Introduction to Low Temperature Plasmas

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Massachusetts Institute of Technology

2025 Introduction to Plasma and Fusion Course
Princeton Plasma Physics Laboratory (PPPL)
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My background:
Aerospace Engineering & Plasma Science

Career Goals

Enable predictive design and control of plasma phenomena and technologies

Engineer plasma technologies that promote a sustainable environment, global security and exploration

Educate a diverse pool of leaders, creative engineers, and entrepreneurs in Aerospace and Plasma Science & Tech

Aerospace Engineer

B.S. Aerospace Engineering
- Aerospace Vehicles

Junior engineer
- Rocket and mission design

Ph.D. Aerospace
- Plasma-Assisted Combustion
- Electrical control of flames

S.M. Aerospace
- Pulsed nanosecond plasmas

Postdoc.
- Electrostatic discharge and lightning to aircraft
- Ion sources for space propulsion

Research Engineer @Boeing
- Electrostatic discharge and lightning to aircraft

Professor @ MIT AeroAstro
- Plasma-assisted technologies for combustion and energy
- Fundamentals of electrical breakdown
- Aircraft safety: lightning, ignition risks

- Teach courses on Ionized Gases & Aerospace Propulsion

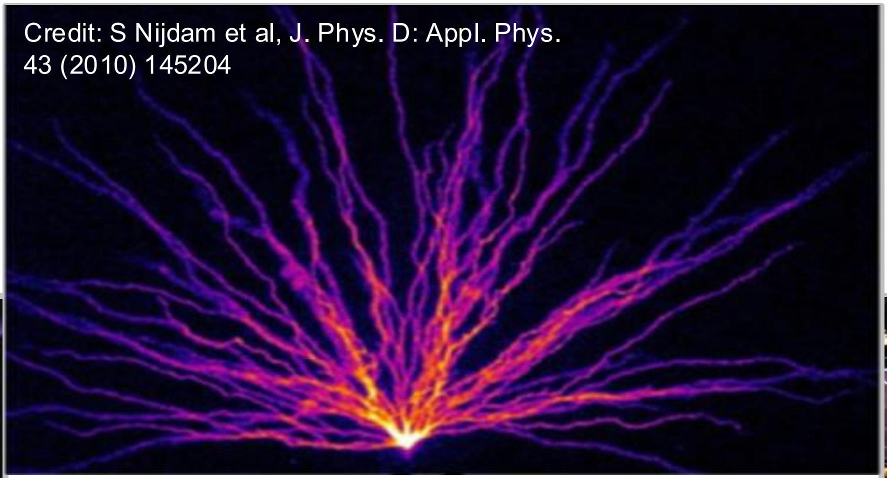
Plasma Scientist

Undergraduate studies | Industry | Graduate studies | Postdoc. | Industry R&D | Academia | time

Spent a few months at Princeton while doing my PhD at MIT!

Mission of the Aerospace Plasma Group

Unveil the physics of transient electrical discharges to understand our natural environment and *enable their control for the benefit of our planet and beyond*



Credit: S Nijdam et al, J. Phys. D: Appl. Phys. 43 (2010) 145204

Fundamentals of electrical breakdown

Credit: University of Windsor, Clean Combustion Engine Lab

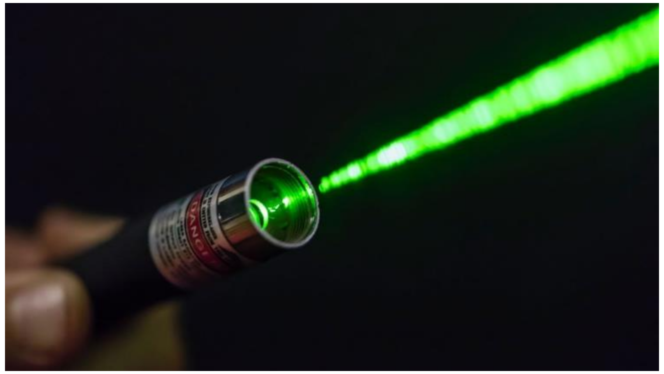
Plasma-assisted aerospace technologies

Credit: Sales Wick, BeyondClouds

Lightning safety

Some of the (fun) things we do to get our research done

- Testing in lightning lab
- Fly drones
- Testing in wind tunnel
- Burn stuff
- Learn about lasers

