Laroussi, Plasma Process. Polym. 2005, 2, 391–400

Atmospheric pressure plasmas



- High pressure – higher densities of reactive species – sterilization in seconds
- Air or Ar/He with O2/N2 typically ~SLM flows, RF or pulsed ~few-tens W
- From the plasma (chemical) point of view, agents that cause bacterial death or injury can be roughly classified as follows [5] :

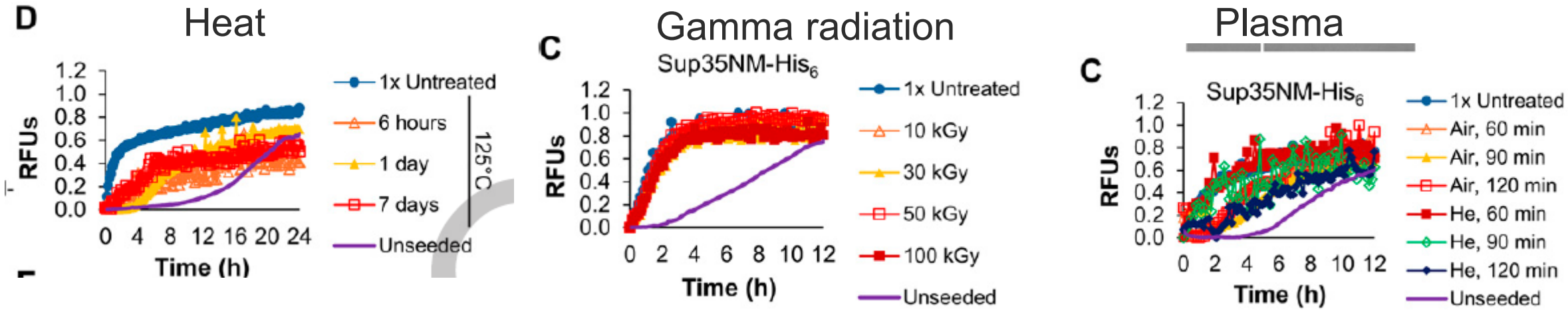
1. heat
2. desiccation
3. UV radiation
4. free radicals
5. charging



1. E Stoffels, *Journal of Physics D: Appl Phys*, 2003
2. M.G. Kong, *Applied Physics Letters*, 2007
3. M. Laroussi et al., Int. J. Mass Spectrom., 2004
4. E. Stoffels, Y Sakiyama, and D. B. Graves, IEEE TPS, VOL. 36, NO. 4, AUGUST 2008
5. Hong et al, Letters in Applied Microbiology 48 (2009) 33–37

Sometimes it does not work

- Prions – non-living infectious proteins, represent hardy challenge agents
- Resistivity to heat (200 C), 100 kGy of gamma irradiation, or 120 min of exposure to ambient air or wet He plasma



1. Hirsch AL, Seto EP, Schubert WW, et al. Impact of Various Inactivation Approaches on Surrogate Proteinaceous Particles for Sample Return Missions. Astrobiology. 2026;26(2):132-147

