

Low Temperature Plasma Science to Advance Human Health and Enable a Sustainable Future

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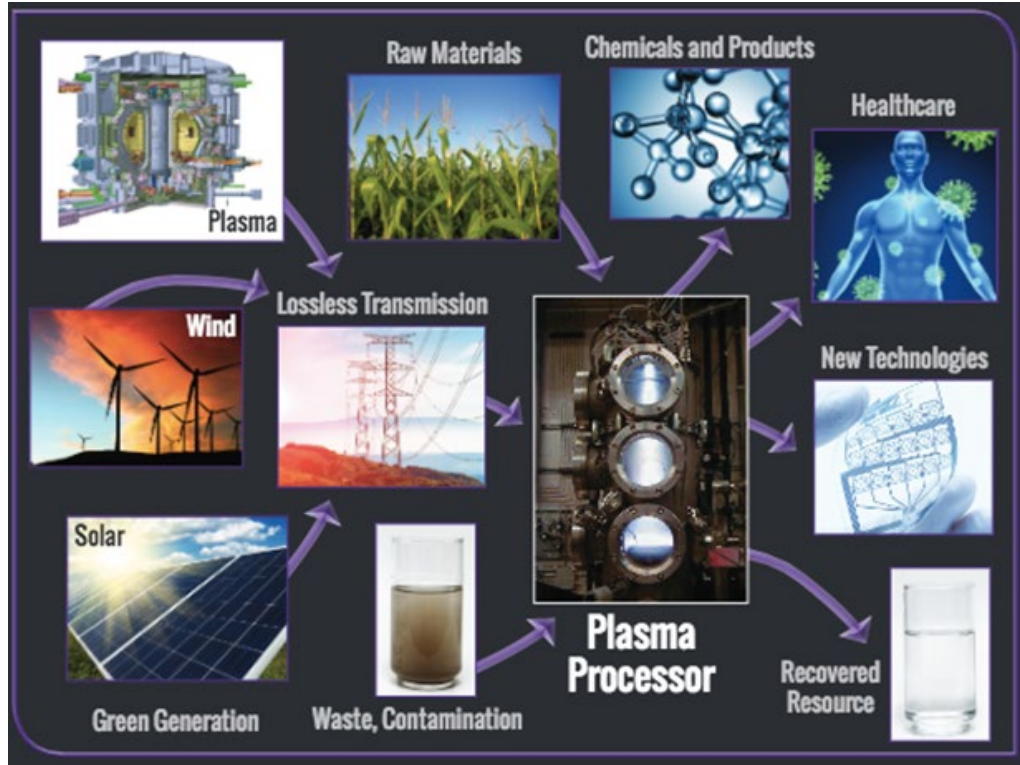
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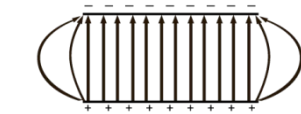
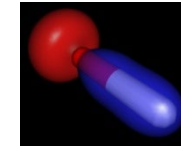
Electrons to Transfer Electrical Power into X

- Electrical energy is used to create 'hot' electrons
- Energetic electrons produce ionization, excitation and radicals leading to plasma chemical reactions



mipse.umich.edu/nsfworkshop

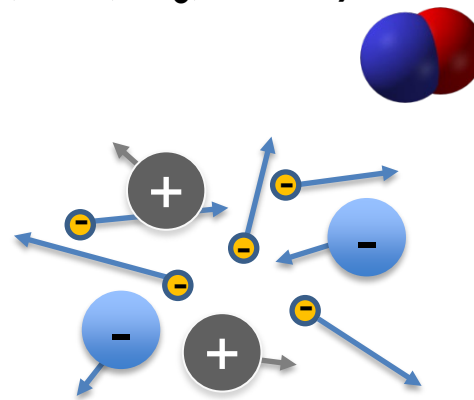
Source of
reactive species
(O, OH, O₃, NO...)



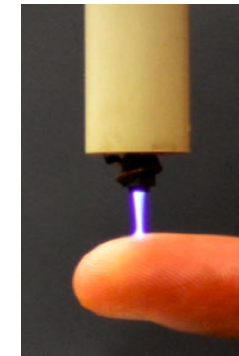
Electric fields



~ T_{room} or
efficient heat
source



Source of charged
particles (e⁻, ions)

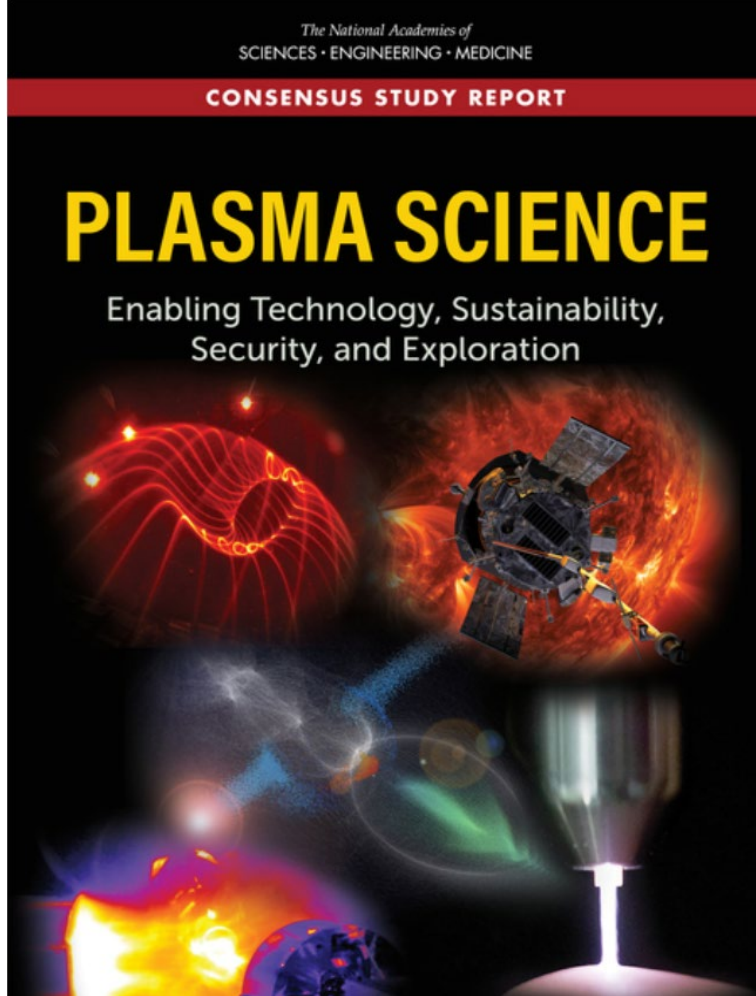


S. Kondeti

Source of (V)UV
photons



NAS Decadal Study: Plasma 2020



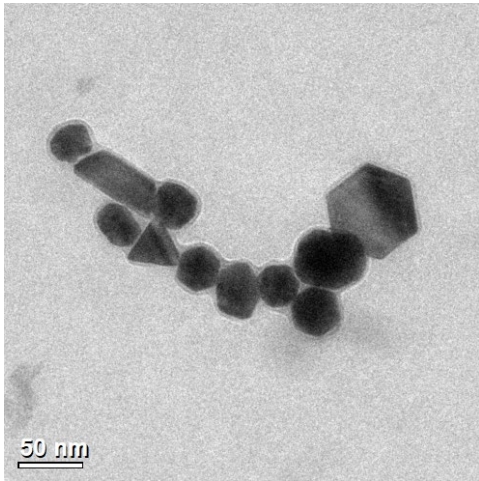
<http://nas.edu/plasma>

Highlighted Opportunities:

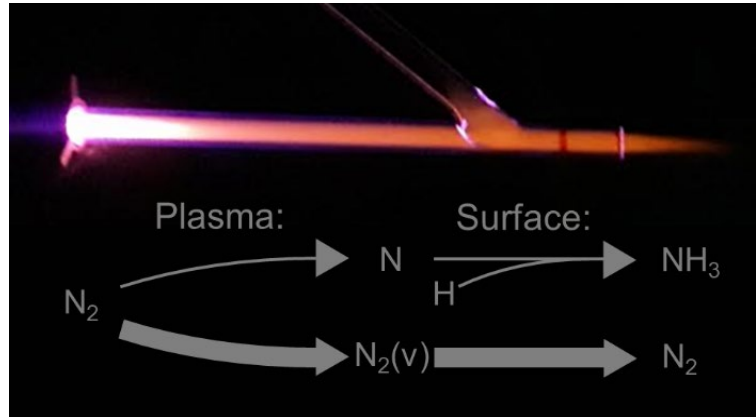
- *Developing **plasma-based tools** for **future health** care and food cycle needs*
- ***Controlling plasma-surface interactions at the atomic level** to enable the **next generation of materials** for quantum computing, new communication, sensor, energy storage and harvesting technologies.*
- ***Electrification of the chemical industry** based on renewable electricity to enable a sustainable society*
- *Enabling **space exploration** and safeguarding communication infrastructure*



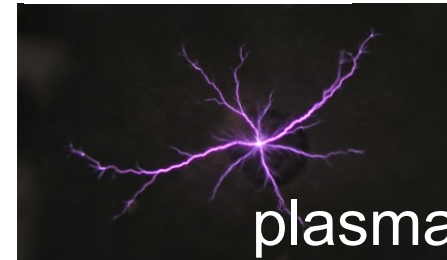
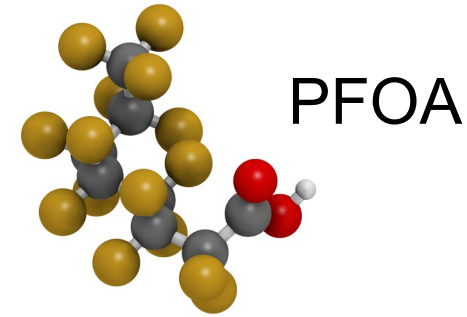
A Quest for Selectivity and Efficiency



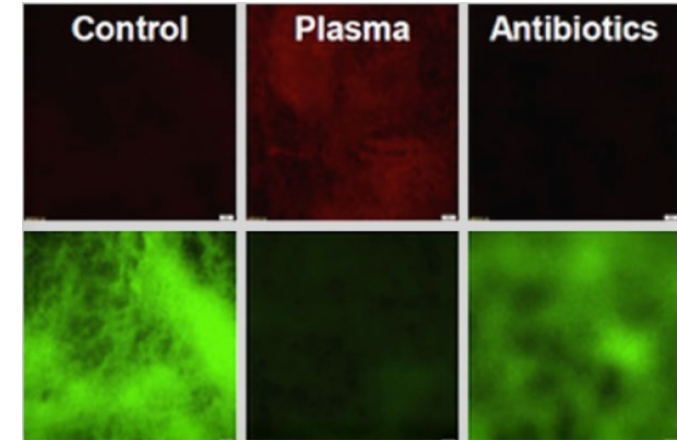
*Material synthesis /
engineering with
property control*



*Plasma catalysis to enable
selective low temperature
molecule generation*



*Pollution mitigation –
defluorination of PFAS*



*Biofilm control – can plasma
selectively inactivate biofilm (in
wound)*

Requires understanding of the fundamental plasma processes enabling applications.



Outline

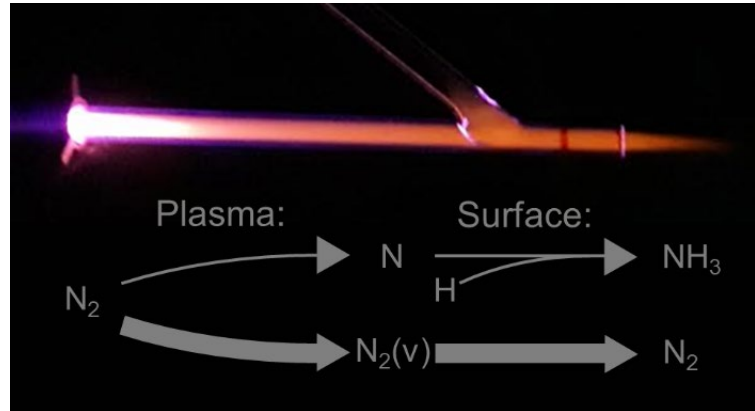
Human Health



- Decontamination (virus)

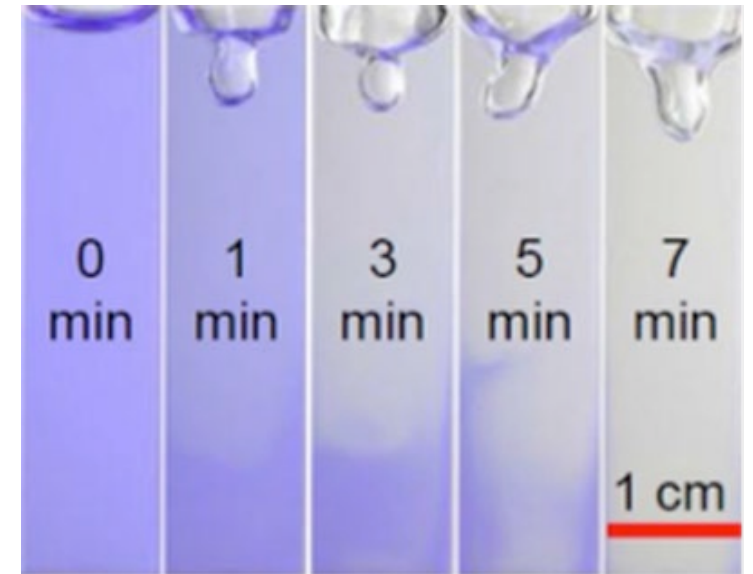
Sustainability

Plasma Catalysis



- Electrification of chemical conversion

Plasma-Driven Solution Electrochemistry



- Liquid phase redox reactions
- Materials synthesis



Outline

Human Health



Gaurav Nayak (ME), Hamada Aboubakr (Vet. Med.), Sagar Goyal (Vet. Med.), Samidha Dabhole (ME), Ankit Moldgy (ME), Jingkai Jiang (ME), Bernard Olson (ME), Montse Torremorell (Vet. Med.) and Peter Bruggeman (ME)



- **Decontamination (virus)**



Food and Food Contact Surface Decontamination

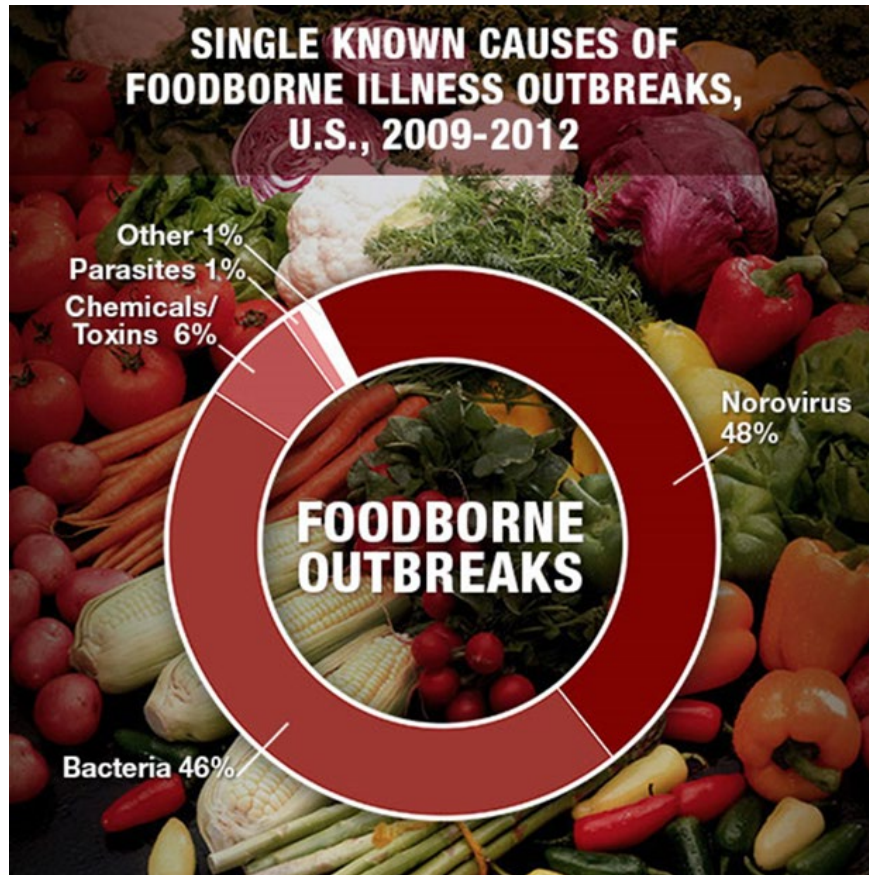
CDC 2014

CENTER FOR DISEASE CONTROL AND PREVENTION



European Food Safety Authority
Committed to ensuring that Europe's food is safe

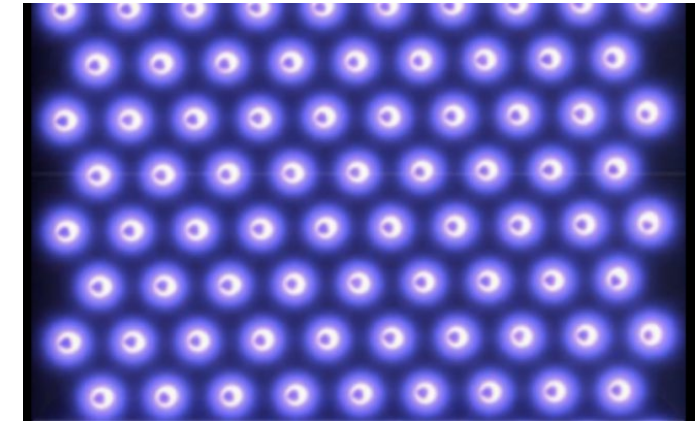
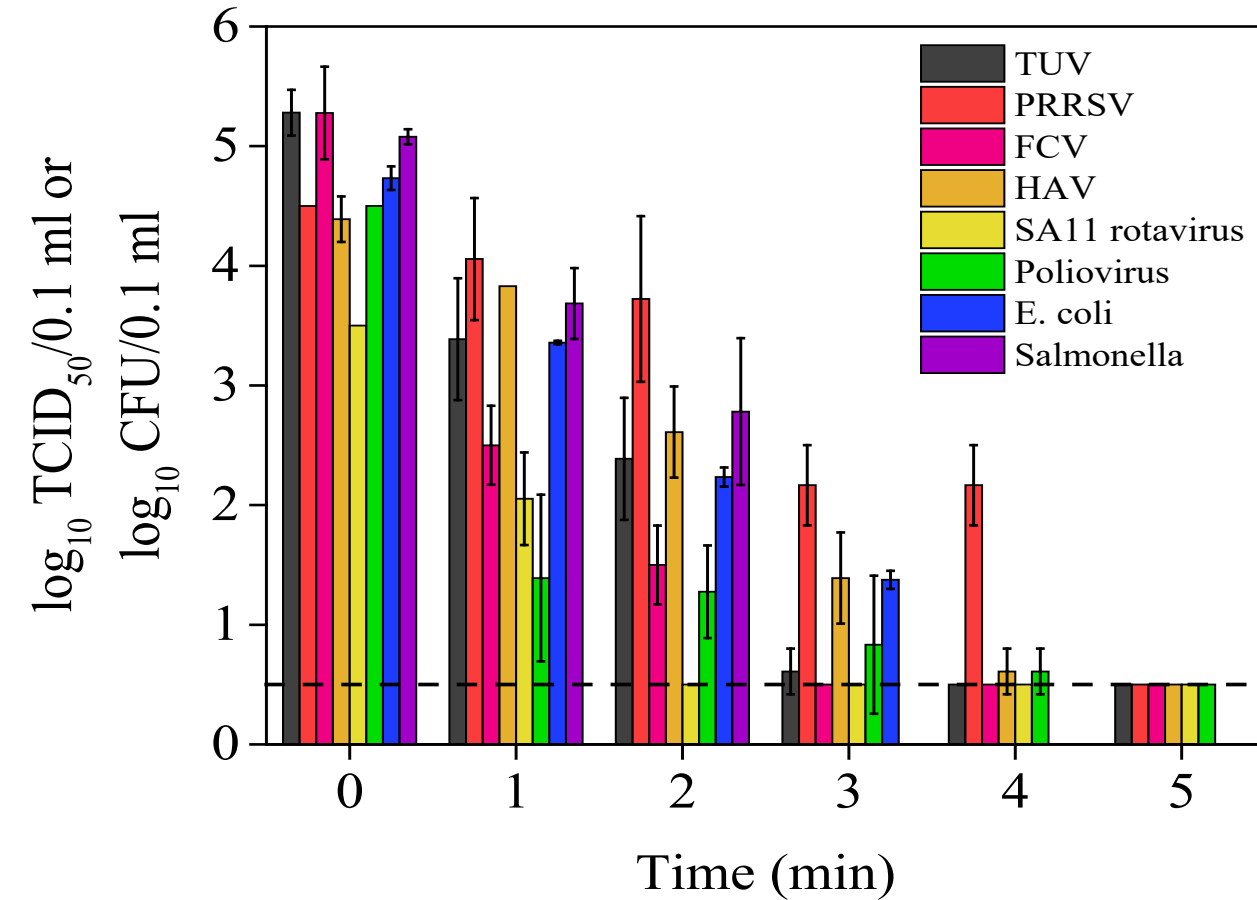
2012



- The annual **economic cost** of foodborne illnesses is approximately **\$77 billion** in the USA (Scharff 2012)
- Enteric viruses, particularly **human norovirus (NoV)** and hepatitis virus type A (HAV), are the leading causes of viral foodborne illnesses
- Conventional disinfection techniques have limitations



Surface Decontamination



DBD

- enveloped and non-enveloped viruses behave similarly (including Human Norovirus)
- selected bacteria: *E. coli* and *Salmonella*.

DBD plasma is highly effective against all investigated pathogens and its decontamination efficacy is largely independent of the virus being treated.



Energy Requirements

Comparison of energy requirements for complete inactivation of FCV-coated stainless-steel discs

Disinfection system	UV-C irradiance ($\mu\text{W}/\text{cm}^2$)	Power or energy	E/V (J/L)	E/A (J/cm^2)
UV-C lamp	340	8 W	-	0.48
Direct DBD	?	1 mJ/pulse	-	1.96
Surface DBD	< 1	0.70 W	131.2	0.66
2D DBD	< 1	14.5 W	53	0.13 – 0.53*

*Estimates based on simple reactor model

Energy cost of plasma is similar to UV-C technology.