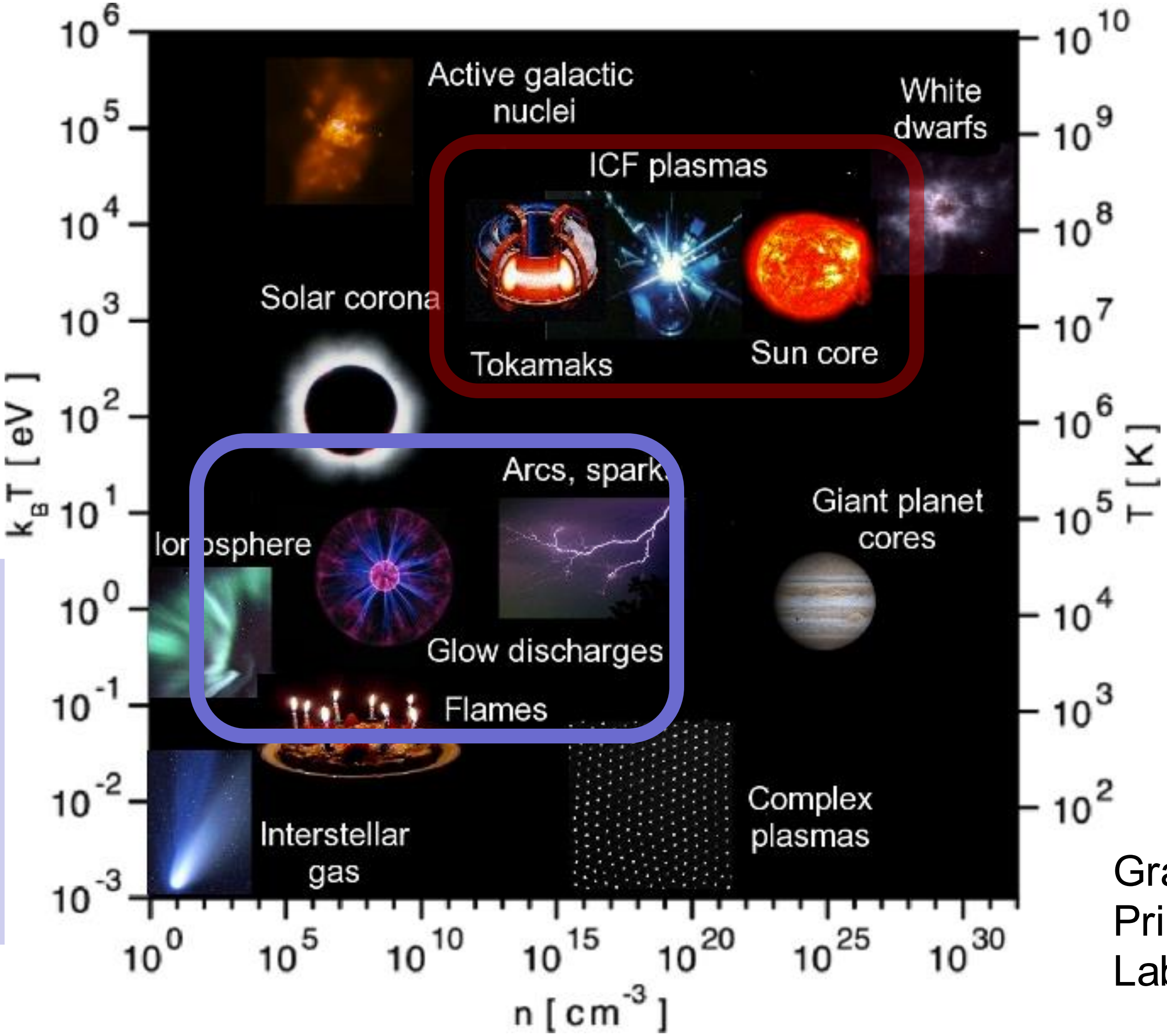


- **Collaborate with scientists from around the country & abroad!**

Agenda for today

- What is a Low Temperature Plasma (LTP)?
- The Electron Energy Distribution Function → Non-Maxwellian
- The Reduced Electric Field, E/N → Plasma Chemistry
- Fluid Models and the Drift-Diffusion Approximation
- Some Examples and Applications (from my grad students)