Atmospheric pressure plasmas

- Longer exposure – minutes – erosion and complete destruction

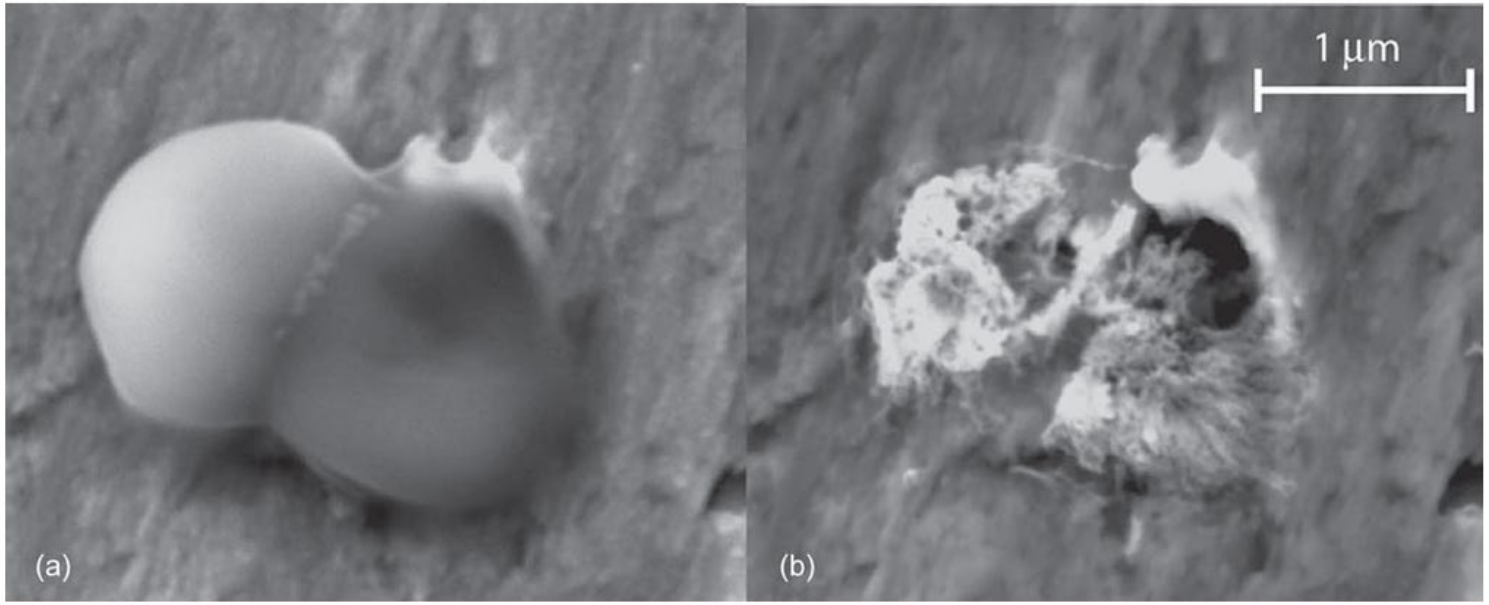
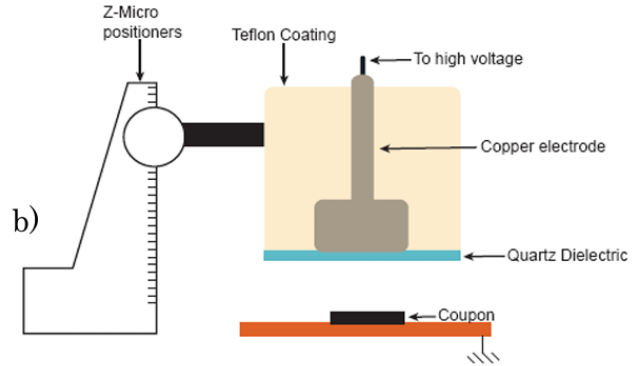
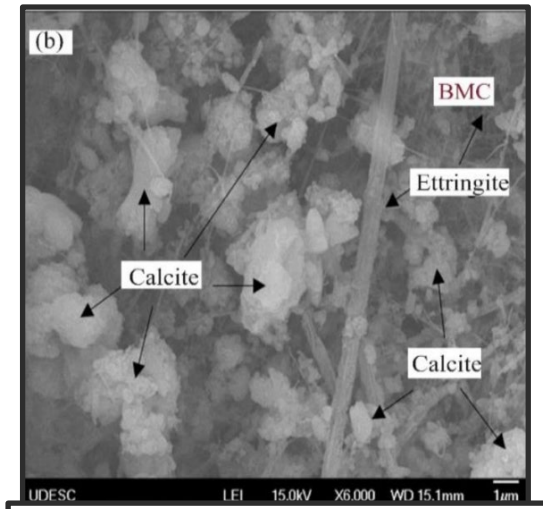


Fig. 4. SEM images of *Deinococcus radiodurans* on blue steel (a) before and (b) after 30 min of DBD plasma treatment.