A. Moldgy et al, Plasma Process. Polym. e1900234 (2020)

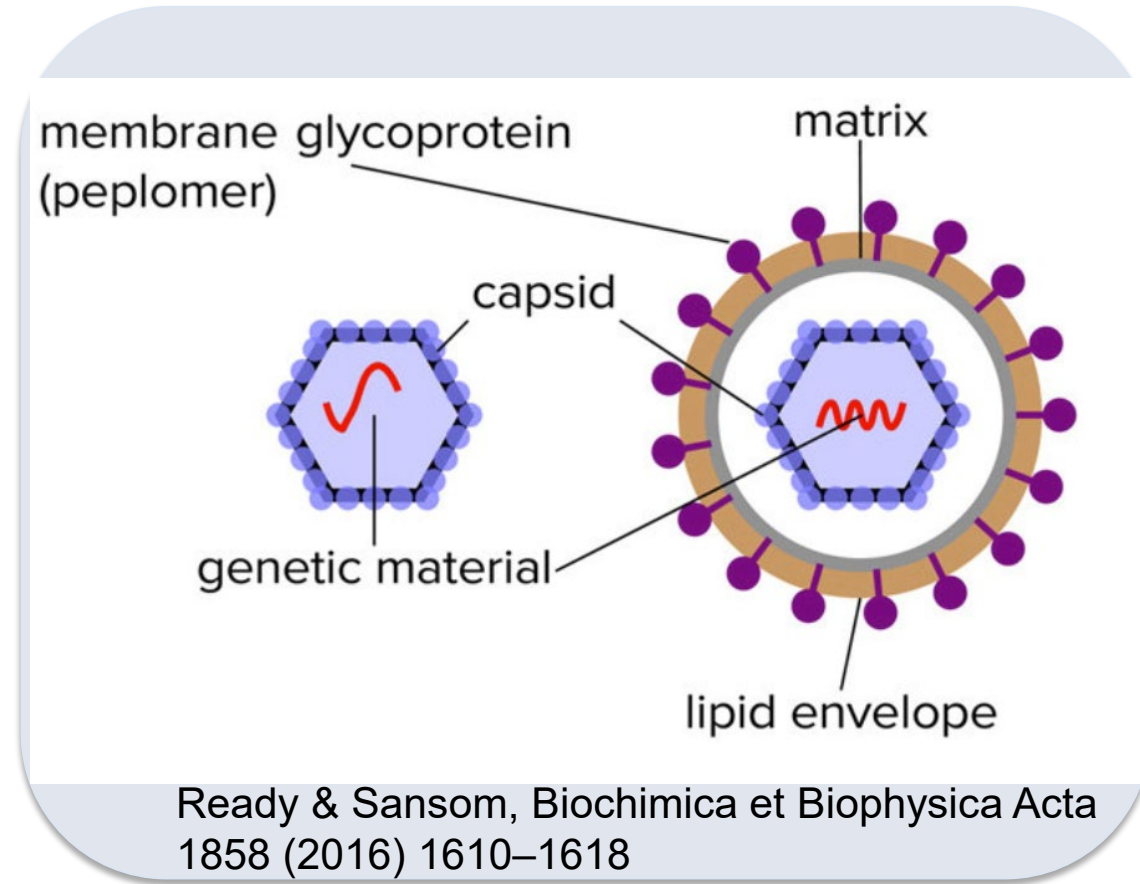


Societal Grand Challenge

- Bioaerosols, major global concern
- Recent Coronavirus pandemic
- 2015 HPAIv outbreaks (Poultry), \$1.6b losses¹
- 2005 PRRSv outbreaks (Pigs), \$560m losses²
- Aerosol transmission over long distances

State-of-the-art

- MERV and HEPA filters
- Huge Δp
- Active virus, while trapped
- Filtration efficacy degrades with loading



¹USDA, APHIS Data from December 2014 through June 17 (2015)

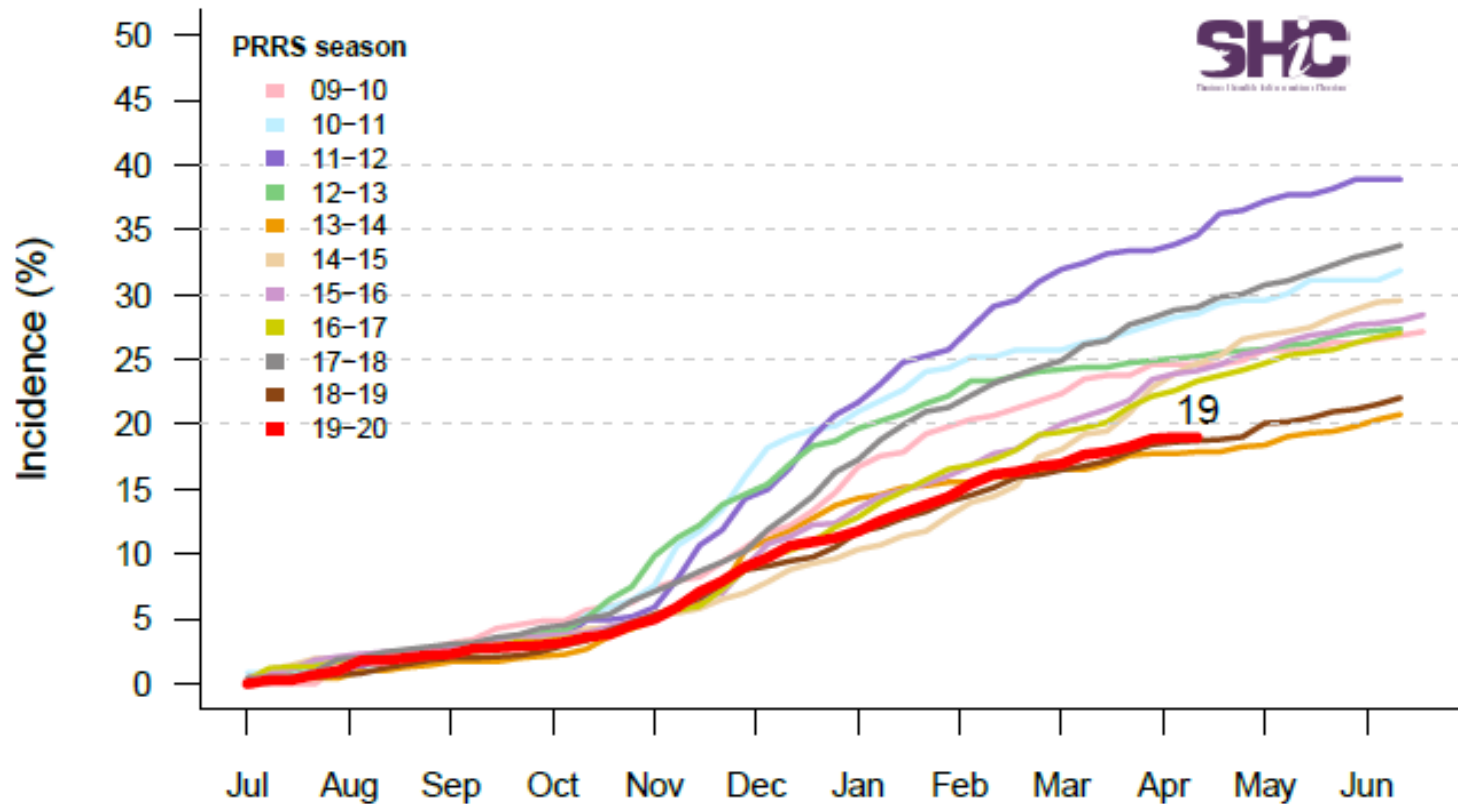
²Neumann *et al*, *J. Am. Vet. Med. A.* **227** 385-392 (2005)



Our Motivation: Swine Industry

- PRRS continues to be # 1 disease in US swine industry

Chart 1 – PRRS cumulative incidence beginning July 01, 2009



- PRRSV control in breeding herds depends on our ability to prevent new virus introductions
- Swine industry has invested significantly in biosecurity to prevent PRRS
- Air filtration has helped decrease the incidence of new PRRSV infections



Plasma control



Gas phase kinetics



Transport



Interface



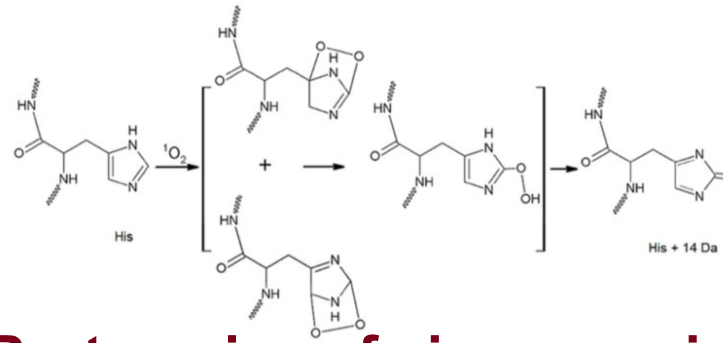
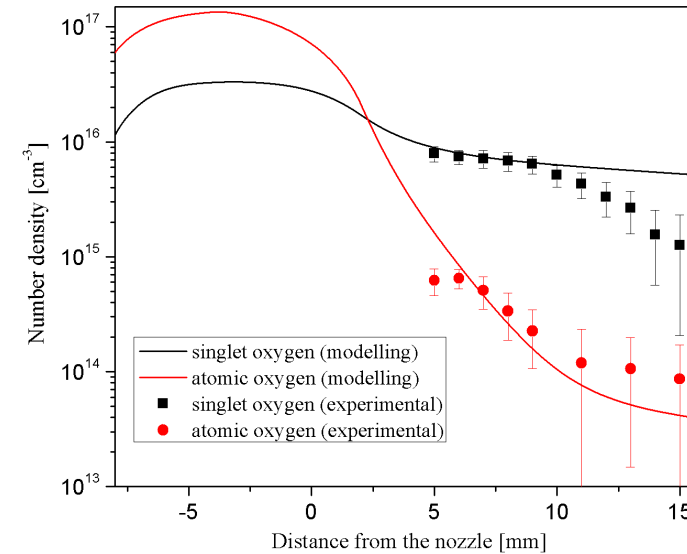
Liquid phase processes



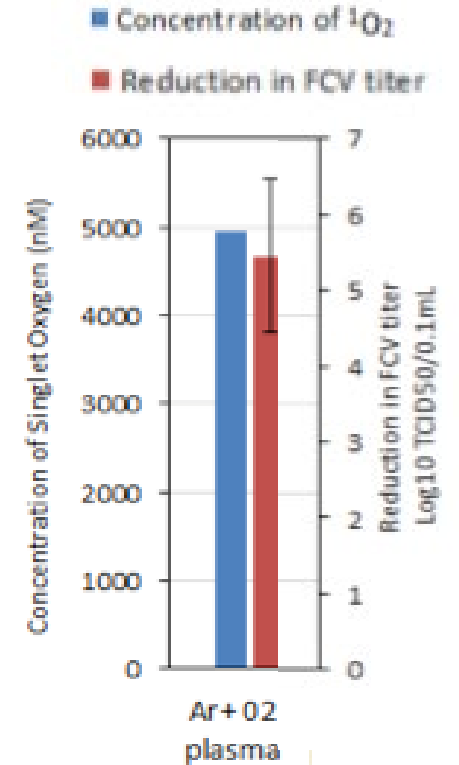
Virus inactivation

Virus Inactivation Mechanism (O_2)

Gas phase plasma measurement + model



Proteomics of virus capsid

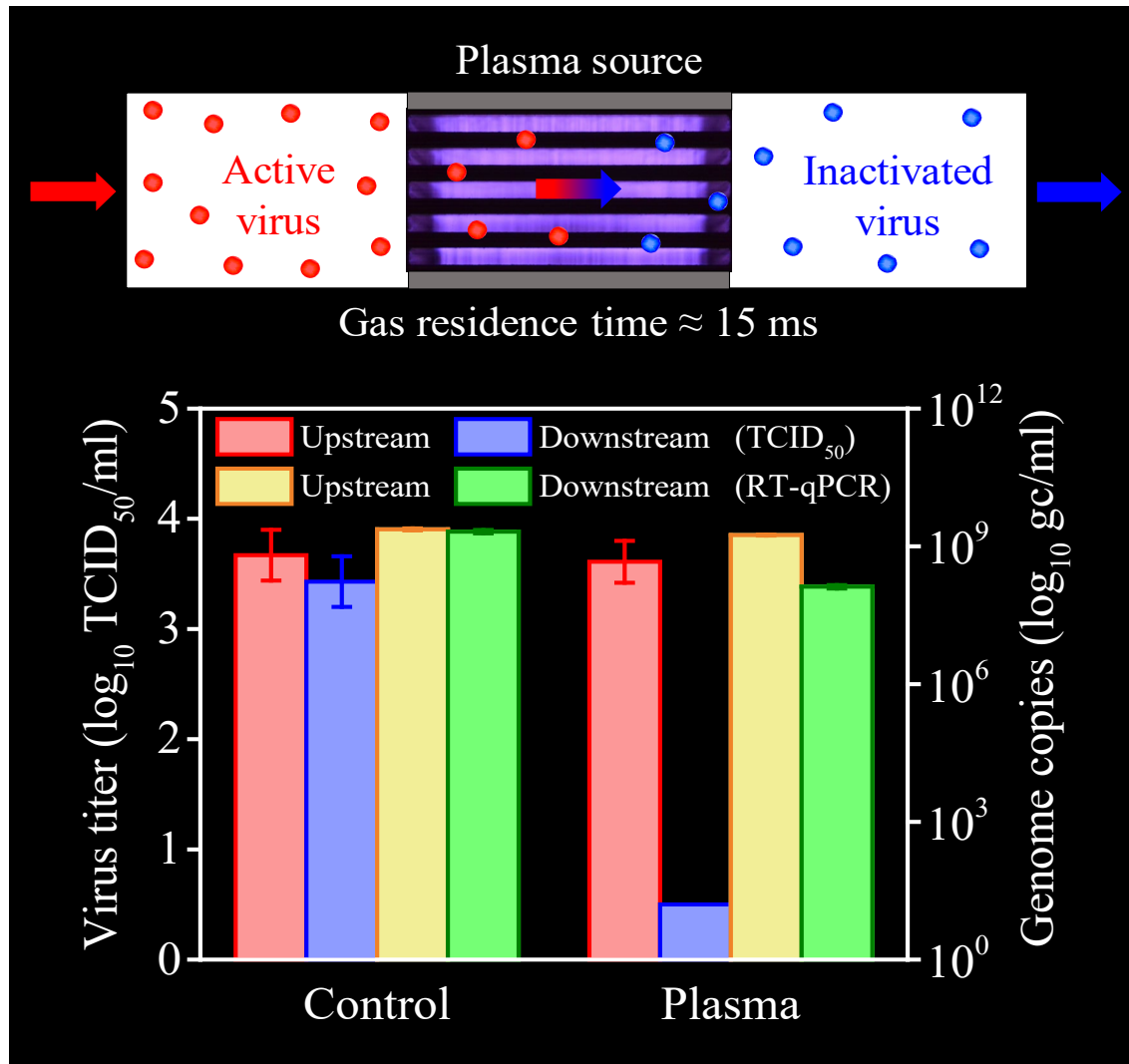


**Liquid phase
 $O_2(a^1\Delta_g)$**

J. Jiang et al, PSST (2020)
Aboubakr et al, JPhysD (2016)



PRRSv Inactivation



- Virus is no longer infectious after plasma treatment
- Independent of power – most likely effective at even lower powers!
- Virus RNA still present (virus is not filtered by plasma)
- Dilution effect, losses to the wall, physical filtration inside reactor
- **NTP approaches HEPA filter efficiency.**
- **Significant lower pressure drop than with filters**

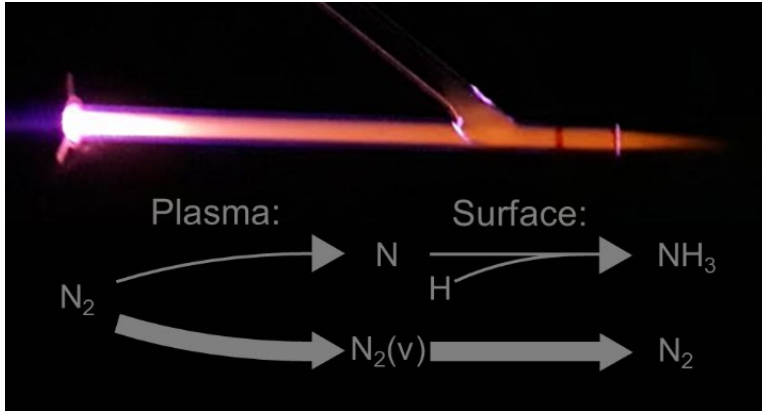


Conclusion: Decontamination

- Plasma is a promising technology for (airborne) virus inactivation.
- RONS enabled virus inactivation. Energy efficiency of plasma-based virus inactivation seems competitive with conventional technology.
- Short-lived species inactivation enabled in plasma on timescales down to ~ 10 ms. Hence technology is compatible with HVAC systems and can have similar 'efficiency' as HEPA filters although with lower pressure drop.



Plasma Catalysis



Electrification of gas phase
chemical conversion

Nitrogen fixation

Outline

**Brian Bayer (CEMS), Aditya Bhan (CEMS) and
Peter Bruggeman (ME)**

Chemical Engineering Journal 482 (2024) 149041



Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej



NO formation by N_2/O_2 plasma catalysis: The impact of surface reactions, gas-phase reactions, and mass transport

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^a Department of Chemical Engineering and Materials Science, University of Minnesota-Twin Cities, 421 Washington Ave. SE, Minneapolis, MN 55455, United States

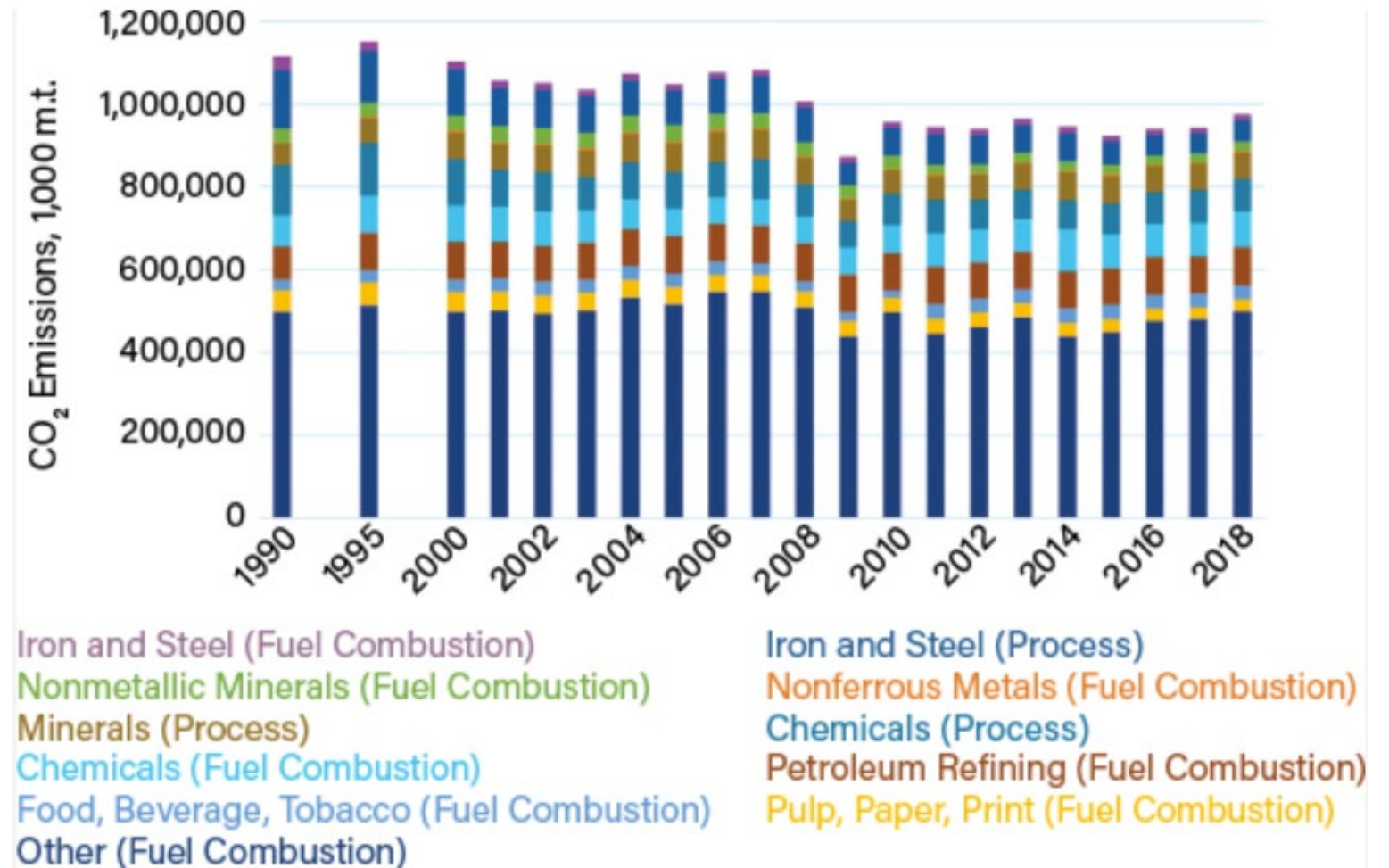
^b Department of Mechanical Engineering, University of Minnesota Twin Cities, 111 Church St. SE, Minneapolis, MN 55455, United States

MBMS diagnostics development: Jingkai Jiang (ME)
and Yolanda Aranda Gonzalvo (CEMS)