Low Temperature Plasma (LTP)



FUSION PLASMAS

- Fully ionized
- Neutrals and ions high T
- Electrons high T

LTP PLASMAS

- Partially ionized
- Neutrals and ions low T
- Electrons high T

Graph shared by Dr. Dominguez, Princeton Plasma Physics Laboratory [Lecture 1]

Low Temperature Plasmas (LTP)

- Also known as: Non-Thermal Plasmas (NTP), Cold Plasmas, Non-Equilibrium Plasmas…

FUSION PLASMAS

- Fully ionized
- Neutrals and ions high T (~10^8 K)
- Electrons high T (~10^8 K)
- In thermal equilibrium
- Fusion reactions for energy
- Fully magnetized

COLD PLASMAS

- Partially ionized
- Neutrals and ions low T (100-1000K)
- Electrons high T (10^4-10^5 K)
- Out of thermal equilibrium
- Very rich and versatile chemistry
- Often unmagnetized

- What is common to LTP: **NON-EQUILIBRIUM** (in several fronts!)

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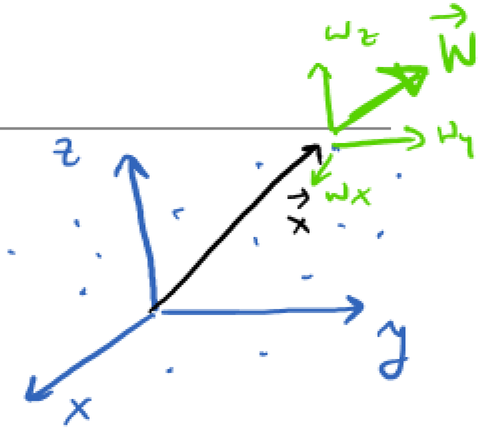
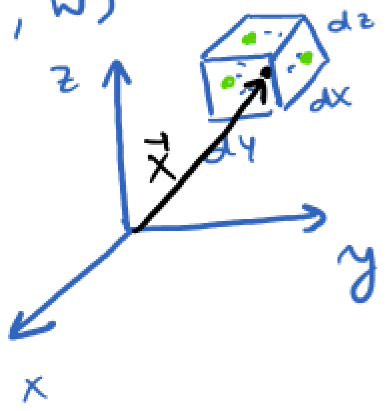
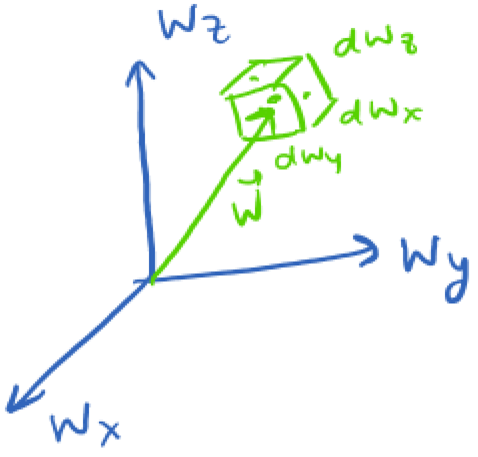
Kinetic Theory and Distribution Functions



- Describes gas behavior based on particle motion & interactions
  - Particles: electrons, ions, atoms, molecules
- Focuses on submicroscopic (statistical) behavior, not just macroscopic properties
- **Phase Space Representation** (6D) $(\vec{x}, \vec{w})$
  - 3D physical space
  - 3D velocity (momentum) space

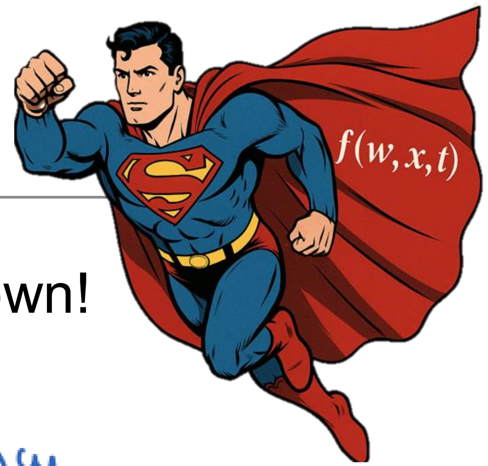




- **Velocity Distribution Function (VDF)**

$$f(\vec{x}, \vec{w}, t) = \frac{\#\text{ of particles in } (\vec{x}, d^3x)(\vec{w}, d^3w)}{d^3x\, d^3w}$$