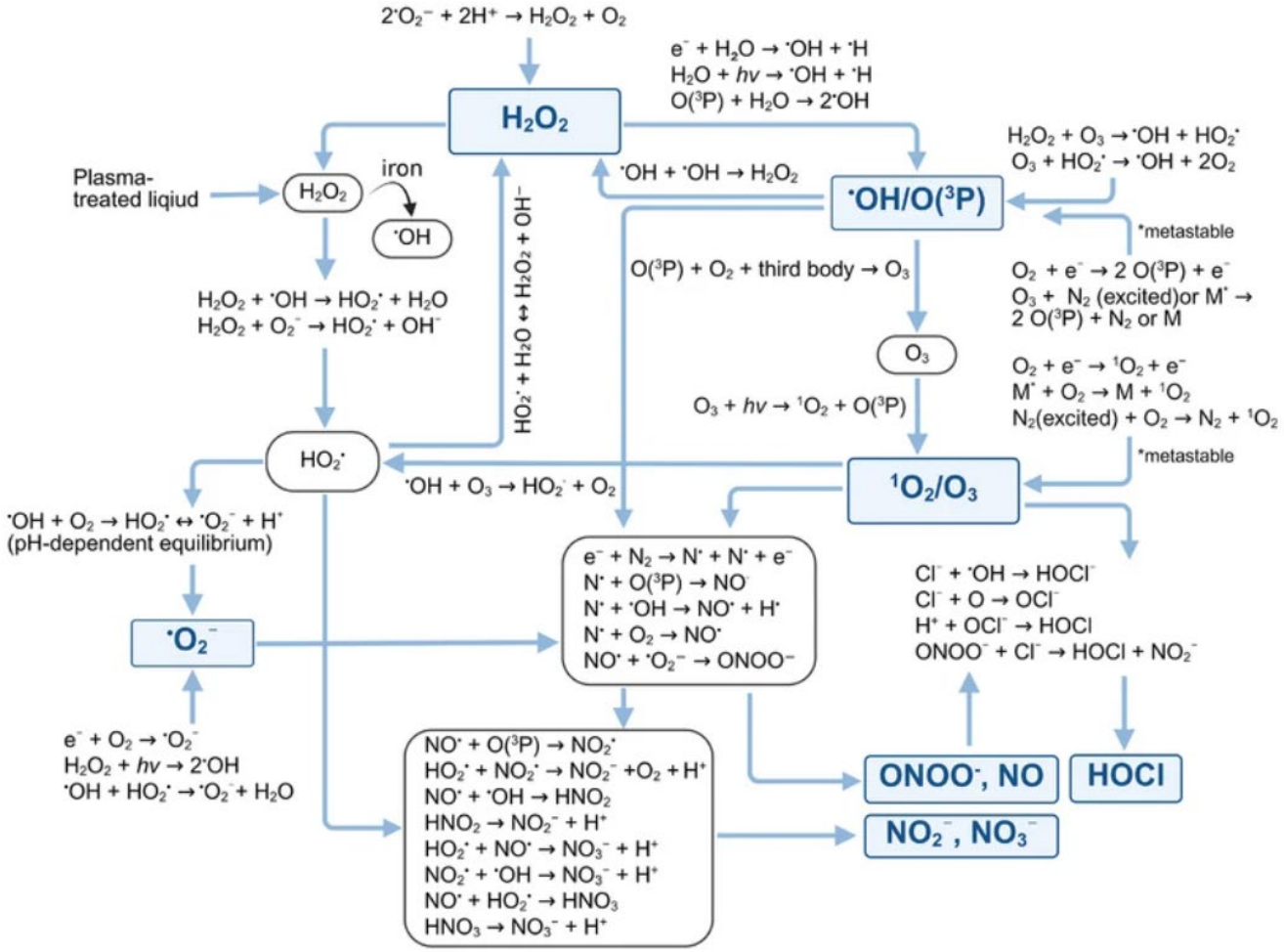


biomineralized concrete – bacteria inside CaCO3 or SiO2?

1. M. Cooper et al, IEEE transactions on plasma science, 37(6), 866-871.
2. dos Santos J. R. et al, Ambiente Construído 25, 2025