Electrification of the Chemical Process Industry

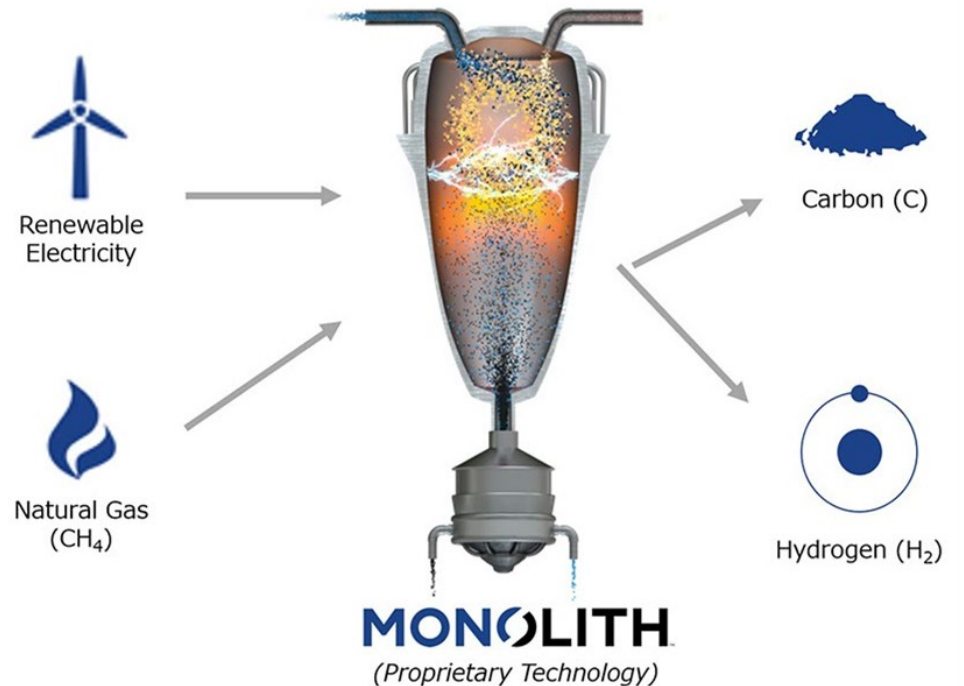
- Most CO₂ emissions in the US due to mineral, chemical, refining, iron, and steel industries
- A lot of CO₂ emission are due to combustion (heating)
- Renewable and green electricity becomes available and is a major focus



Bonheure et al, Dream or Reality? Electrification of the Chemical Process Industries- Aiche – March 2021

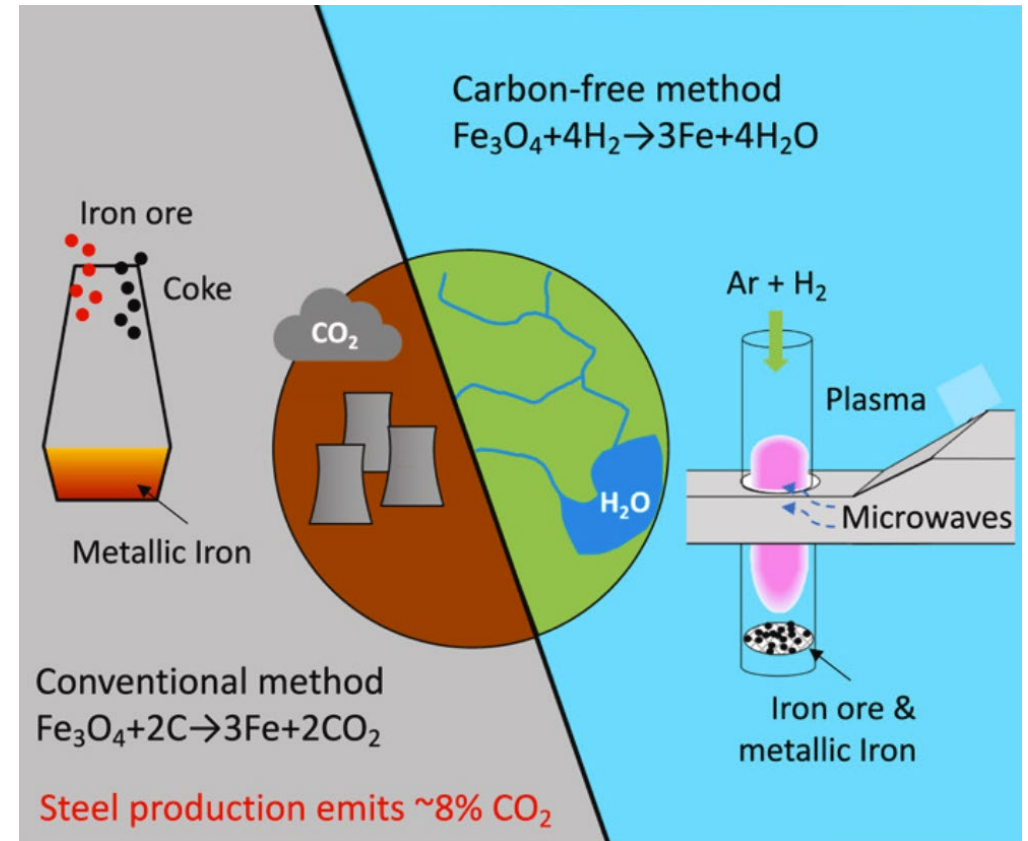


Electrification of Chemical Industry: Thermochemistry



<https://www.mhi.com/news/201130.html>

- Green H₂ and solid carbon from CH₄

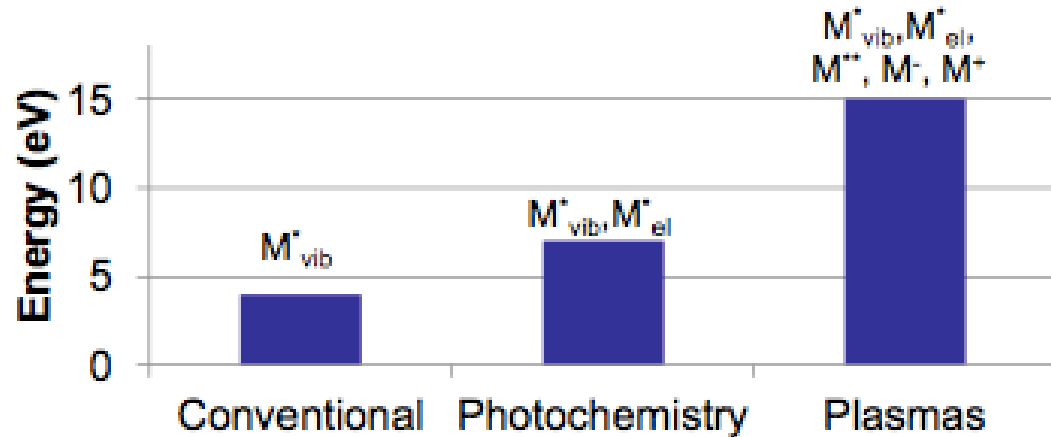


- Plasma-enabled iron ore reduction

Kumar et al, Chem. Eng. J., 472 (2023) 145025



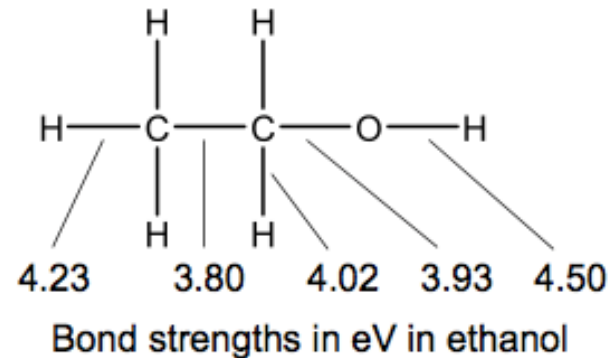
Why (not) Chemical Synthesis with Plasma?



- Ionization energy similar
- Bond energy similar

Selectivity is a great challenge!

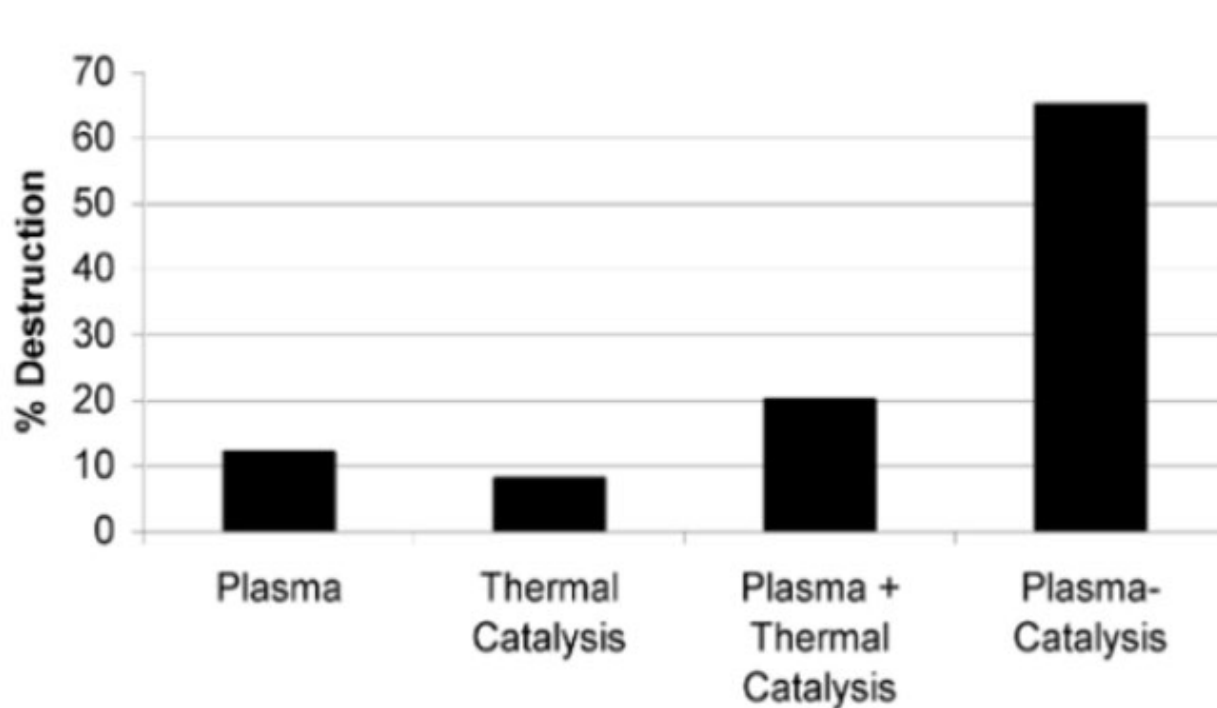
Heat
Ultrasound
Microwave
....



To date plasma mainly successful for polymerization and decomposition with few exceptions.

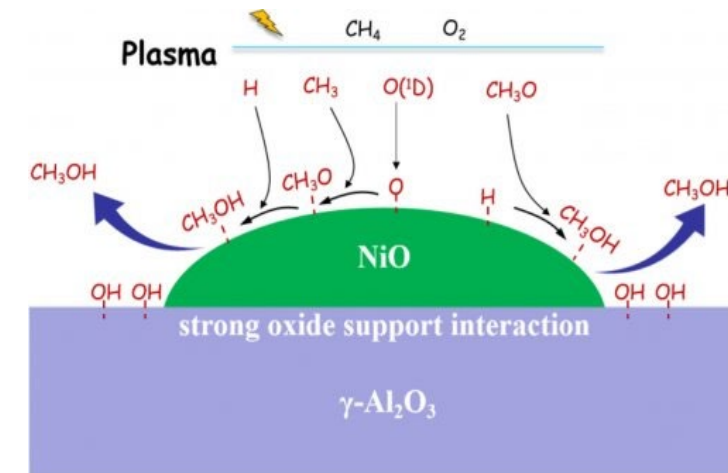


Plasma Catalysis: The Quest for Selectivity



Synergy in the destruction of toluene in air at room temperature¹

Plasma-catalysis exploits the ability of plasma to *activate strong bonds* and the ability of catalysts to facilitate more selective reactions compared to gas phase chemistry.



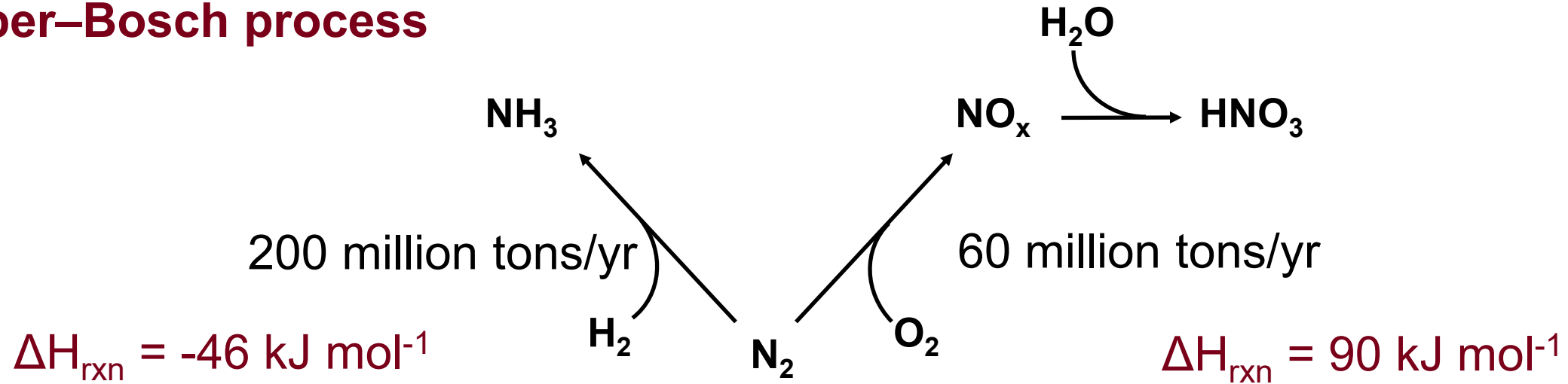
Yi, et al, App. Cat. B: Env., 296, 120384 (2021)

Plasma catalysis to enable selective low temperature molecule generation



Nitrogen Fixation: Importance and Challenges

Haber–Bosch process



< 0.01% conversion below 1000 K

Birkeland–Eyde process

30 GJ electric / ton of HNO_3



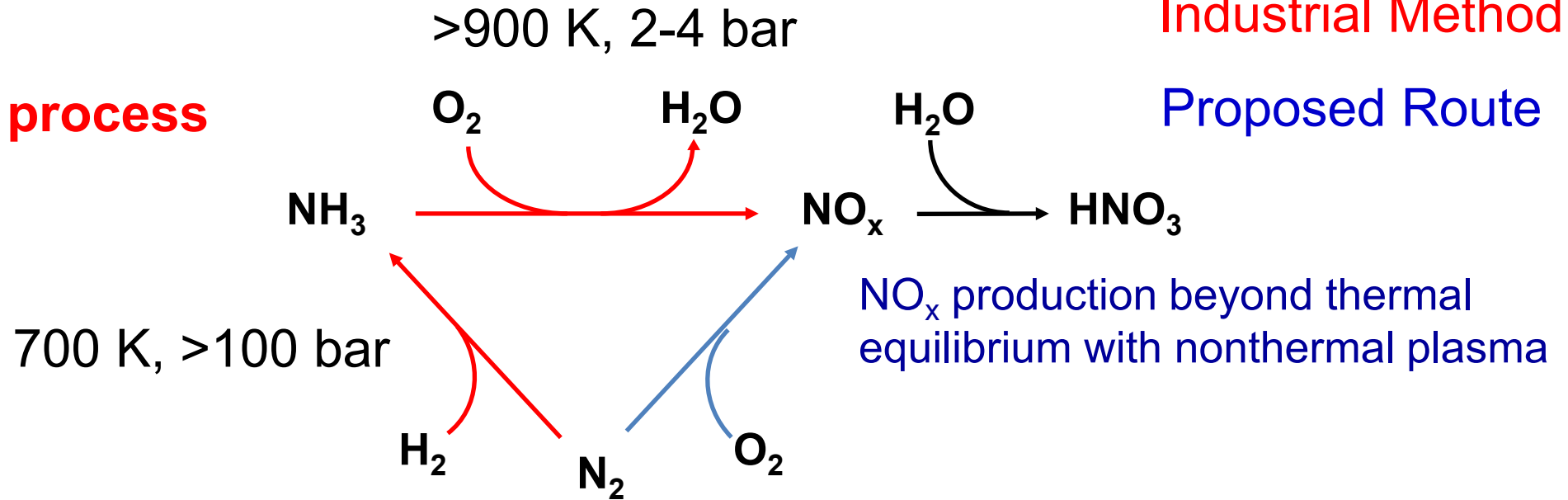
N₂ Oxidation: Industrial Process & Opportunities

Ostwald process

Industrial Method

Proposed Route

Haber–Bosch process

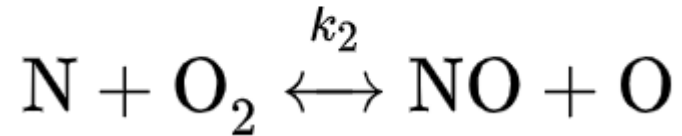
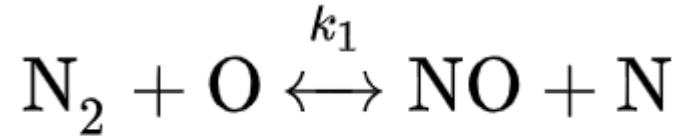


- NO_x formation by thermocatalytic processes requires NH₃ oxidation rather than N₂ oxidation
- Excited and radical species can form NO_x in (non)thermal plasma
- **Can conversion or selectivity be enhanced by coupling a heterogeneous catalyst with the plasma?**

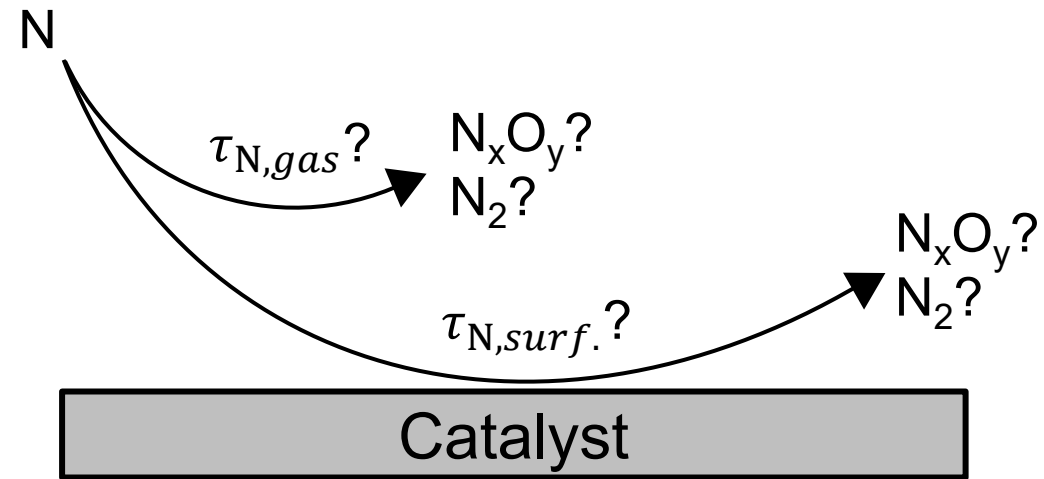


Research Questions

Zeldovic mechanism:



- enhanced by electronic excitation in plasma $\text{N}_2(\text{A})$

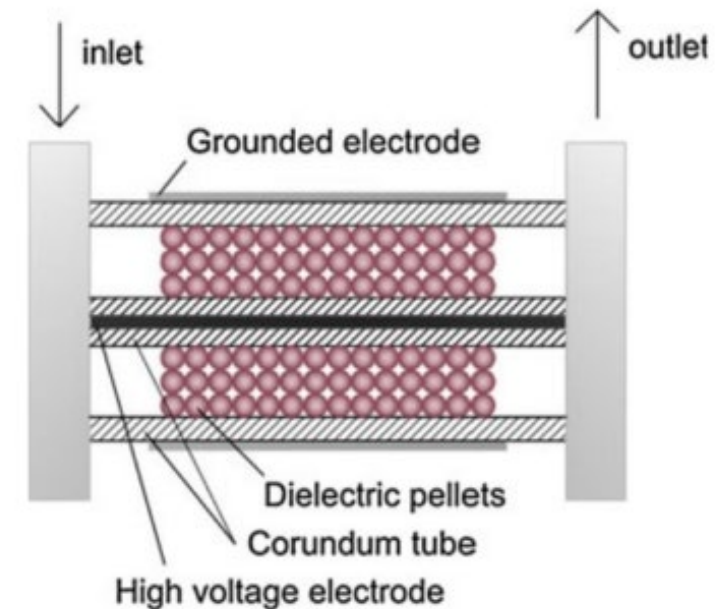
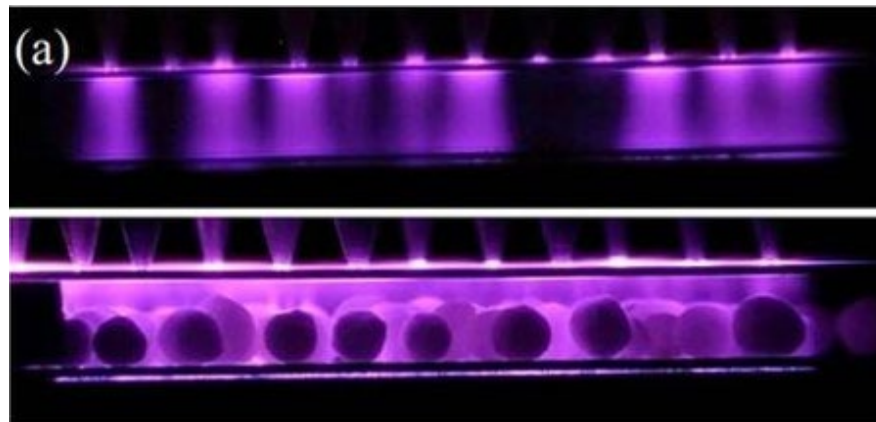


1. What pathways form NO_x in the gas phase and over the catalyst surface?
2. What are the relevant timescales for these processes?