Recovering the macroscopic behavior



- If $\boldsymbol{f}(\vec{\boldsymbol{x}}, \vec{\boldsymbol{w}}, t)$ is known → all macroscopic values of physical interest are known!

- **Macroscopic Properties from** $f(\vec{\boldsymbol{x}}, \vec{\boldsymbol{w}}, t)$ → Remove the $\vec{w}$ dependency
  - Macroscopic quantities: density, pressure, temperature (n, p, T)
  - Can be obtained via averages (or moments) of the velocity distribution
  - E.g. 1) Total number density, n$(\vec{\boldsymbol{x}}, t)$: # of particles per u. volume, irrespective of velocity

$$n = n(\vec{x},t) = \iiint_{w_z\, w_y\, w_x\to-\infty}^{w_x\to+\infty} f(\vec{x},\vec{w},t)\, d^3w = \frac{\#\text{ of particles in } (\vec{x}, d^3x)}{d^3x}$$

Recovering the macroscopic behavior

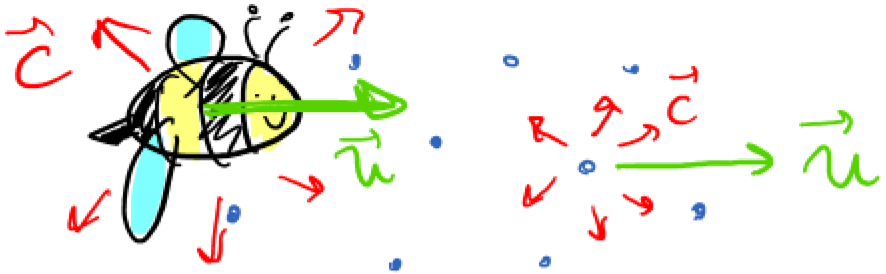
- E.g. 2) Mean velocity, $\vec{\boldsymbol{u}}(\vec{\boldsymbol{x}}, t)$: average velocity of all particles at that location, $\vec{\boldsymbol{x}}$

$$\langle \vec{w} \rangle = \vec{u}(\vec{x}, t) = \frac{\iiint_{-\infty}^{\infty} \vec{w} f \, d^3w}{\iiint_{-\infty}^{\infty} f \, d^3w} = \frac{1}{n} \iiint_{-\infty}^{\infty} \vec{w} f \, d^3w$$

  - The concepts of temperature and pressure are related to the motion of individual particles with respect to this average fluid velocity
  - Definition: random (or peculiar) velocity of a particle, $\vec{\boldsymbol{c}}(\vec{\boldsymbol{x}}, t)$: velocity of a particle with respect to the mean:

$$\vec{c} = \vec{w} - \vec{u}$$

- E.g. 3) Temperature, $\boldsymbol{T}(\vec{\boldsymbol{x}}, t)$: thermal energy equivalent to the random KE



$$\left\langle \frac{1}{2} m c^2 \right\rangle = \frac{3}{2} k T(\vec{x}, t)$$

Boltzmann equation & distribution functions

- Governing equation that describes $\boldsymbol{f}(\vec{\boldsymbol{x}}, \vec{\boldsymbol{w}}, t)$

material derivative: change of f in time as it follows the fluid parcel.