What makes plasmas so active

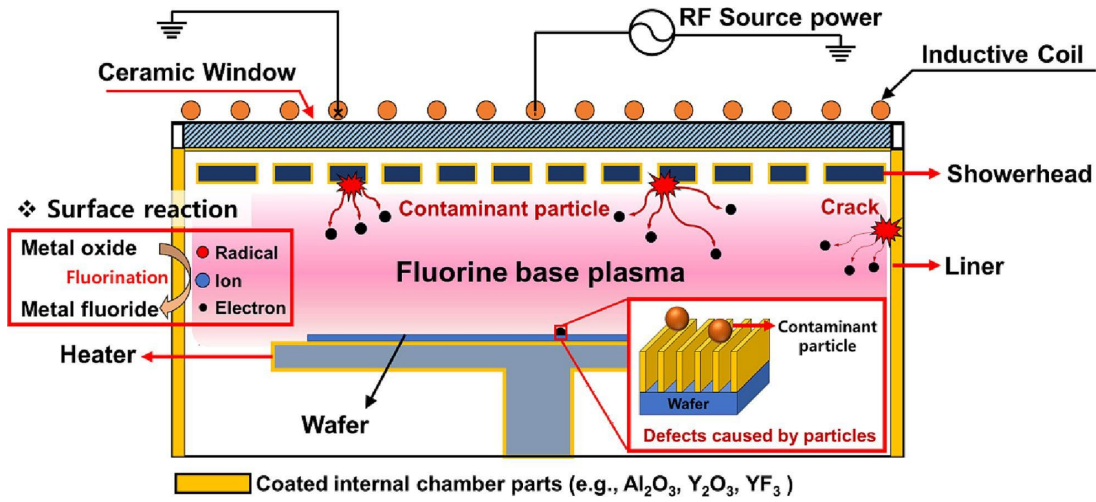
- Plasma reactive species drive oxidative damage to proteins, amino-acids, lipids, DNA…
- Oxidation: $OH + R \rightarrow ROH\ (radical)$
- Dehydrogenization: $OH + RH \rightarrow R + H_2O$
- Very reactive with rates limited by diffusion: e.g., OH with organic molecules ~10^{10} $M^{-1}s^{-2}$
- But… almost no effect on inorganic material (except ion etching)



Mohsen A. et al, (2025) Advanced Healthcare Materials. 15.

What can we learn from semiconductor industry?

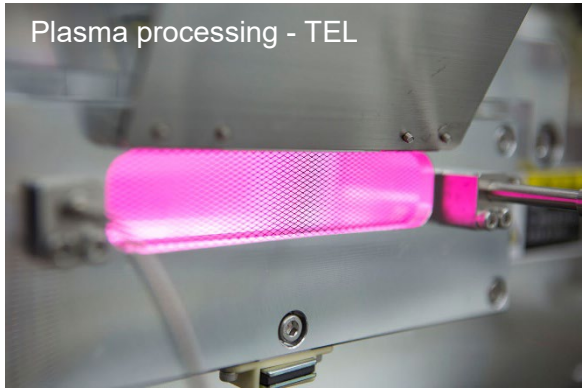
- Plasma cleaning systems are widely in use in the semiconductor industry as a means of mass-producing printed circuit boards by etching away unwanted material – for example, after thin film deposition (chamber cleaning)
- Plasma-generated active fluorine species react with material to produce gas-phase products that are then evacuated from the chamber
  - Atomic F is highly reactive and will break down all organic and inorganic bonds.
  - The products of these reactions are stable molecular gasses which are easily evacuated from the test chamber.