State of the Art: Plasma Catalysis

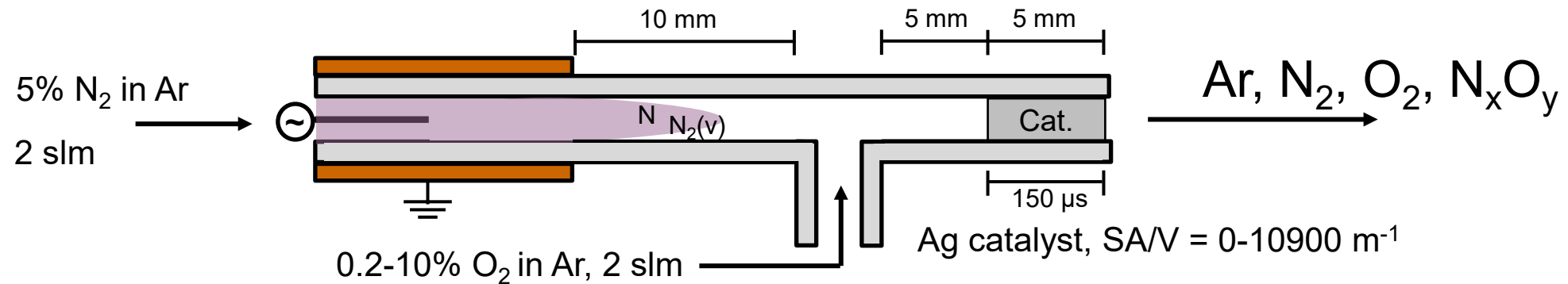
- Plasma-catalysis leverages **ability of plasma to activate strong chemicals bonds** with **selectivity of thermal catalysis**.
- **Underlying mechanism of synergistic coupling is to date not understood**
- Typical plasma source (DBD packed-bed reactors)
 - inhomogeneous
 - difficult to diagnose



Yu, Qinqin, et al. Plasma Chemistry and Plasma Processing 32.1 (2012): 153-163
Zhang, Li, et al. Scientific reports 6 (2016): 25242



N₂ Oxidation by Plasma Catalysis: Reactor Setup

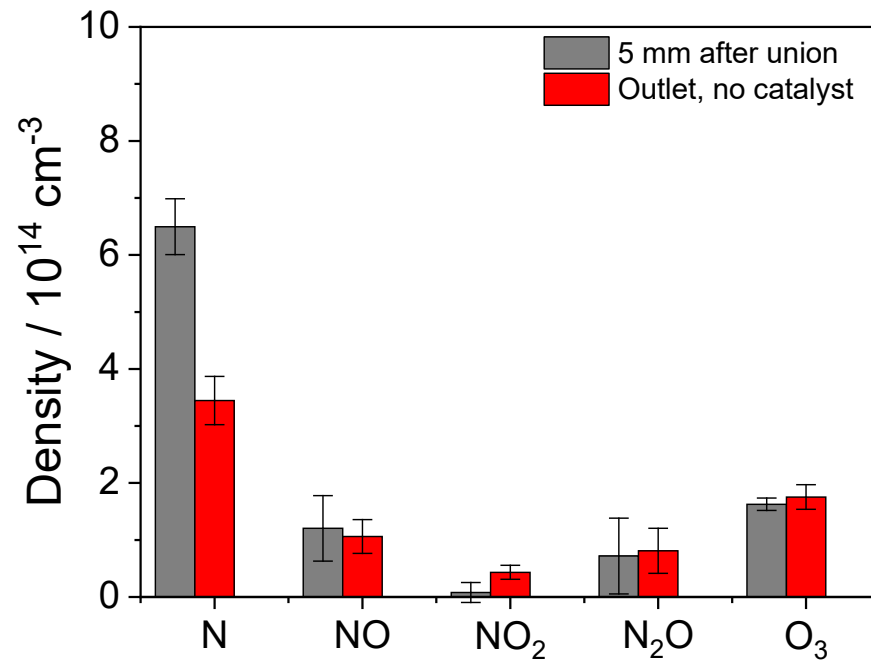
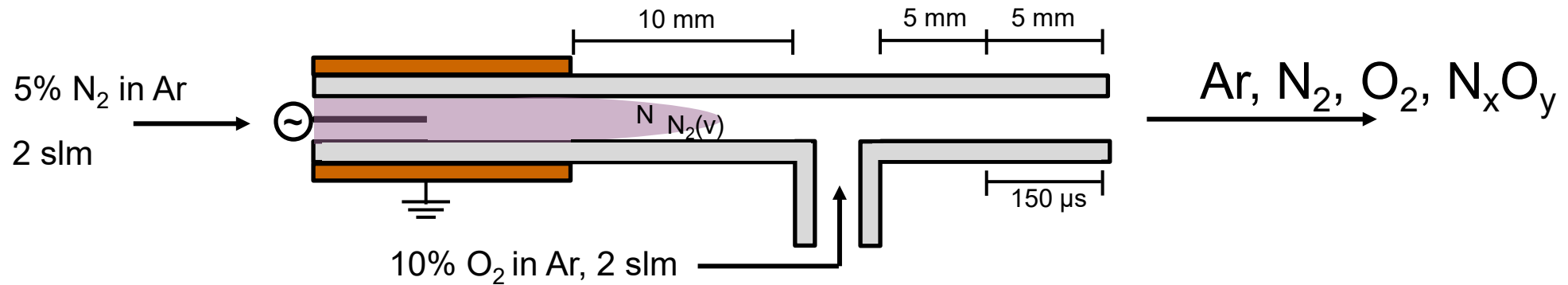


Ag wire was ~70 μm

- Activate N₂ in plasma
- O₂ introduced in afterglow
- Short residence times to assess timescales for gas-phase and surface processes



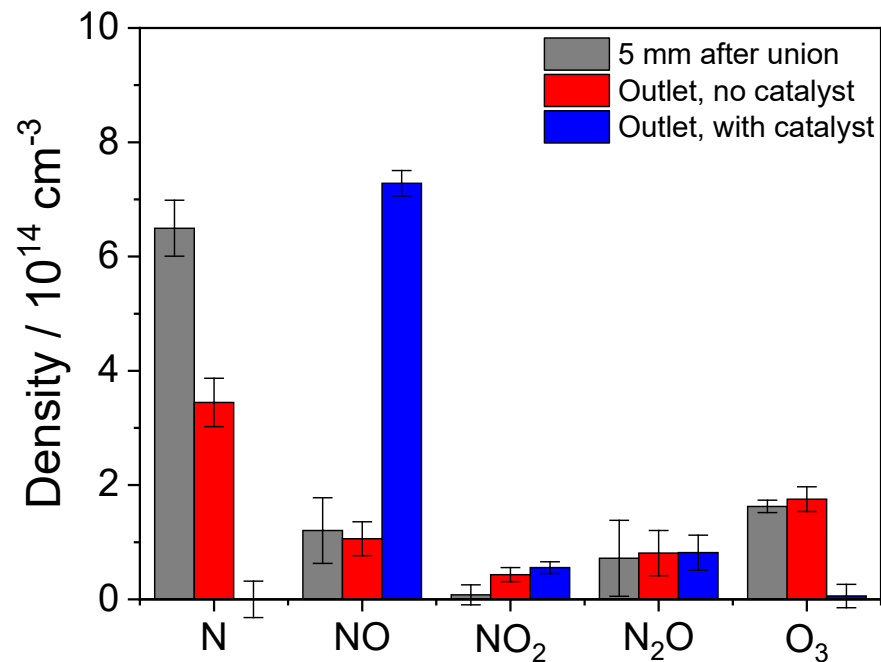
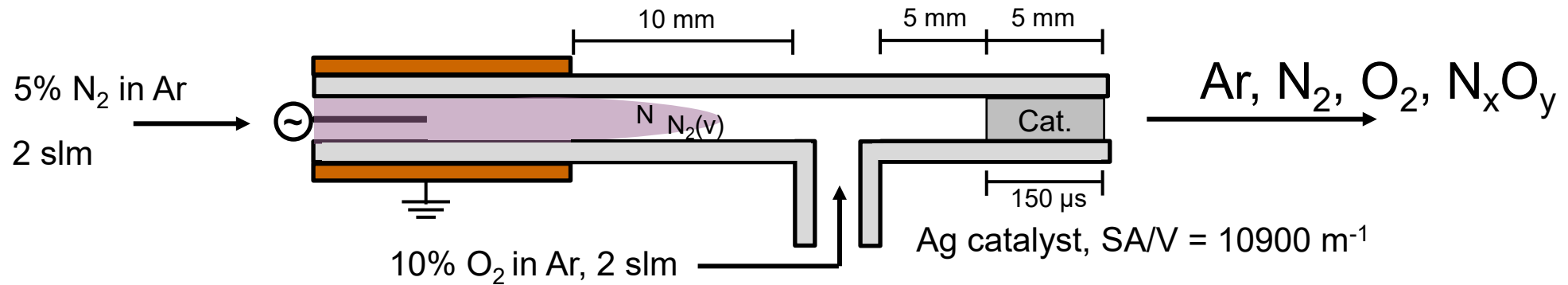
N_xO_y Production With and Without Catalyst



- Gas-phase processes consume N



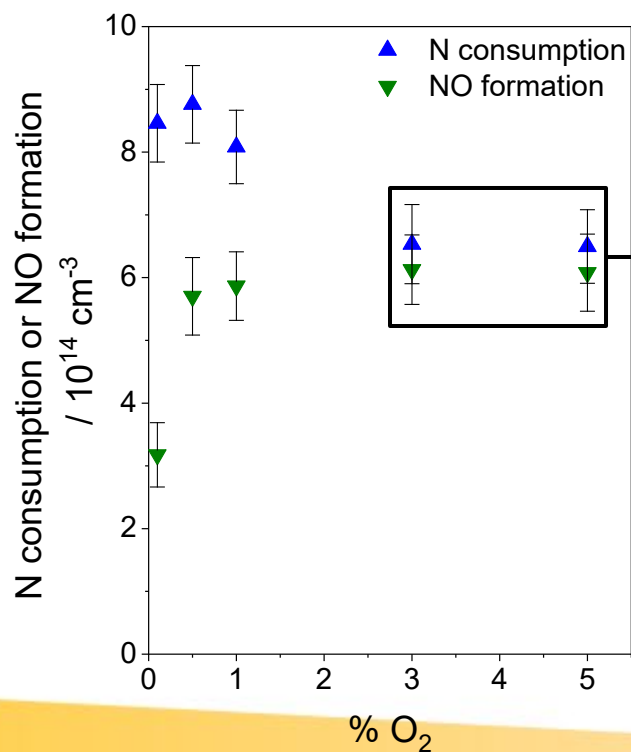
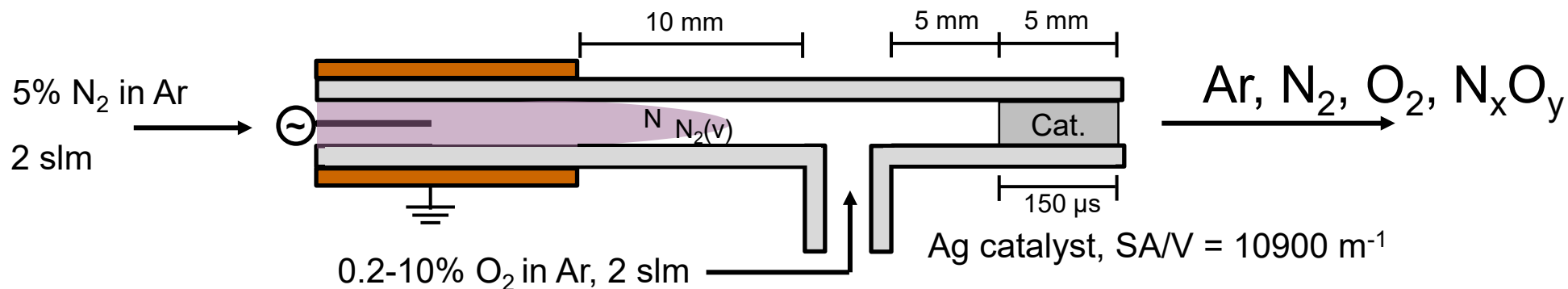
N_xO_y Production With and Without Catalyst



- Gas-phase processes and surface processes consume N
- Surface processes contribute to NO formation



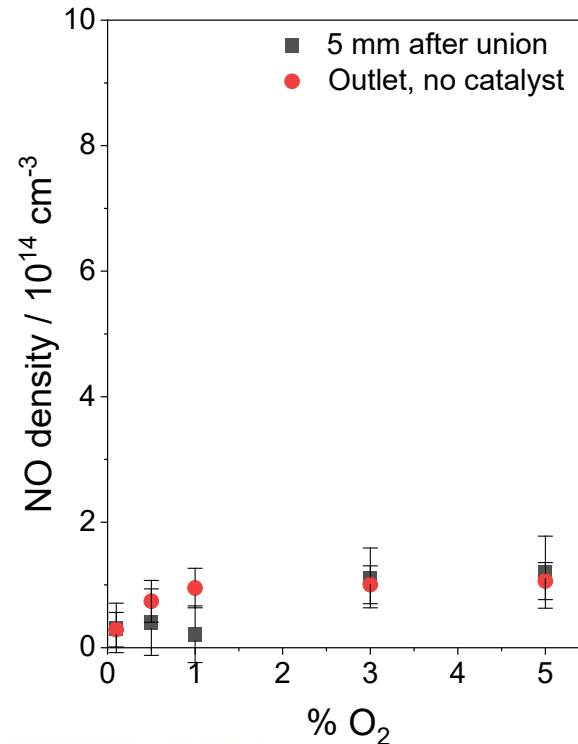
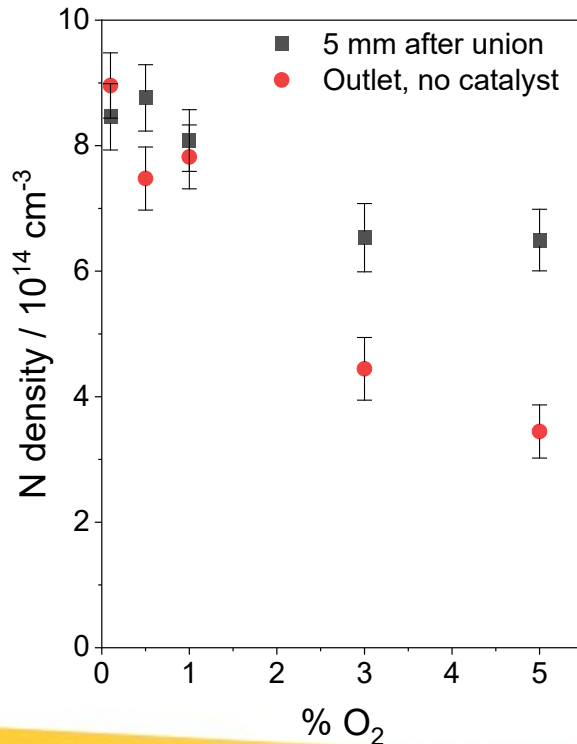
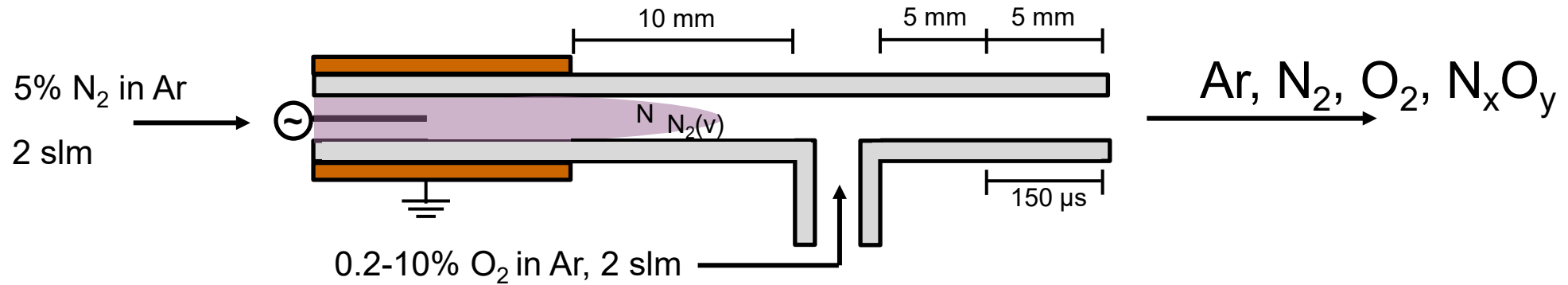
N Consumption and NO Formation over Ag



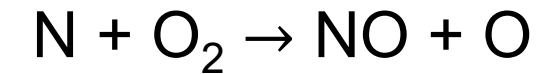
1 N → 1 NO when %
O₂ ≥ 3



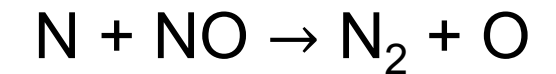
Gas-Phase N Consumption and NO Formation



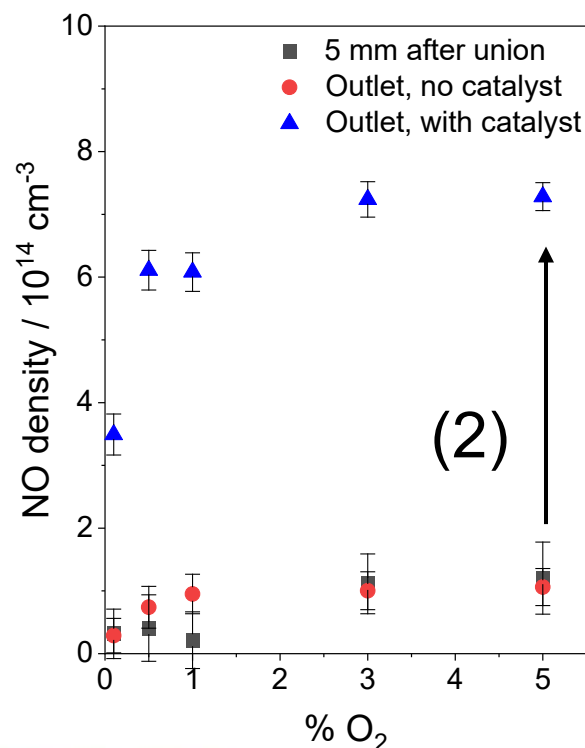
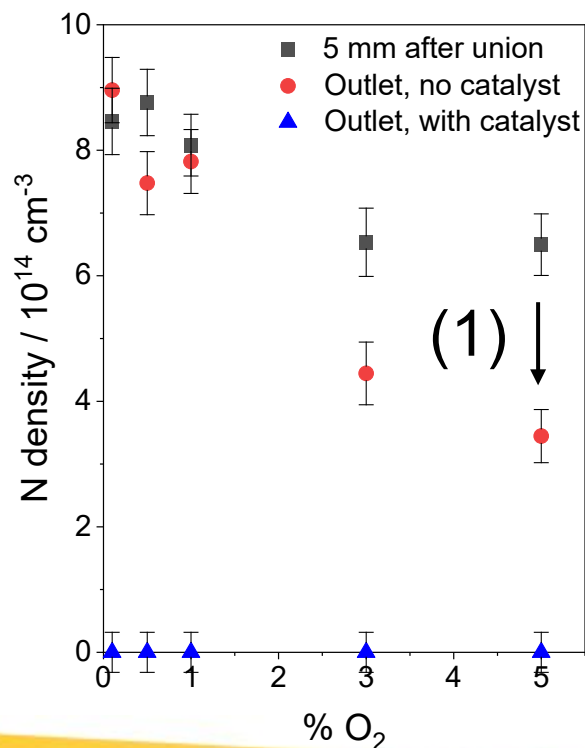
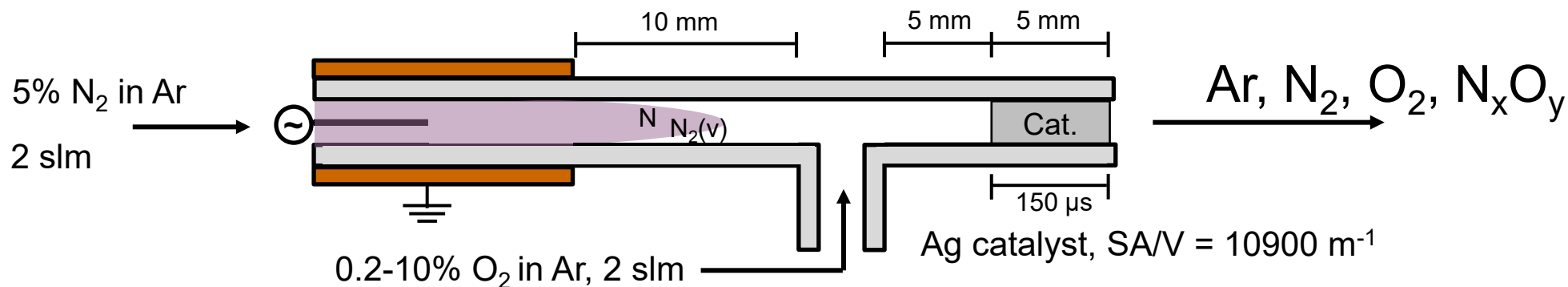
- Extent of N consumption increases with % O₂



- N consumption does not stoichiometrically form NO



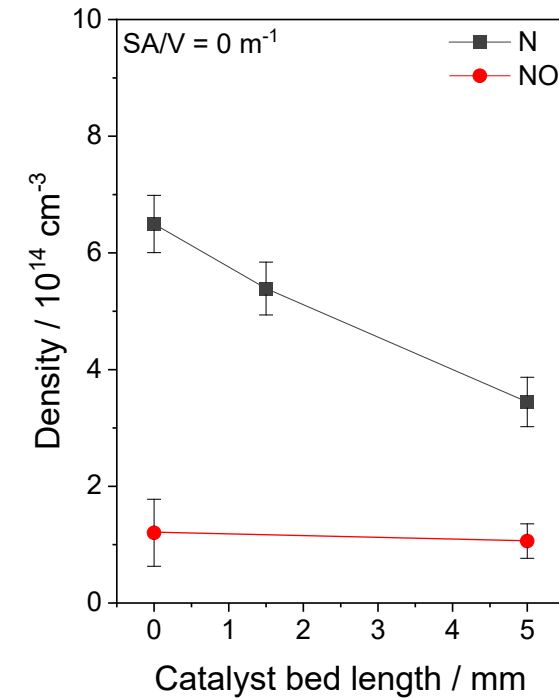
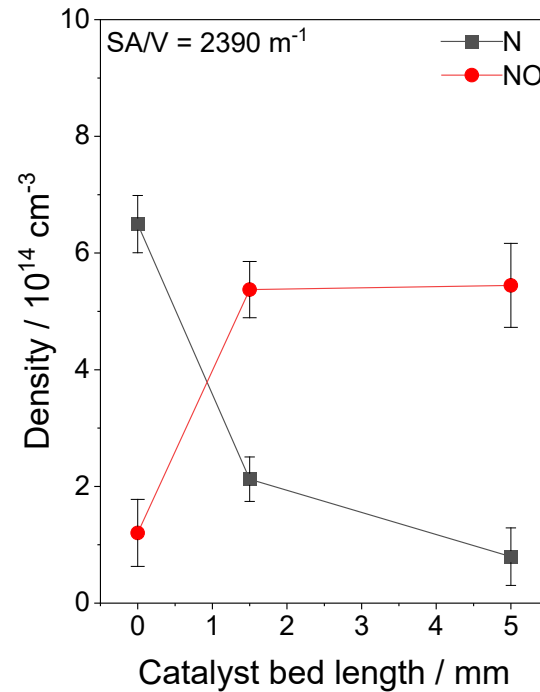
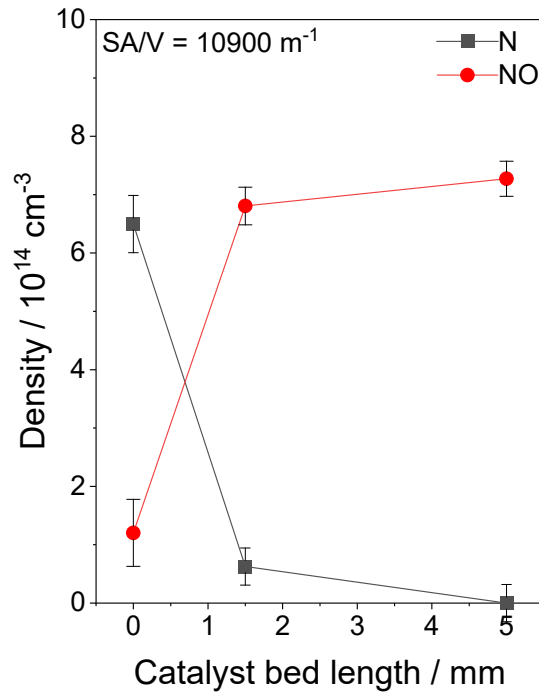
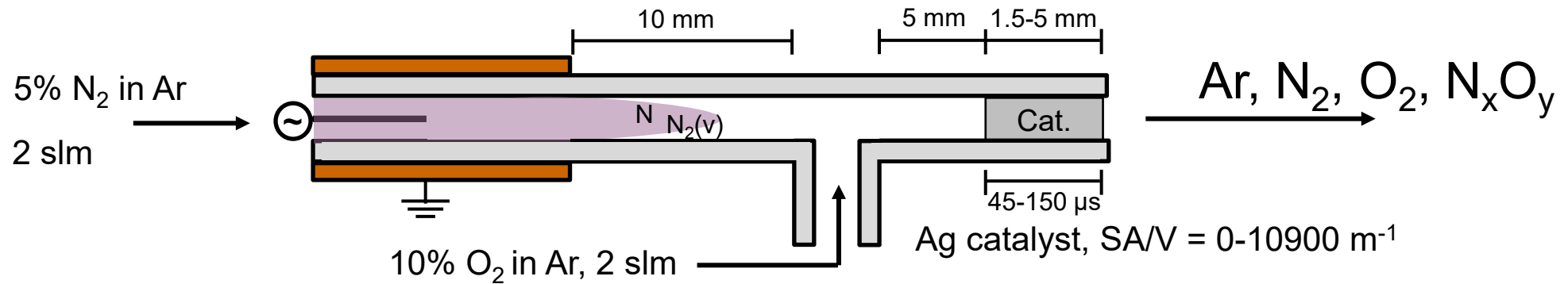
Comparison of Gas-Phase and Surface Pathways