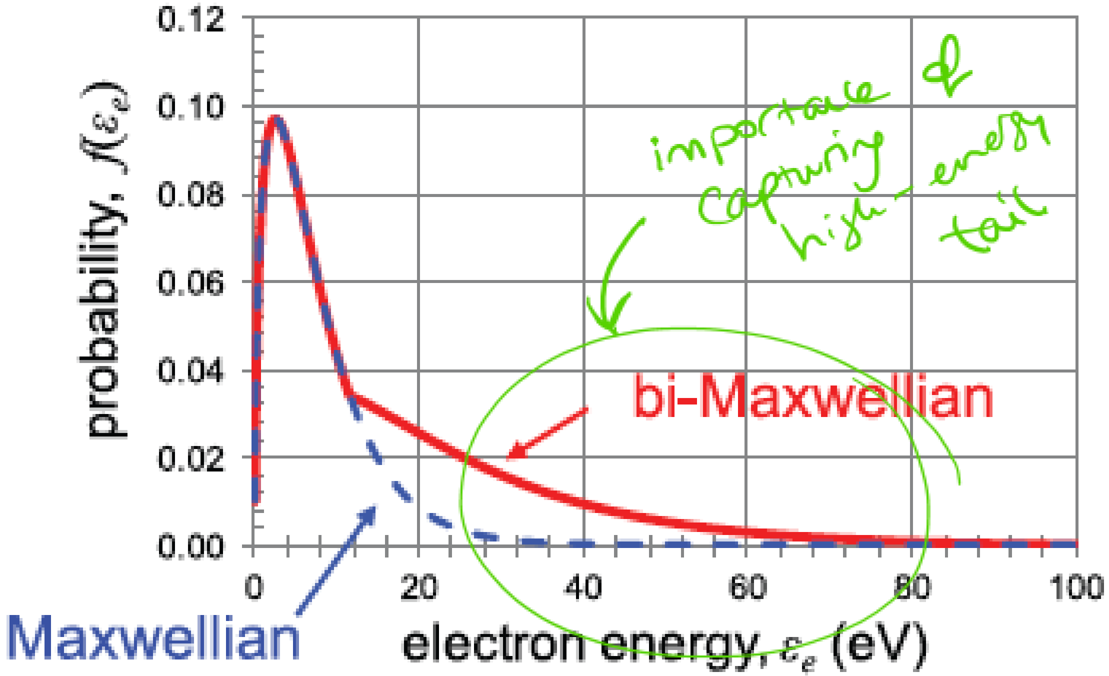
$$\frac{Df_s}{Dt} = \frac{\partial f_s}{\partial t} + w_i \frac{\partial f_s}{\partial x_i} + \frac{F_i}{m_s}\frac{\partial f_s}{\partial w_i} = \left(\frac{df_s}{dt}\right)_{\text{coll}}$$

a_i collisions!!

- In equilibrium, $\boldsymbol{f}$ follows a Maxwellian distribution

- In LTP, we often must solve the Boltzmann equation to find the electron energy distribution function → **Non-Maxwellian** electron energy distribution function

- The high energy-tail is very important for the chemistry!!



D. Go. Ionization and Ion Transport (Second Edition): A primer for the study of gas discharges and plasmas - https://doi.org/10.1088/978-0-7503-3991-9

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The local field approximation

- Electrons gain energy from the field

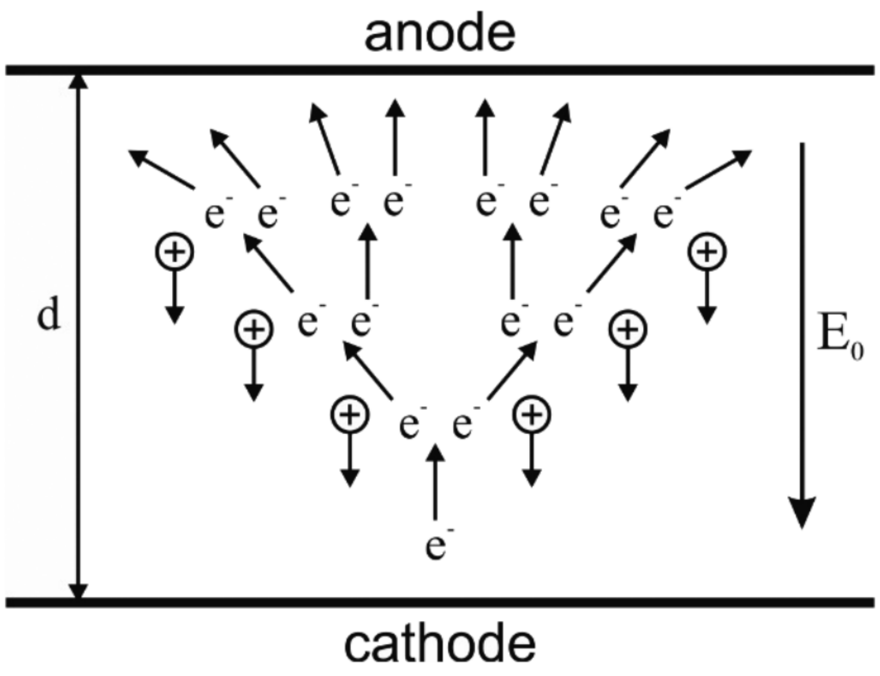
$$\dot{\epsilon}_{gain} = n_e \vec{v}_e \cdot (-e\vec{E}),\ \vec{v}_e = -\mu_e \vec{E}$$