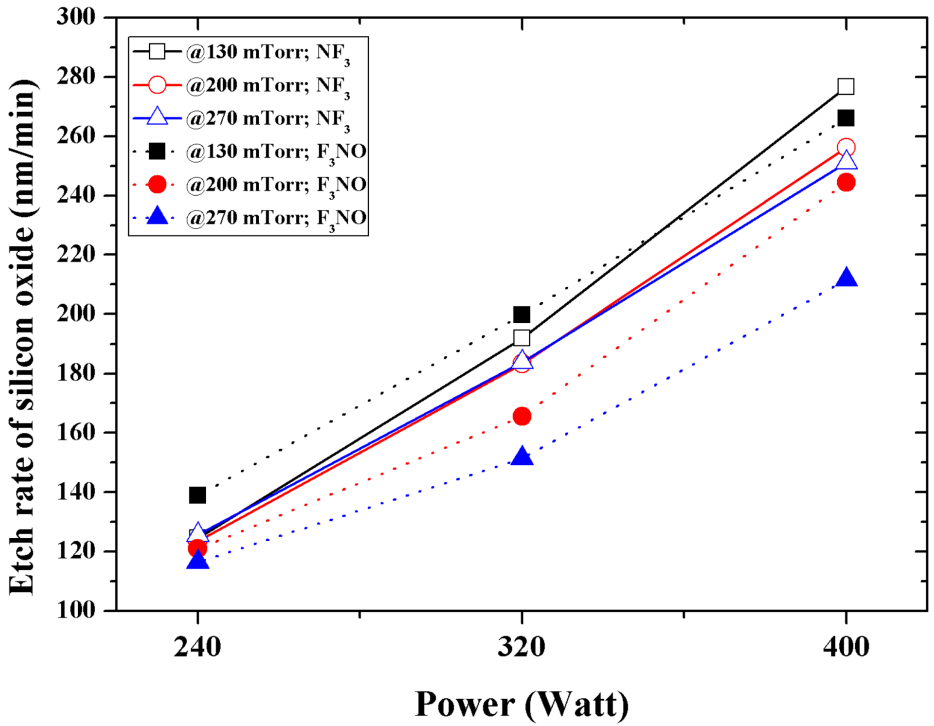


1. J. So et al., Applied Surface Science 629 (2023): 157367.

Plasma cleaning in industry

- Typical plasma chamber dimensions ~300-400 mm
- Vacuum – fraction of Torr (<100 Pa)
- RF plasmas 100-1000 W
- Process requires fast treatment – seconds or minutes
- $e + NF_3 \rightarrow e + NF_2 + F$
- $Si(s) + 4F(g) \rightarrow SiF_4(g)$



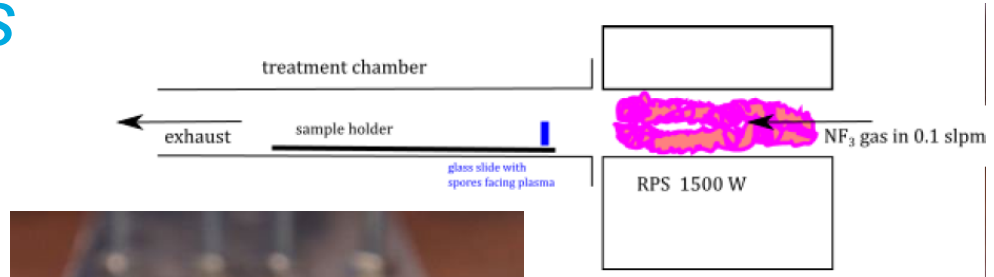


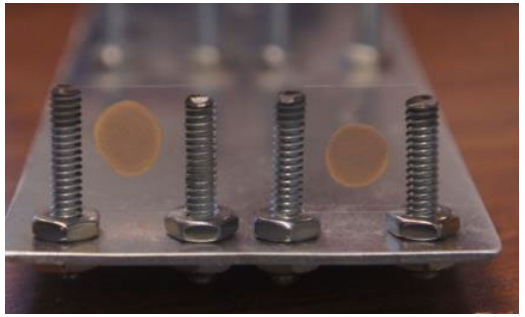
Elements	Fluorides
Al	AlF_3
As	AsF_3
	AsF_5
C	CF_4
Cr	CrF_2
Cu	CuF
	CuF_2
Ga	GaF_3
Ge	GeF_4
In	InF_3
Mo	MoF_5
	MoF_6
	MoO_2F_2
	$MoOF_4$
P	PF_3
	PF_5
Si	SiF_4
Ta	TaF_5
Ti	TiF_4
W	WF_6
	WOF_4