- High O₂ concentration promotes both unselective conversion of N in the gas phase (1) and selective conversion of N over the surface (2)
- Requires analysis timescales for gas-phase and surface reactions to determine when selective chemistry can occur



Timescales for NO Consumption/Formation



- Decreasing SA/V decreases quantity of NO that is formed



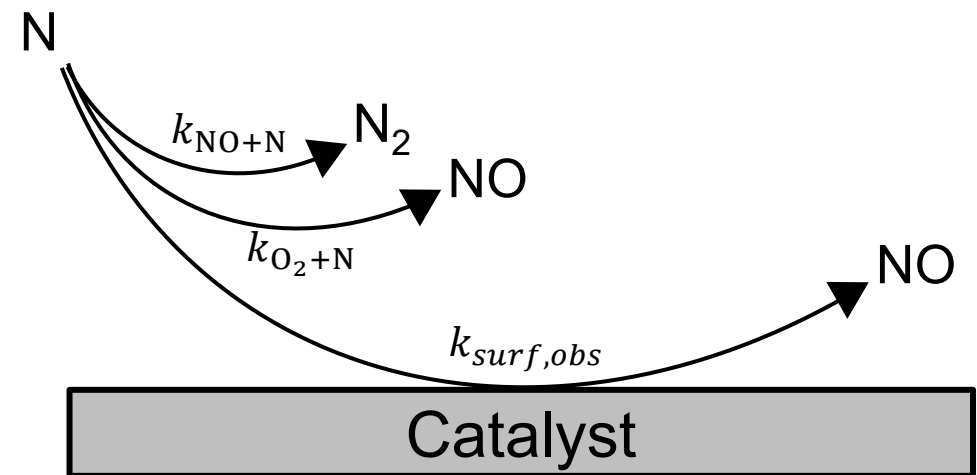
Parameter Fit to Determine Rate Constants

$$v_{flow} \frac{dc_N}{dz} = -k_{surf,obs} \frac{SA_{cat}}{V_{void}} c_N - k_{O_2+N} c_{O_2} c_N - k_{NO+N} c_{NO} c_N$$

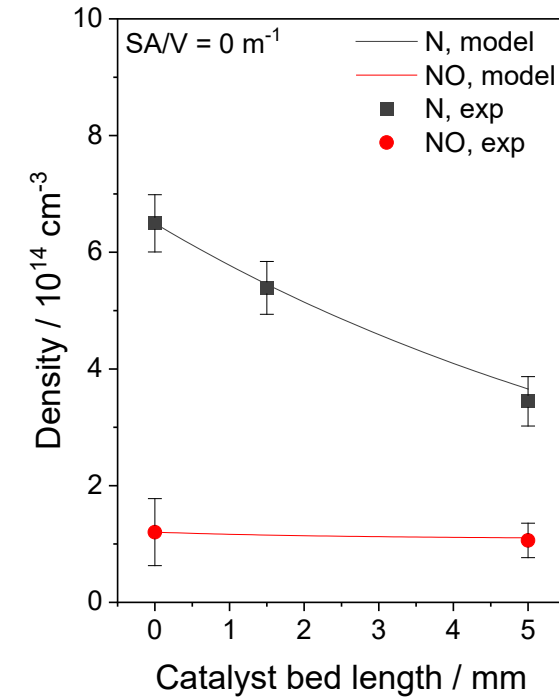
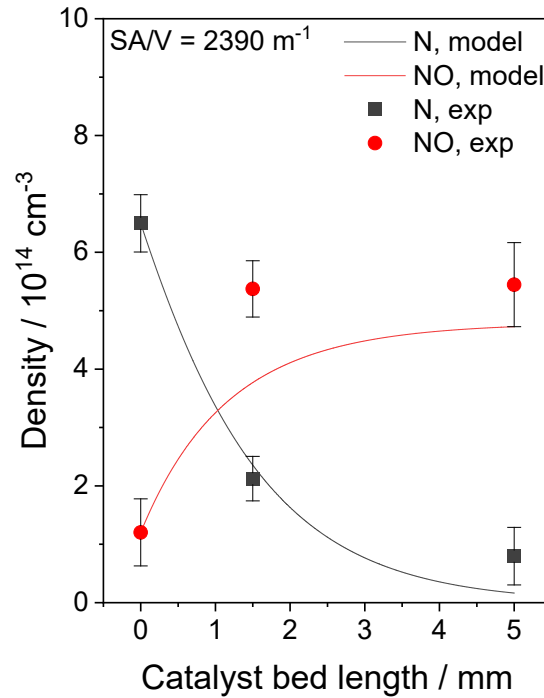
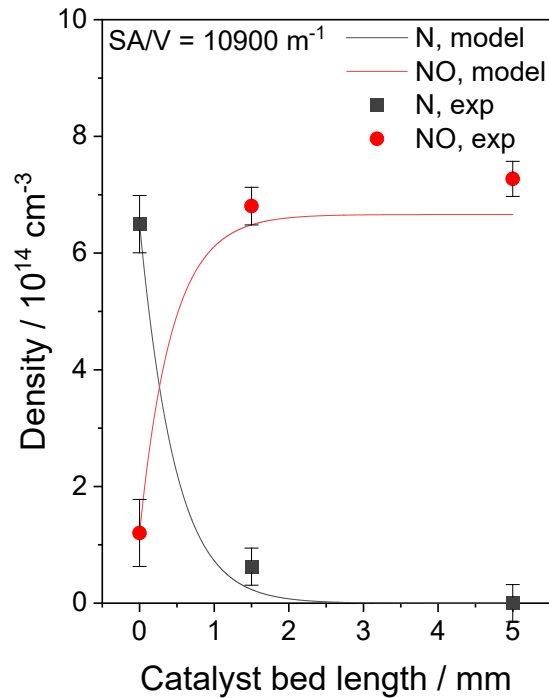
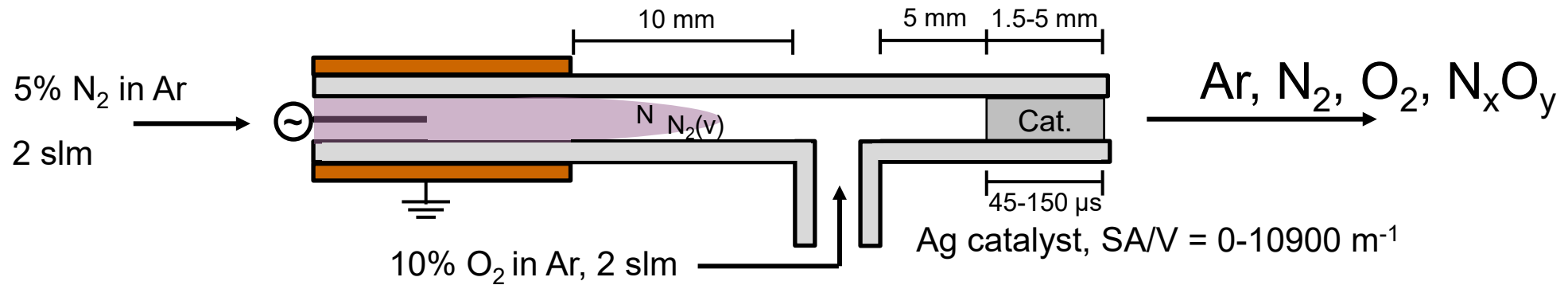
$$v_{flow} \frac{dc_{NO}}{dz} = k_{surf,obs} \frac{SA_{cat}}{V_{void}} c_N + k_{O_2+N} c_{O_2} c_N - k_{NO+N} c_{NO} c_N$$

Determine values for $k_{surf,obs}$, k_{O_2+N} , k_{NO+N} by minimizing the sum of square errors between experimentally measured densities and densities determined by the reduced kinetic model:

$$\min\left(\sum (c_{I,exp} - c_{I,sim})^2\right)$$



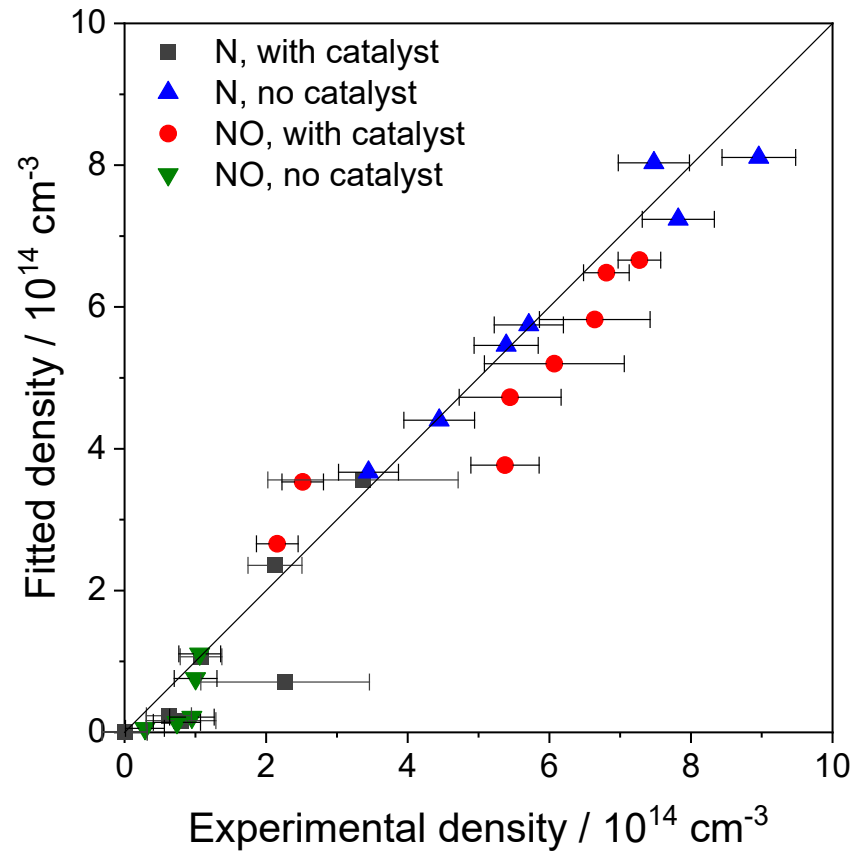
Parameter fit: Results (1)



- Kinetic model captures behavior observed in experiments



Parameter Fit: Results (2)



Rate constant	Value	Reference
$k_{surf,obs}$	$7.28 \pm 2.05 \text{ m s}^{-1}$	–
$k_{\text{O}_2+\text{N}}$	$(2.54 \pm 1.37) \times 10^{-15} \text{ cm}^3 \text{ s}^{-1}$	$7.82 \times 10^{-15} \text{ cm}^3 \text{ s}^{-1}$ [1]
$k_{\text{NO}+\text{N}}$	$(1.78 \pm 0.73) \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}$	$2.31 \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}$ [1]



Role of Mass Transfer in NO Formation from N (1)

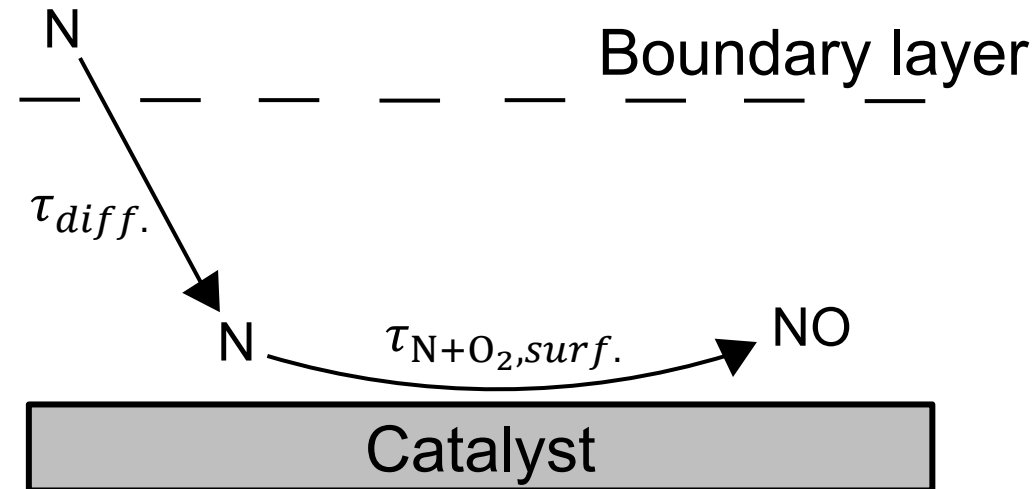
$$k_{surf,obs} = 7.28 \pm 2.05 \text{ m s}^{-1}$$

$$k_{M.T.} = f(D_{N,Ar}, Re_{wire}) \approx 10 \text{ m s}^{-1} \text{ at } 483 \text{ K [1]}$$

- Comparison of mass transfer rates and observed rate of N consumption:

$$k_{surf,obs} = \left(\frac{1}{k_{M.T.}} + \frac{1}{k_{surf}} \right)^{-1} \rightarrow k_{surf} = 26.8 \pm 19.4 \text{ m s}^{-1}$$

- Consumption of N on the surface is mass transfer limited ($\tau_{diff.} > \tau_{N+O_2,surf.}$)



Role of Mass Transfer in NO Formation from N (2)

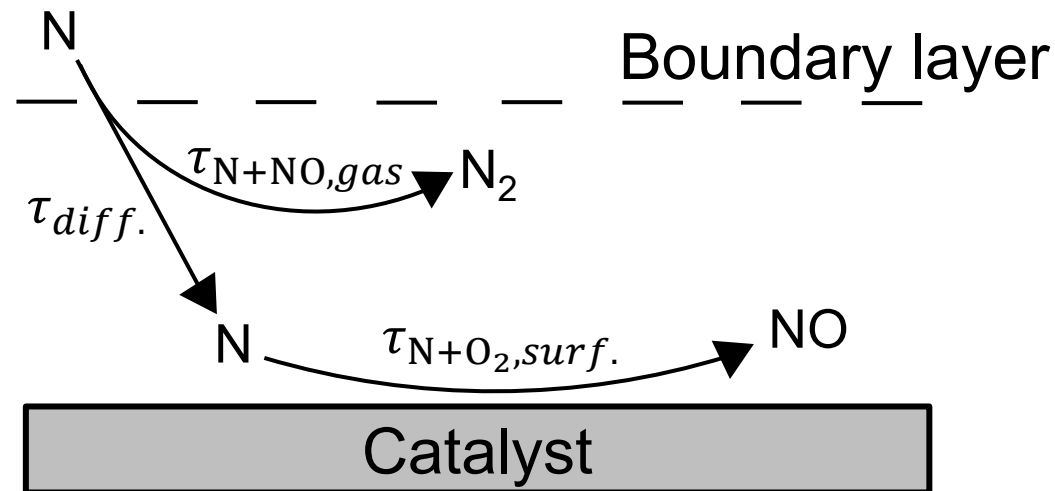
$$k_{M.T.} = f(D_{N,Ar}, Re_{wire}) \approx 10 \text{ m s}^{-1} \text{ at } 483 \text{ K [1]}$$

$$k_{NO+N} = 1.78 \times 10^{-11} \text{ cm}^3 \text{ s}^{-1}$$

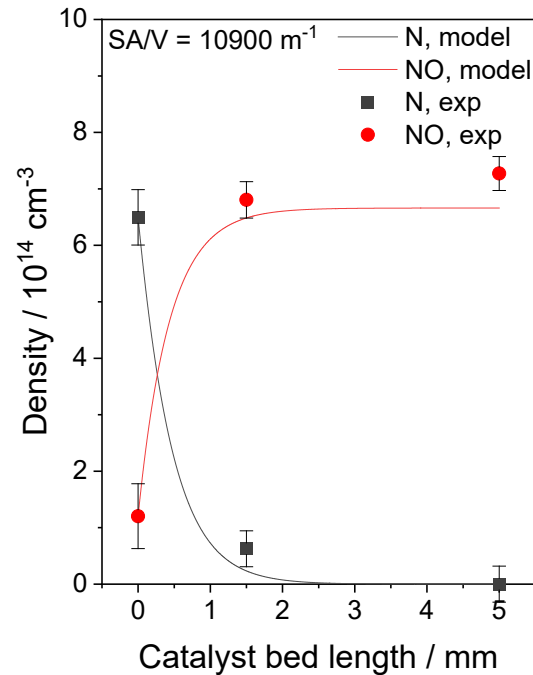
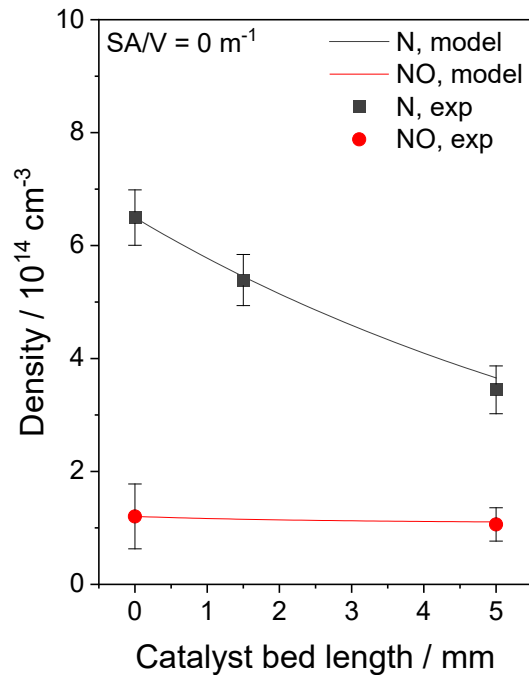
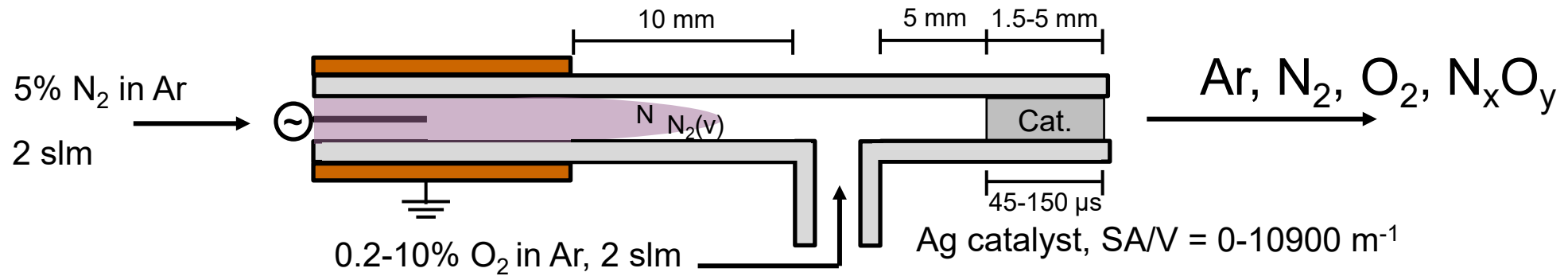
For N to react on the surface faster than it is consumed in the gas phase:

$$k_{M.T.} \frac{SA_{cat}}{V_{void}} c_N > k_{NO+N} c_{NO} c_N \quad (\tau_{diff.} < \tau_{N+NO,gas})$$

- Satisfied when $c_{NO} < 6.1 \times 10^{15} \text{ cm}^{-3}$ (250 ppm) for $\frac{SA_{cat}}{V_{void}} = 10900 \text{ m}^{-1}$



Summary (1)

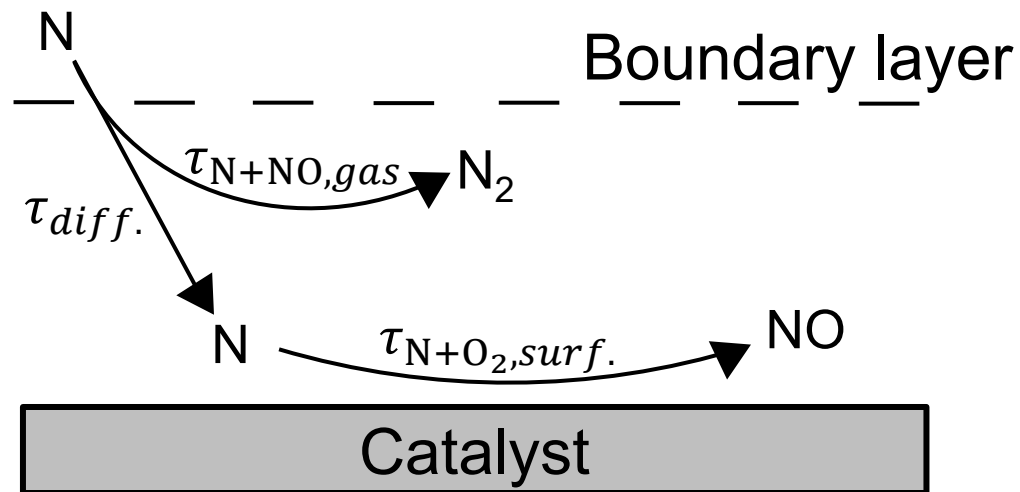
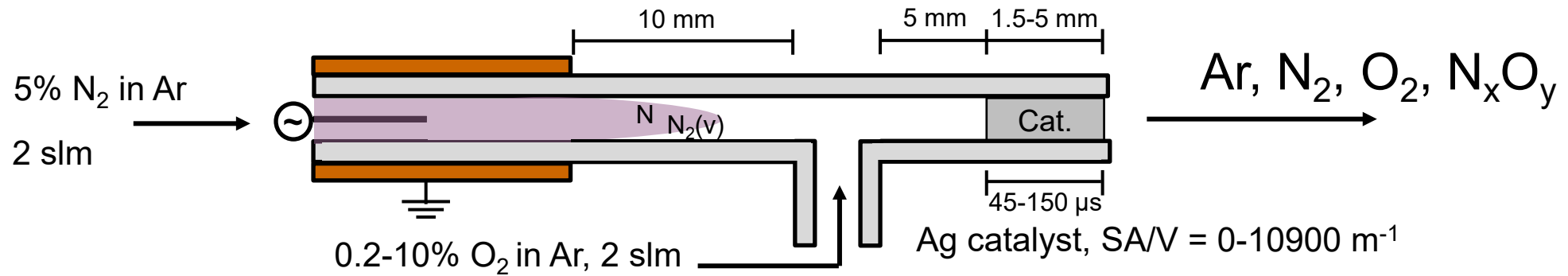


What pathways form NO_x in the gas phase and over the catalyst surface?