1. W.-J. Kim et al, Materials 2021, 14, 3026

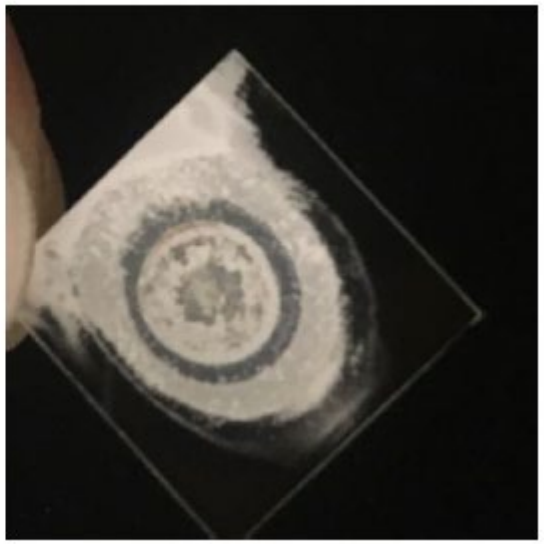
NF_3 plasma cleaning - *B. atrophaeus*

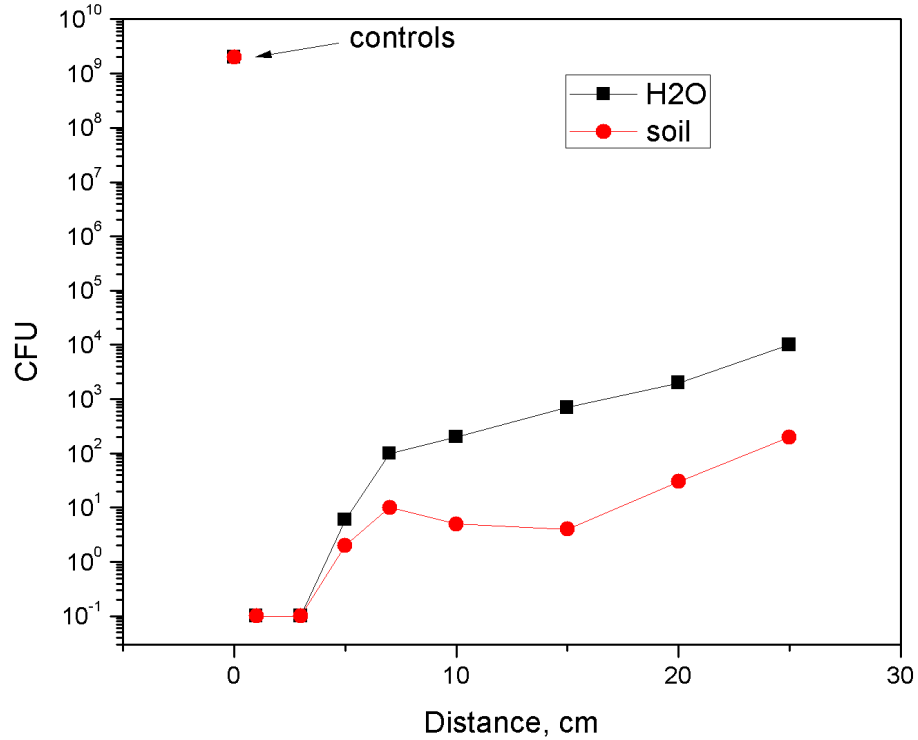
- *B. atrophaeus* ~10^9 CFU with and without Martian soil simulant dried on grass slides
- Remote plasma treatment 0.1 slm NF_3 at ~1 Torr 1.5 kW







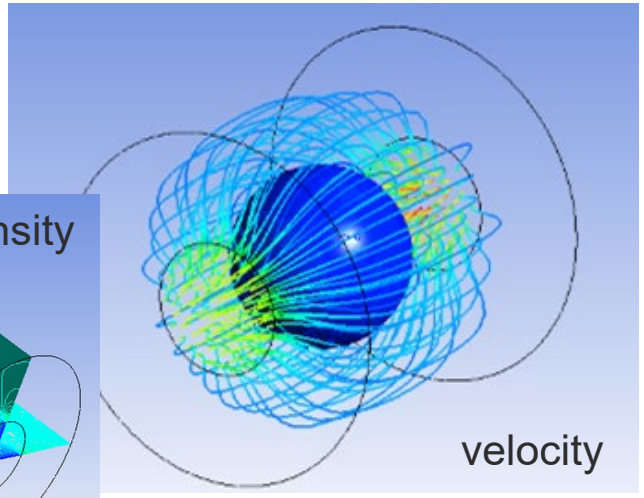


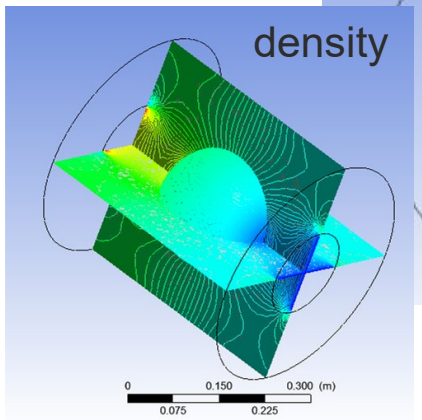


Challenges of plasma sterilization for sample return

- Effects of reactive species depends on their number – limited by recombination in transport
- Lower pressure – longer transport time, but lower densities
- Power dependence: lower power – less radicals, longer treatment with more losses (recombination)
- Atmospheric pressure: 1 W/cm^3 → ~1 kW for OS
- Low pressure: 0.1 – 1 kW in 5000 cm^3 chamber → 10-100 W for OS
- Gas tank, power and plasma generator (weight, space…)
- Uniformity of treatment (diffusion, transport)







Concluding remarks

- Plasma treatment affects surface (not volumetric effect, except when treating gas or liquid)
- Can be very selective (bacteria vs cells) or etch away almost everything
- Plasma chemistry and surface chemistry is known
- Challenge – engineering (mechanical and electrical constrains, transport organization)