- N consumption occurs in the gas phase and over the surface
- Ag enhances the extent of N consumption and can selectively form NO



Summary (2)



What are the relevant timescales for these processes?

1. $\tau_{diff.} > \tau_{N+O_2,surf.}$
2. For low c_{NO} :
 $\tau_{diff.} < \tau_{N+NO,gas}$
3. For high c_{NO} :
 $\tau_{diff.} > \tau_{N+NO,gas}$

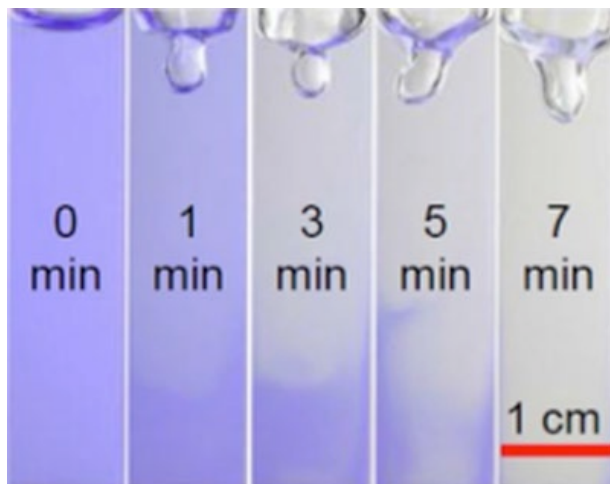


Conclusion: Plasma Catalysis

- Plasma-catalysis exploits the ability of plasma to *activate strong bonds* and the ability of catalysts to facilitate more selective reactions compared to gas phase chemistry.
- Reactor design and controlling transport is critical to study plasma-surface interactions. Selective NO production is possible when N is not quenched by NO in the gas phase before reaching the catalyst.
- Our results for NH_3 and NO synthesis show that radical driven chemistry dominates plasma-catalytic reactions.



Plasma-Driven Solution Electrochemistry



Plasma-liquid interactions:

- Liquid phase redox chemistry
- Material synthesis

Outline

Jae Nam, Gaurav Nayak, Stephen Exarhos,
Chelsea Muller (NM), George Schatz (NW)

Chemical
Science



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All publication charges for this article have been paid for by the Royal Society of Chemistry

Mechanisms of controlled stabilizer-free synthesis of gold nanoparticles in liquid aerosol containing plasma†

Jae Hyun Nam,^a Gaurav Nayak,^a Stephen Exarhos,^a Chelsea M. Mueller,^b Dongxuan Xu,^a George C. Schatz^b and Peter J. Bruggeman^{*a}

MURI: Plasma-Driven Solution Electrochemistry



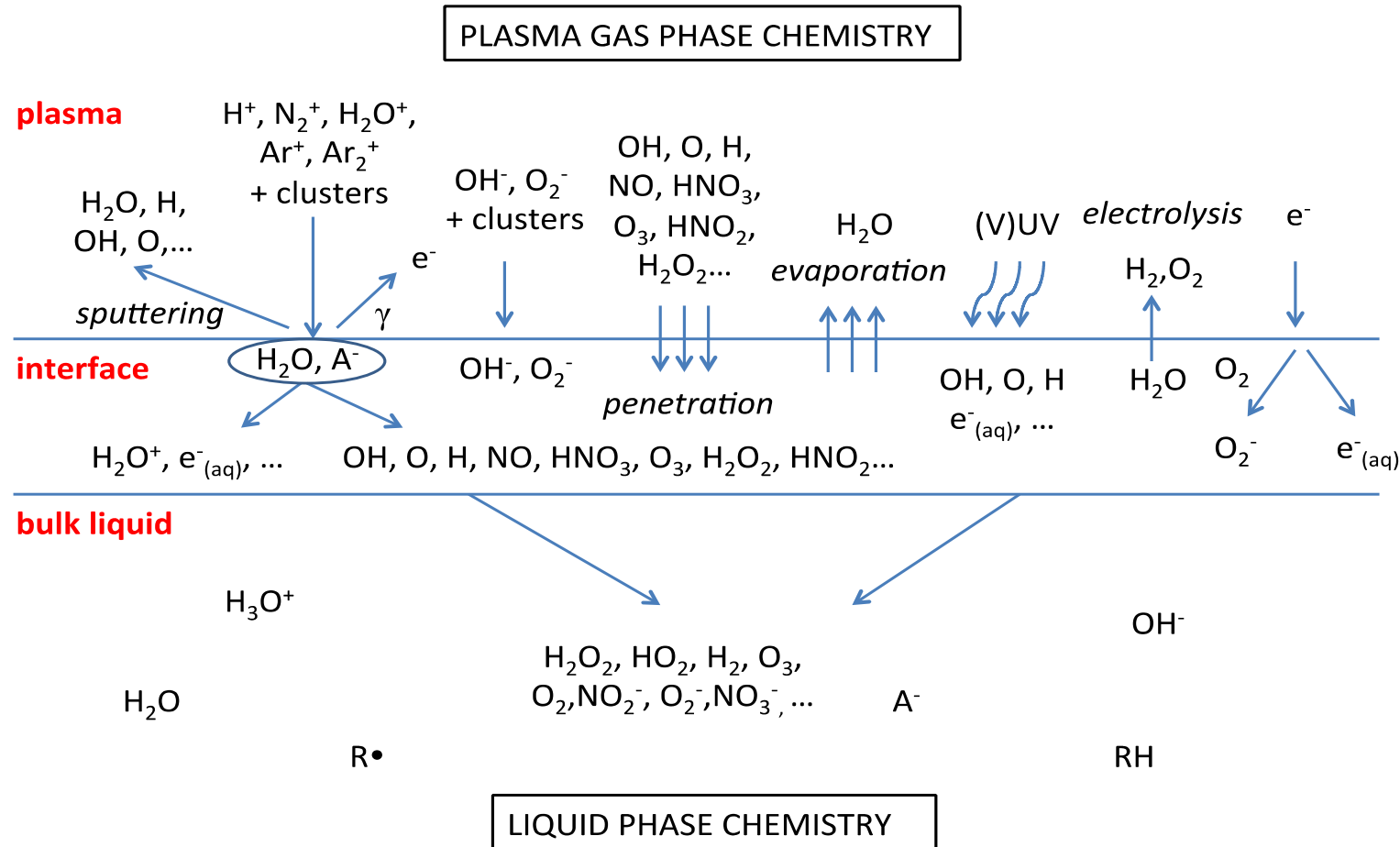
Plasma-Liquid Interactions

- **Gas phase plasma**

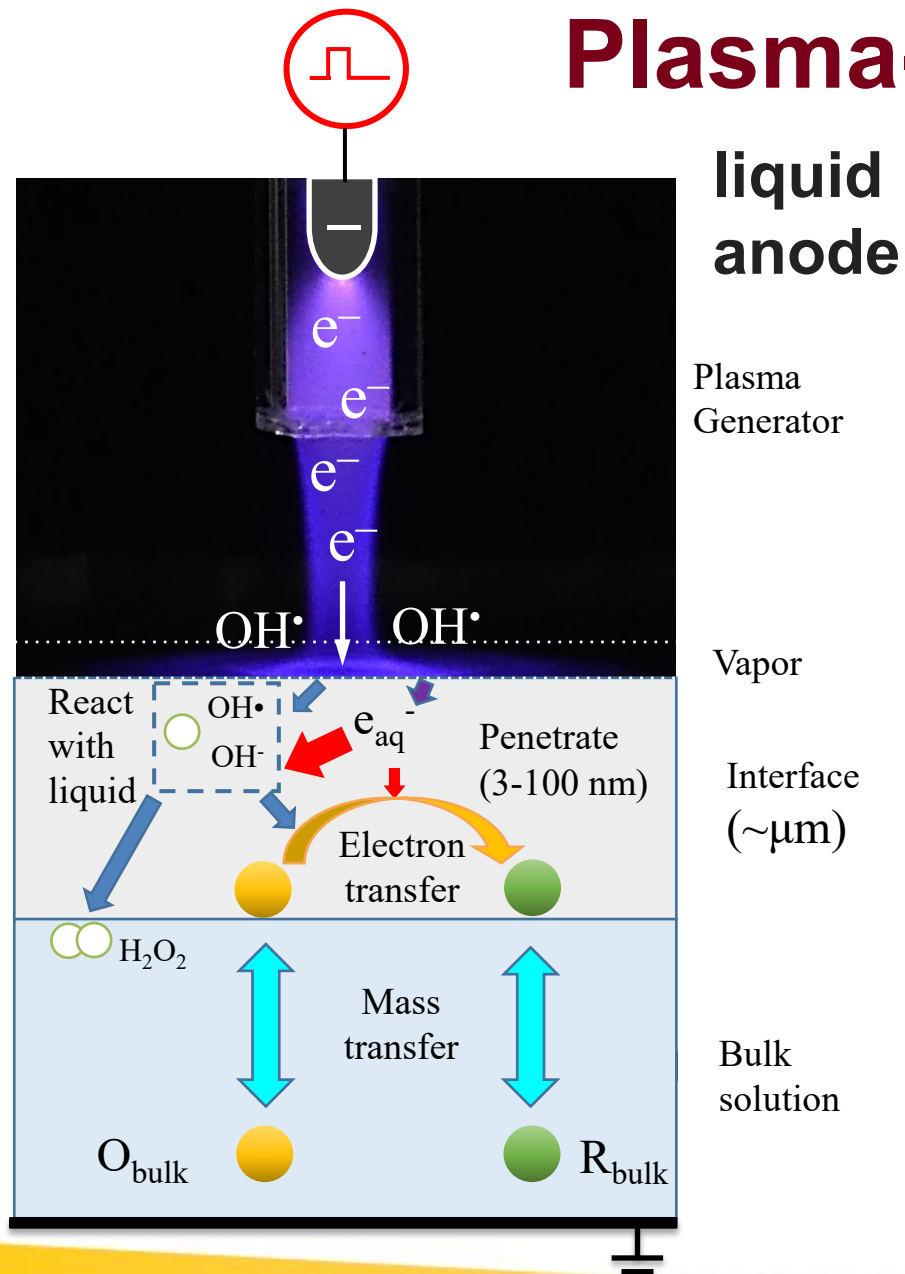
- Inefficient energy transfer from e^- to neutrals ($T_e \gg T_{\text{gas}}$)
- Hot electrons (1-10 eV), energetic ions (1-100 eV)
- Rich source of radicals and photons

- **Solution phase (interface)**

- Injection of hot electrons, ions, photons, radicals
- Large concentration gradients



Plasma-Driven Solution Electrochemistry

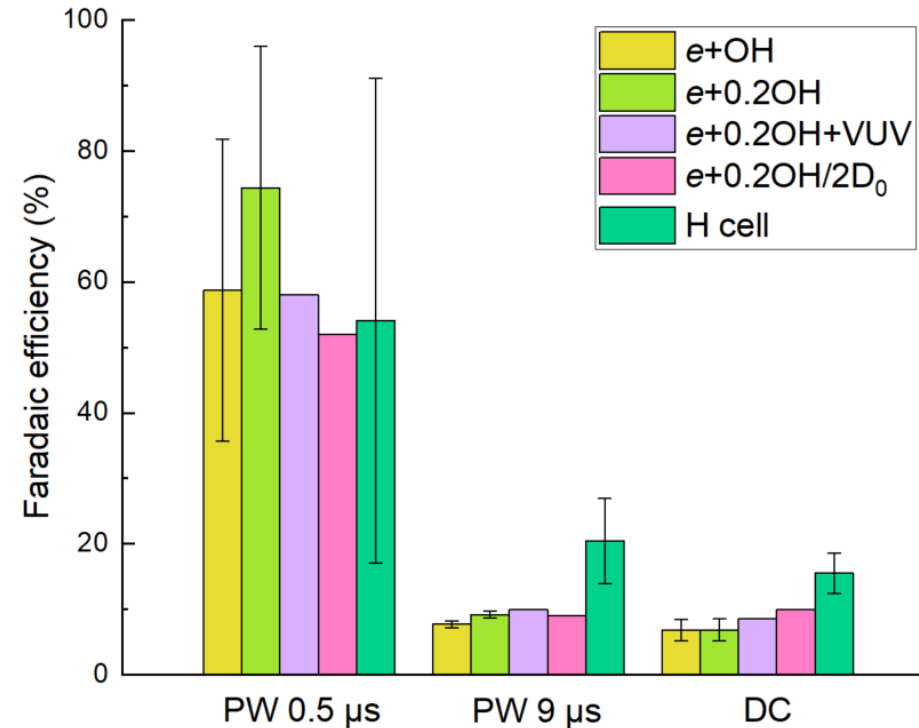
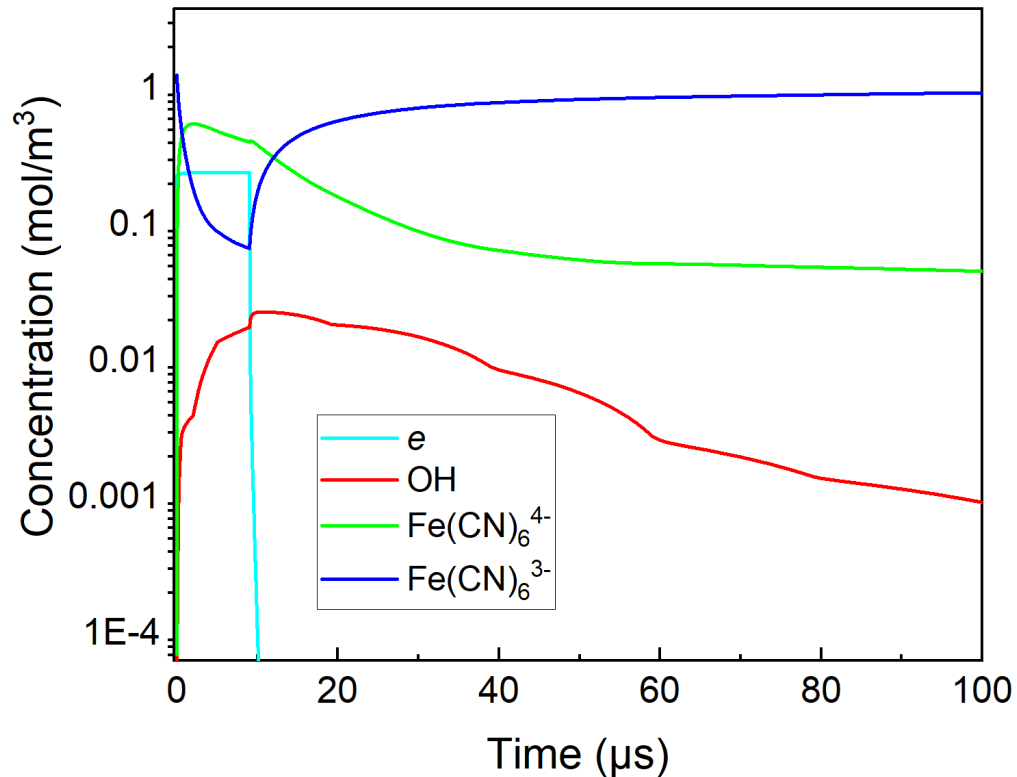


- Electrodeless electrolysis
- Electrolytical cell with one of the electrodes replaced by a plasma.
- Interfacial redox reactions
- **PDSE enables temporal control on times scales of reactive intermediates.**
- Sustainable green process
- Very high yields

MURI team, PDSE, JAP (2021) : doi: 10.1063/5.0044261



Model Framework for PDSE

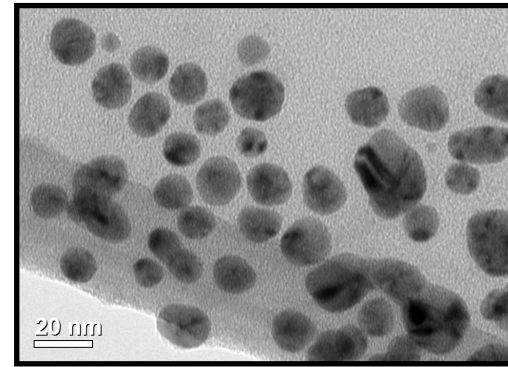
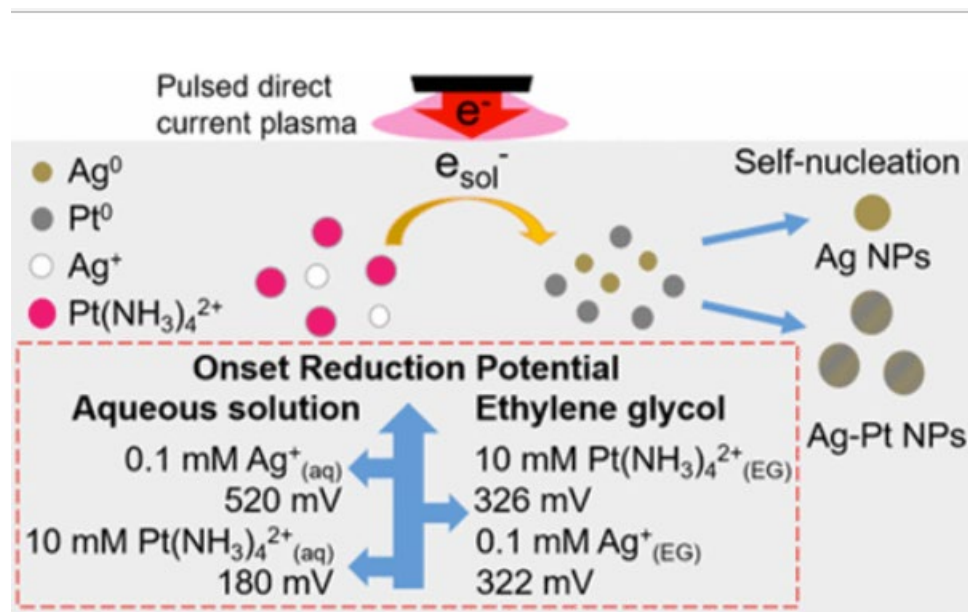


- Plasma loads liquid up with e^-_{aq} (-2.77 V)
- Plasma-produced OH (**2.8 eV**) are injected
- Excellent agreement between model and experiment for PDSE enabled Fe(CN)_6^{3-} (Ferricyanide) reduction.

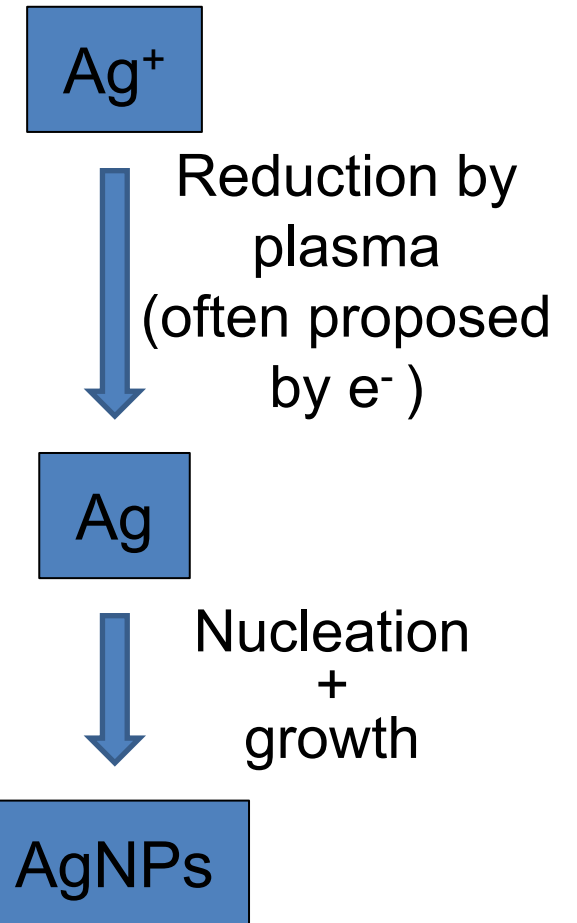
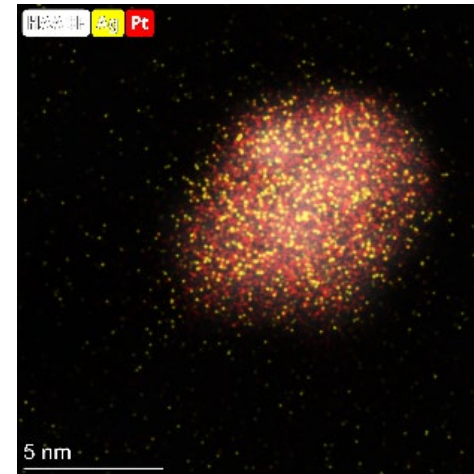
Yue, Linic, Bruggeman et al, Plasma Source Sci. Technol. (2022)



Mechanisms for PDSE Enabled Synthesis



Nanoparticles



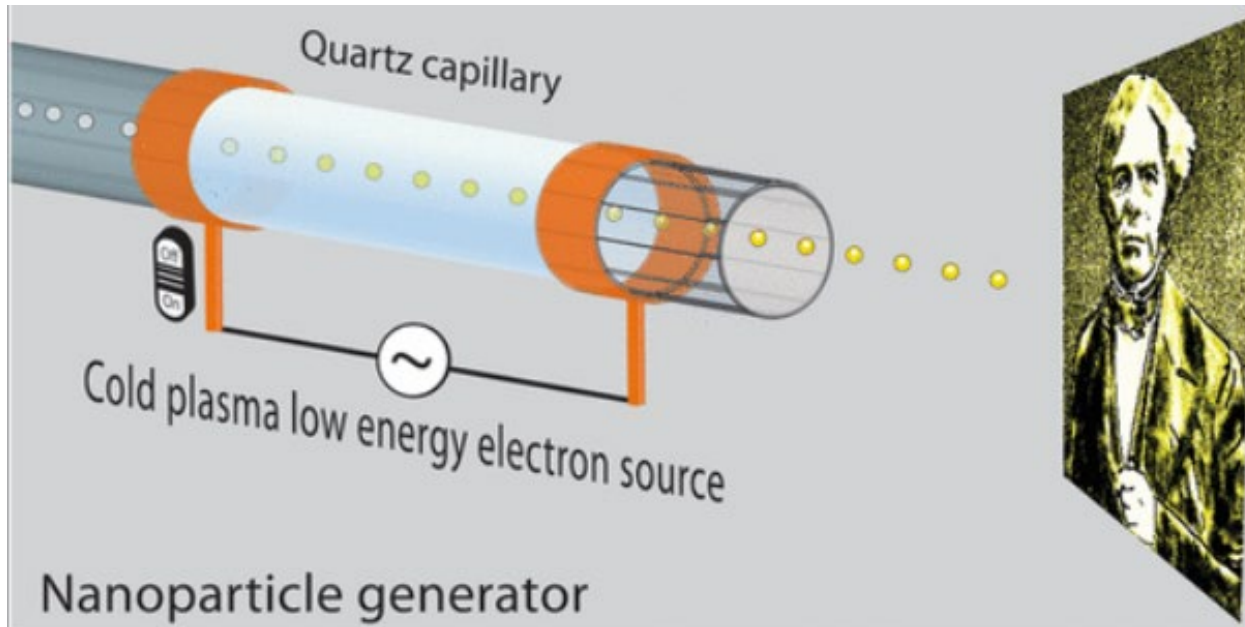
Short-lived reducing species (e^- , H , ...) **Interfacial chemistry**

Species	Standard Electrode Potential
e^-	- 2.8 V
H	- 2.3 V
OH	2.8 V

Chen, Lee, Linic, Chem. Mater. (2023) 35, 16, 6557–6565
 Mariotti *et al.* PPP (2012) (9) 1074-1085
 Richmonds *et al.*, Appl. Phys. Lett. 93, 131501 (2008)

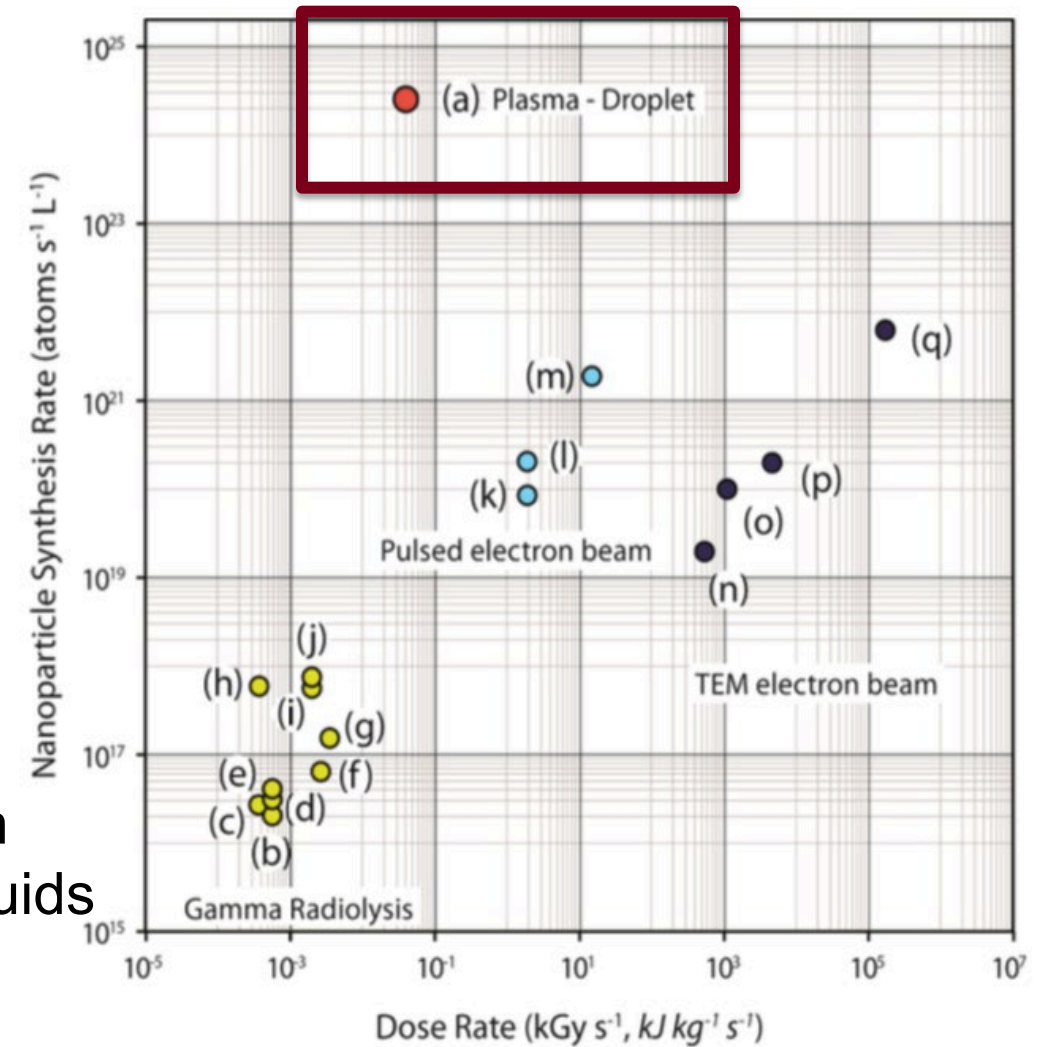


Plasma-Enabled Nanoparticle on Demand Delivery



To date: ($\text{Au}_3^+ \rightarrow \text{AuNP}$)

- Many seem to believe that electron reduction can explain most plasma-enabled NP synthesis in liquids
- Limited control of reactions is explored
- Knowledge of underpinning processes is lacking



Maguire et al

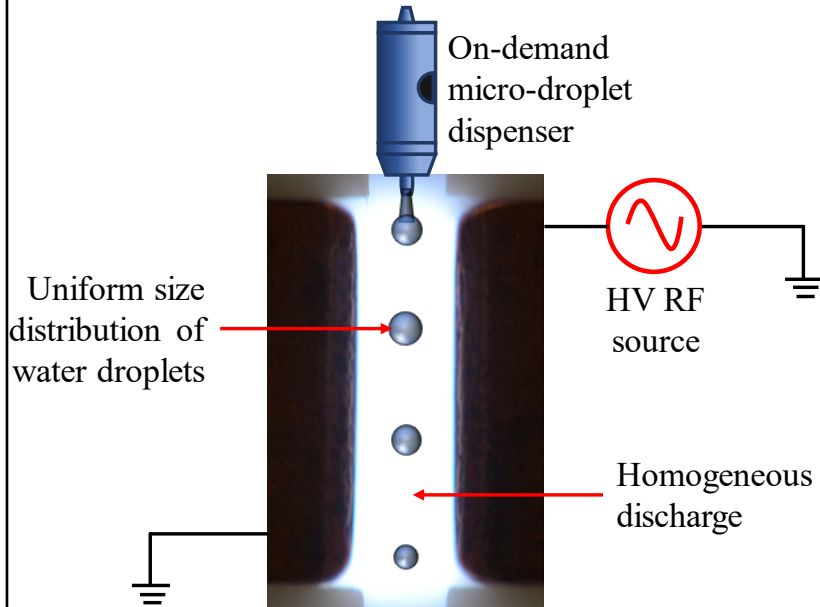
Nano Lett. 17(3), 1336-1343 (2017)



- Can we assess the Au^{3+} reduction in PDSE, especially plasma-microdroplet environment?
- What is dominant reduction/particle growth mechanism?
- Can we predict experimental findings by a simple 1-D model?

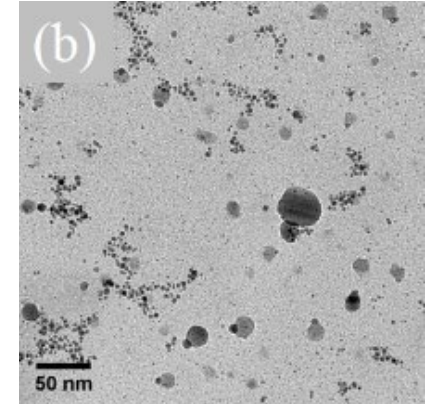
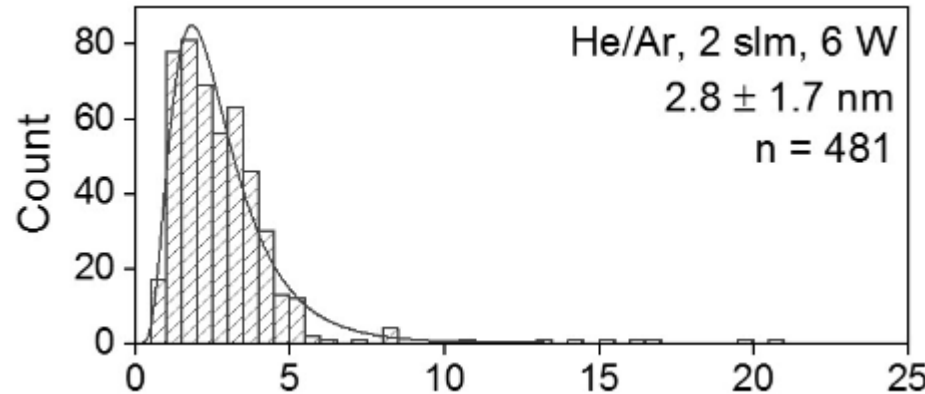


Droplet reactor



Well-defined species fluxes and diffusion transport in solution

Ligand-free on demand Au nanoparticles



- Synthesizing ligand free on demand metallic nanoparticles (example – Au)

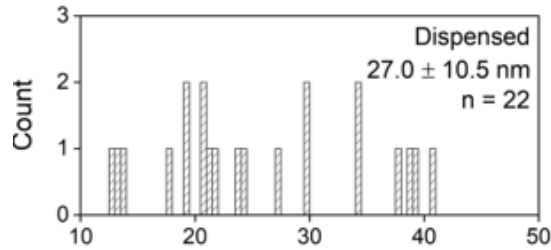
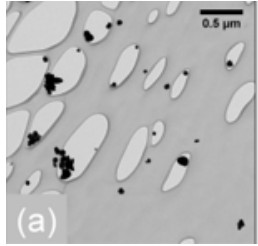
Characterization and modelling

- Electron densities in gas phase
- *Ex situ* liquid analysis (TEM, UV-Vis absorption)
- 1D liquid phase reaction-transport model (sphere in 'homogeneous' plasma)



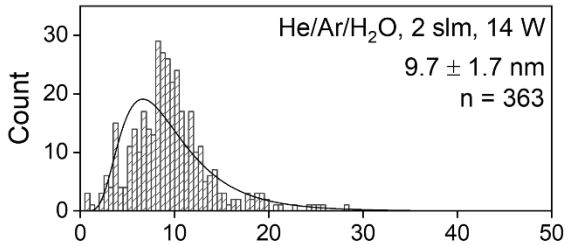
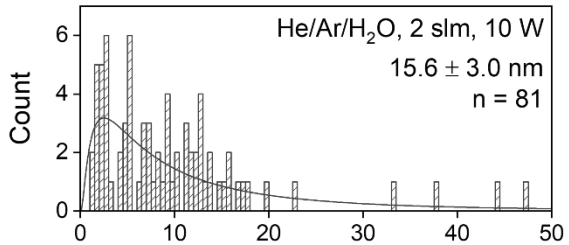
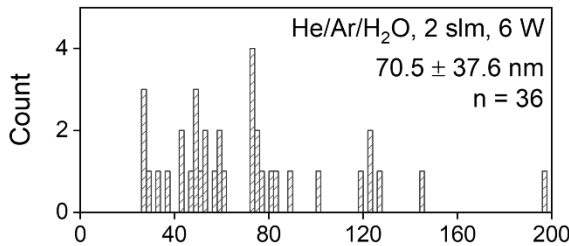
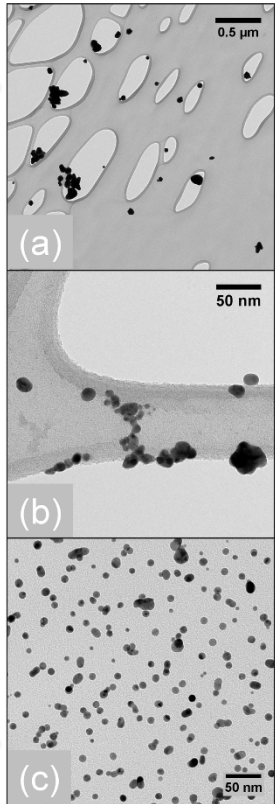
AuNP Synthesis

Dispensed



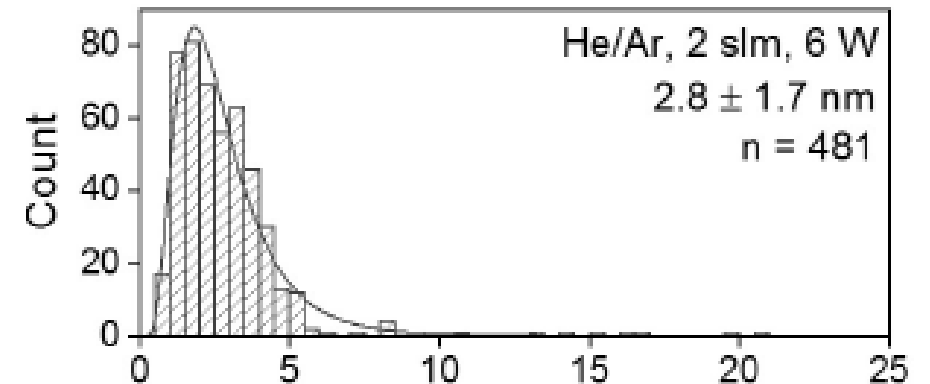
- Dispensing the precursor-loaded droplets leads to small number of nanoparticles (**D. Zare**)
- Significant AuNP has a threshold power effect - supports classical nucleation theory
- **Larger reducing species flux yields smaller particles**

Plasma+
Dispensed

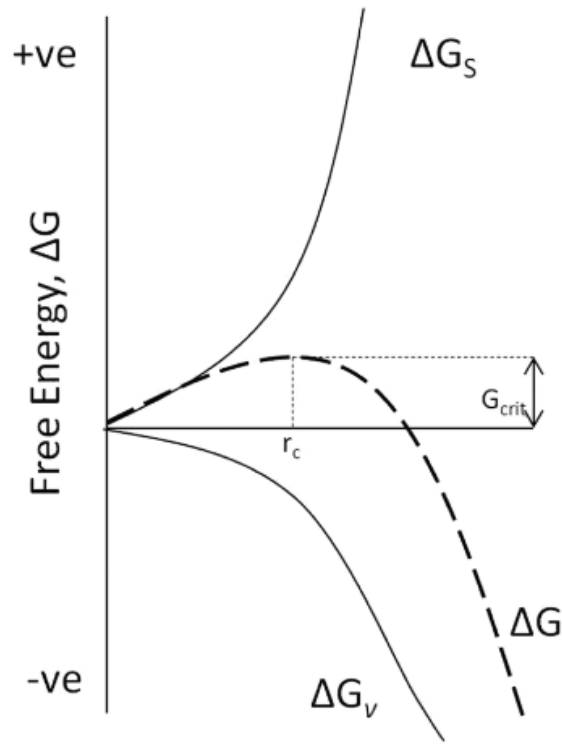


(d) Au NP Diameter (nm)

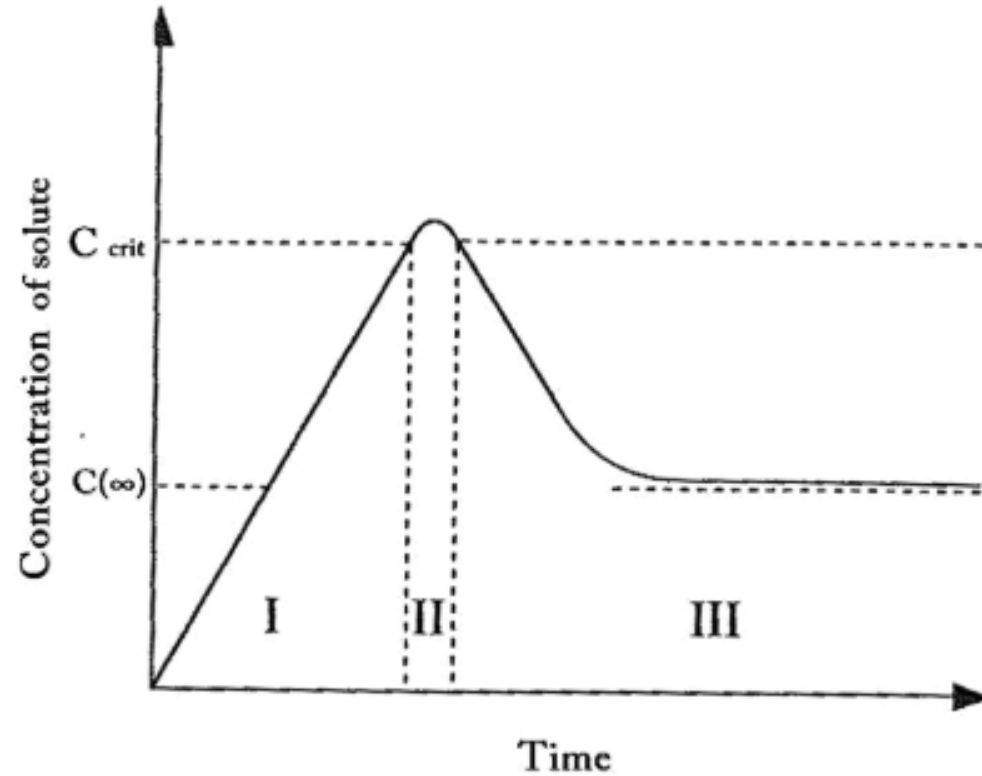
1 mM $\text{HAuCl}_4 \cdot 3\text{H}_2\text{O}$



Classical Nucleation Theory



Free energy diagram for nucleation *



LaMer's diagram **

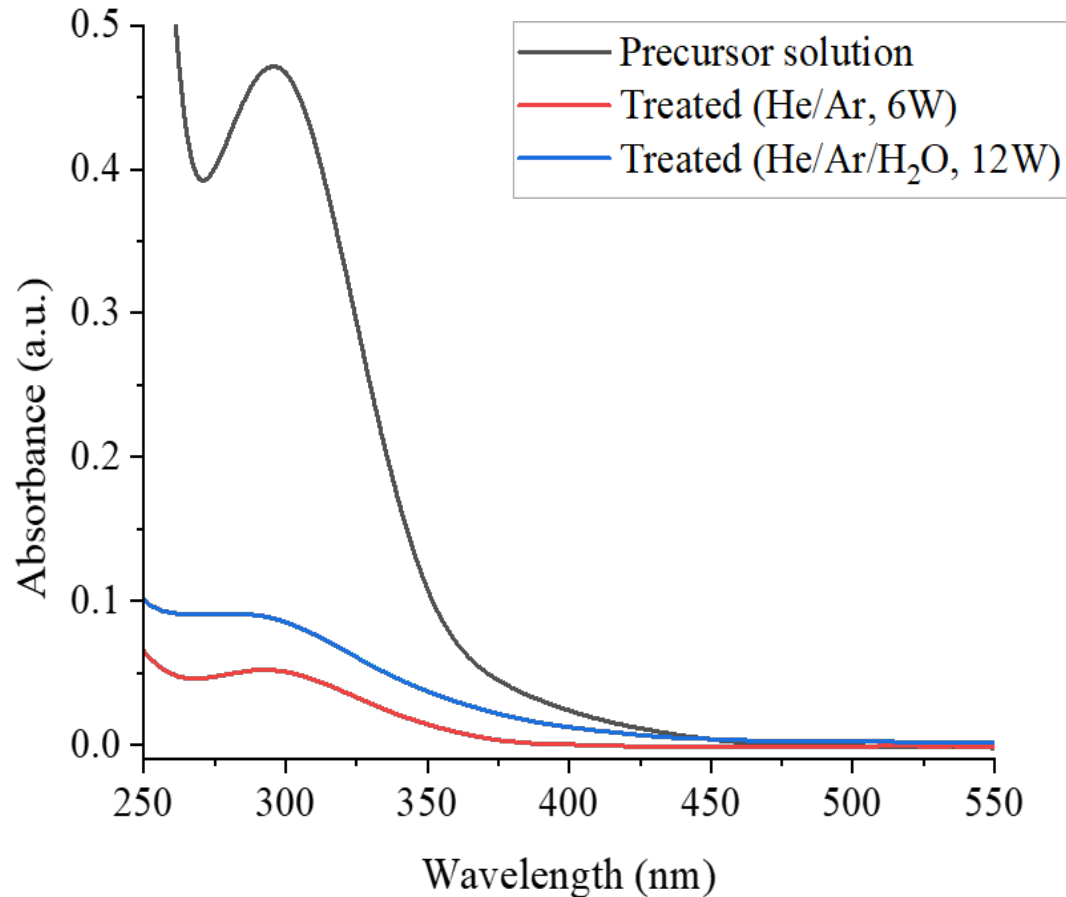
- The reduced metallic monomers precipitates to minimize free energy
- A critical level of supersaturation is needed
- Fast reduction by short-lived species (e, VUV photon) $\Rightarrow$ critical saturation $\Rightarrow$ nucleation



* Thanh, N. *et al.*, *Chem. Rev.*, 114.15 (2014)

** Sugimoto, T., *J. Coll. inter. sci.* 309.1 (2007)

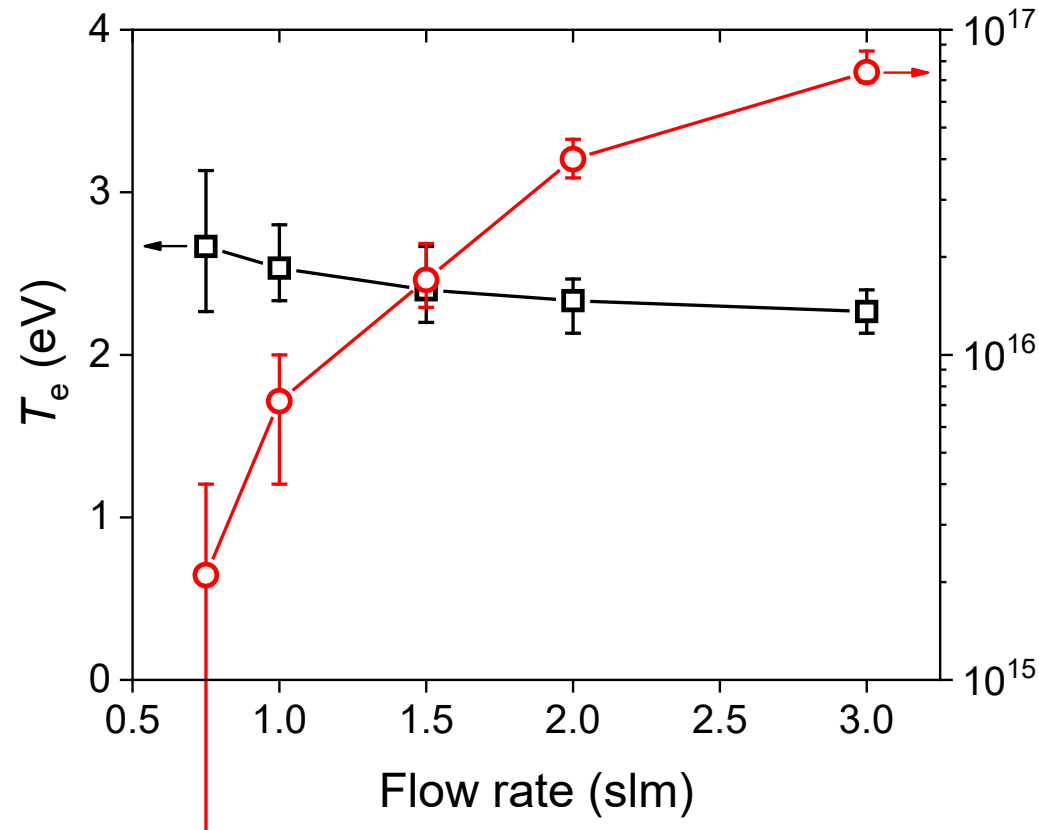
Precursor Conversion



- Gold ion complex (AuCl_4^-) concentration
- > 70% of ions in the precursor in the droplets were converted by the plasma
- Maximum conversion possible for diffusion-limited interfacial reduction (e.g. solvated electrons) for residence time of 10 ms is only 27%
- **Reduction process occurs not only in the plasma but also during afterglow (long-lived species are involved $\rightarrow \text{H}_2\text{O}_2$)**



The Role of Electrons: Faradaic Efficiency



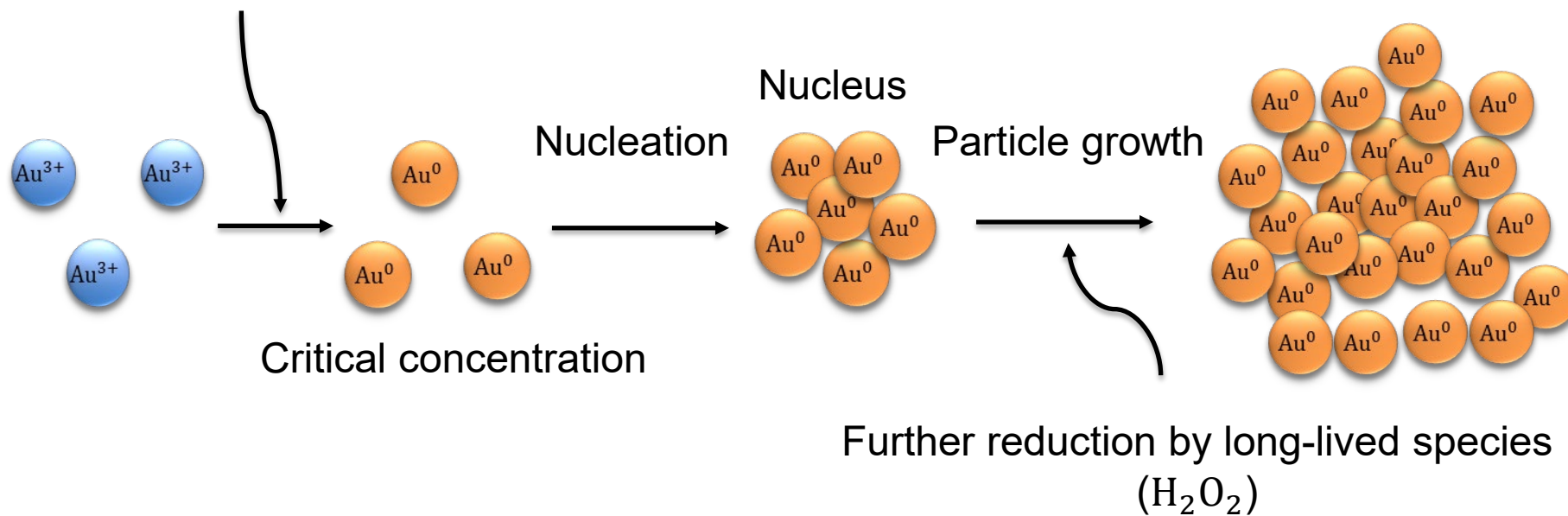
- Electron density measured from absolute optical emission measurements (Bremsstrahlung)
- Electron current into a droplet is $n_e \frac{Da}{L_s} \pi R_p^2 \leq 10^{10} \text{ s}^{-1}$.
- Thermal electron flux is significantly larger (collisional sheath!!!)
- During droplet residence time (10 ms), less than 1.0×10^8 electrons are injected into a droplet
- 1.4×10^{10} Au^{3+} ions are reduced (1 mM, >70% converted)
- Faradaic Efficiency (FE) for $\text{Au}^{3+} + 3\text{e}^- \Rightarrow \text{Au}^0$
FE > 250%

Electrons alone cannot explain the process!

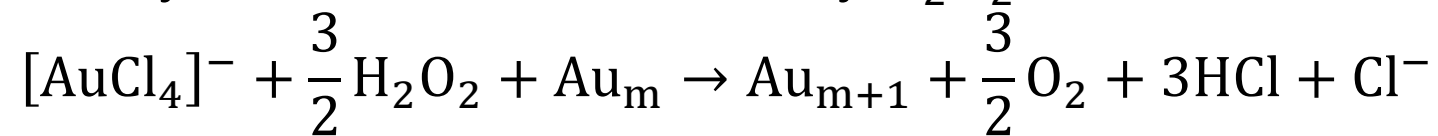


Proposed Mechanism

Fast reduction by short-lived species
(e^- , VUV)



- Autocatalytic reduction is enabled by H_2O_2



$$k_{AC} = 0.94[H_2O_2]^{0.54}$$

V. K. Meader, M et al., *J. Phys. Chem. A*, 121, 36,(2017)



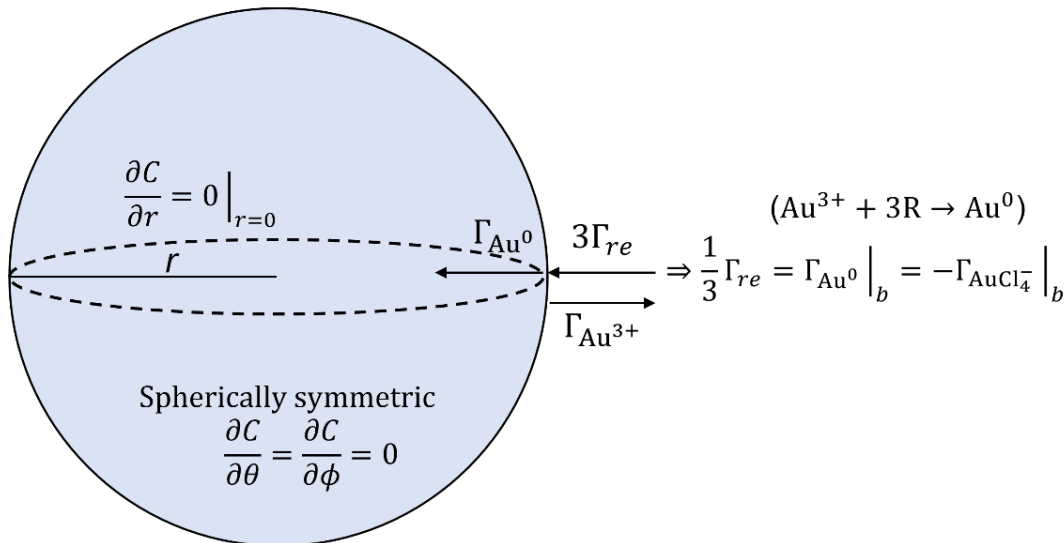
Nucleation and Growth Model – Gold Nanoparticles

Reaction-diffusion model in droplet (Au³⁺, Au⁰, H₂O₂, NPs)

1 – D reaction-diffusion equation

$$r^2 \frac{\partial C}{\partial r} = \frac{\partial}{\partial r} \left(r^2 D \frac{\partial C}{\partial r} \right) + r^2 \dot{S}$$

C: AuCl₄⁻, H₂O₂, Au⁰, AuNP



Assumed 100% FE for reducing species

$$\Gamma_{\text{electrons}} = 10^9 - 10^{10} \text{ s}^{-1}$$

- **Classical nucleation theory**
 - results in Au₁₃ (first magic number)



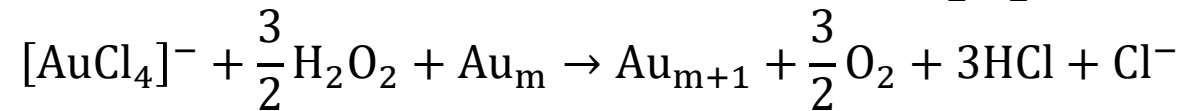
$$\dot{R}_{nu} = A \cdot \exp \left(- \frac{16\pi\gamma^3 v^2}{3k_B^3 T^3 \ln S^2} \right)$$

$$S = \frac{C_{Au^0}}{C'_{Au^0}}, C'_{Au^0}: \text{solubility}$$

- **Particle growth mechanisms**
(Only average particle size is considered)
 - Diffusion-limited adsorption of Au⁰

$$k_d = 4\pi D_{Au^0} R_{NP} C_{Au^0}$$

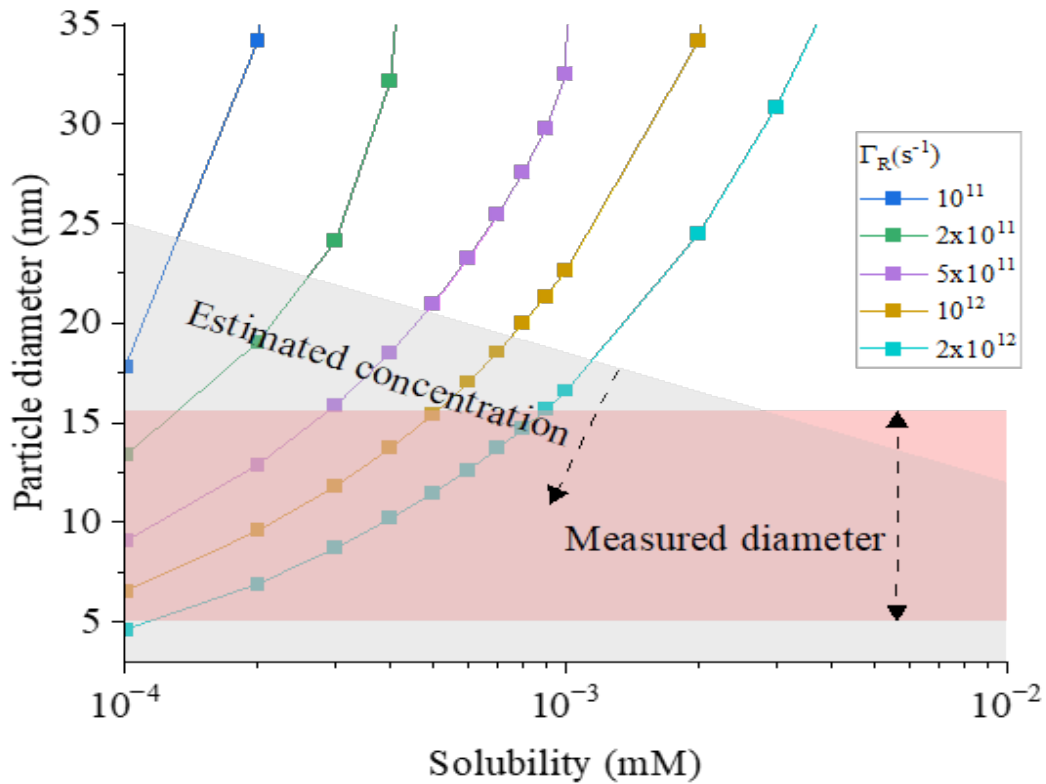
- Autocatalytic growth facilitated by H₂O₂



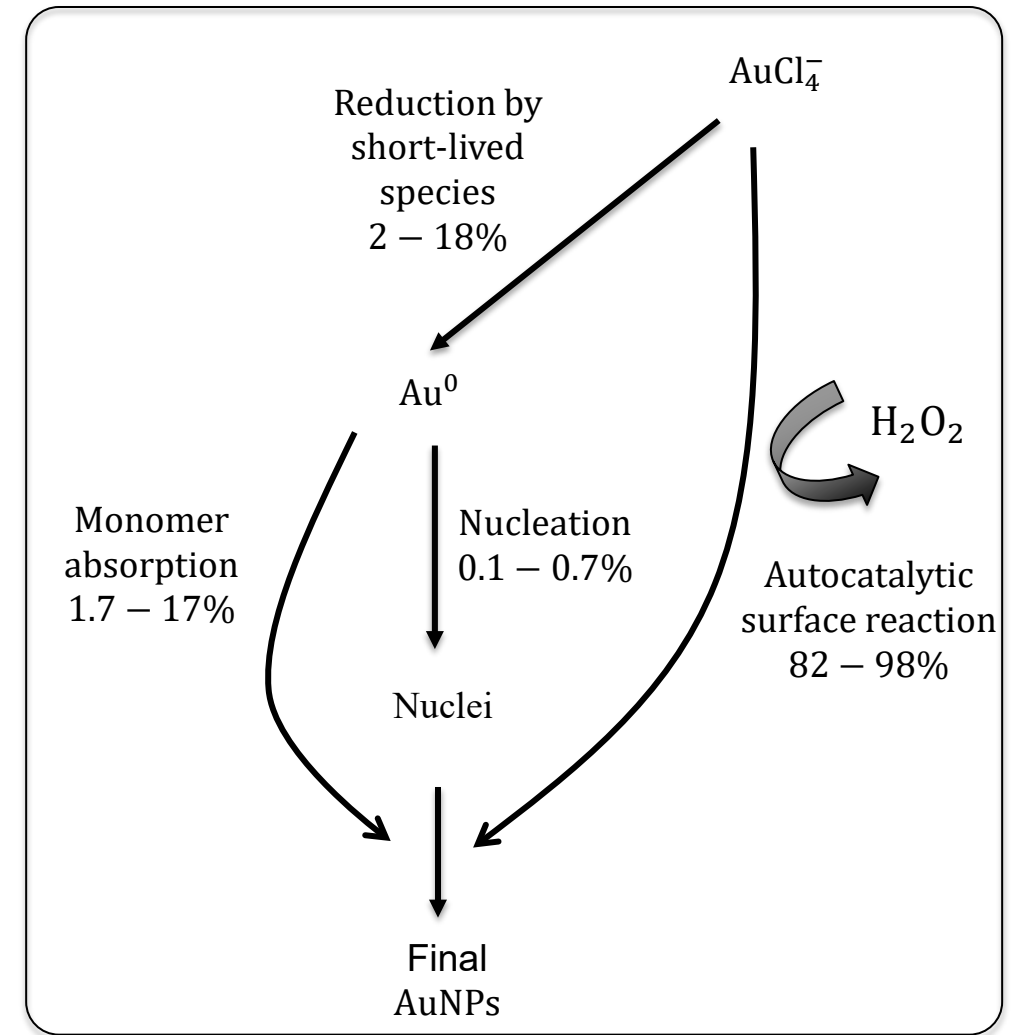
$$k_{AC} = 0.94 [H_2O_2]^{0.54} \quad (\text{Meader et al. } JPC A \text{ 2017})$$



Particle Diameter and Consumption Pathways of Au_3^+



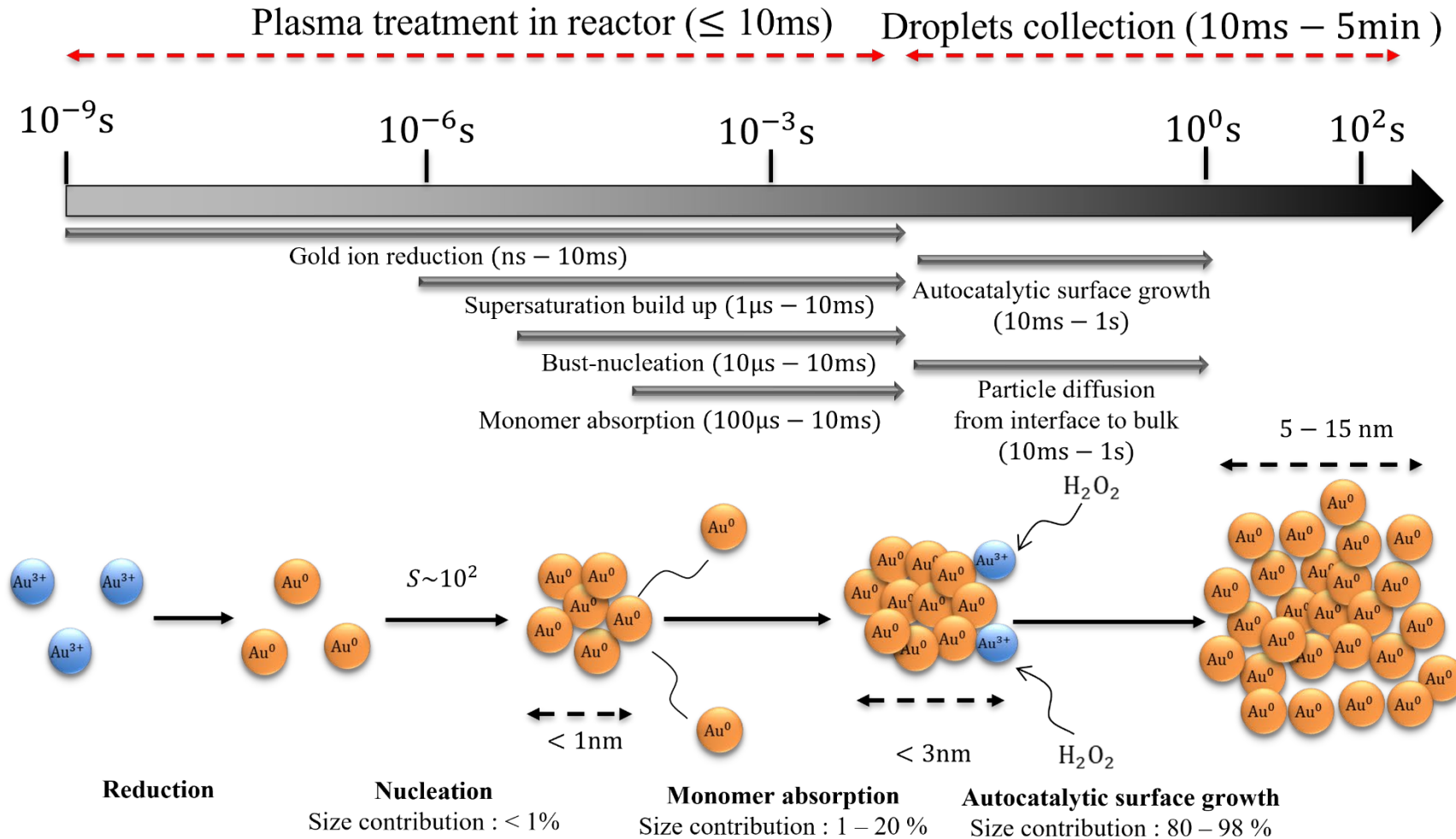
- Particle diameter & concentration from estimated from experiments (UV-vis abs, TEM)
- To satisfy these conditions: $\Gamma_R > 2 \times 10^{11} \text{ s}^{-1}$ ($\times 20 \Gamma_e$), C'_{Au} : $10^{-4} \text{ mM} - 10^{-3} \text{ mM}^*$



- Precursor ions are mostly reduced (>80%) by autocatalytic growth within 1s.



Proposed Mechanism of AuNP production



Conclusion: PDSE

- PDSE can drive redox chemistry in liquid phase (electrodeless electrochemistry) and is a **green alternative for materials synthesis**.
- **Different species** can be responsible for nucleation and growth. Decoupling timescales of nucleation and particle growth can lead to small NPs with narrow size distribution.
- PDSE processes can be exceeded by **250 times the maximum Faradaic efficiency**.



Conclusion

- Plasma technology has the potential to play a significant role in **enabling a healthy and sustainable society**.
- Plasma is a **promising technology for (airborne) virus inactivation**.
- Plasma-catalysis synergies might provide a promising avenue to explore in the context of **electrification of the chemical industry** leveraging newly emerging insights might be needed to drive progress.
- Plasma driven solution electrochemistry is a **green alternative for materials synthesis**. Emerging understanding is opening perspectives of materials property control. Multiple processes can drastically enhance Faradaic efficiency up to **~250** times the Faradaic limit for electron-reduction only.