- And spend it in collisions (locally)

$$\dot{\epsilon}_{lost} = n_e \nu_{eh} \frac{2m_e}{m_h} \delta \frac{3}{2} k (T_e - T_h)$$

- Electron temperature/ energy is defined by the reduced electric field

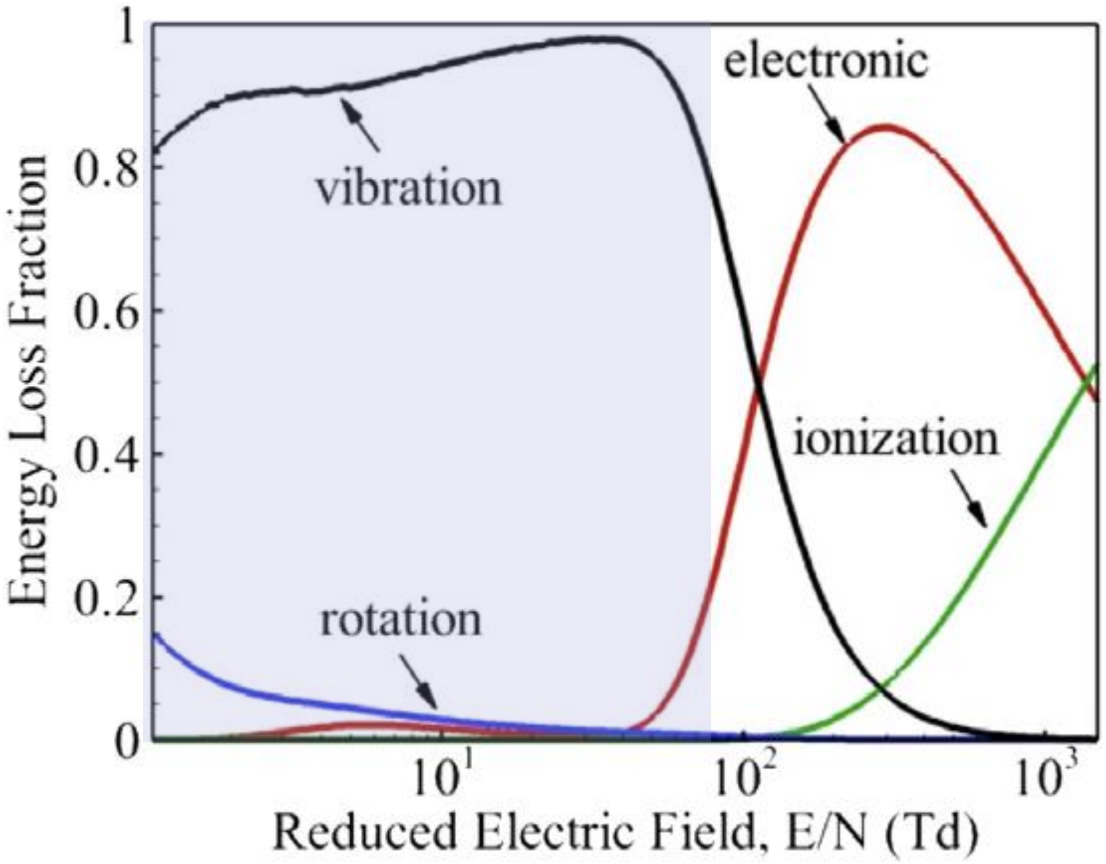
$\dot{\epsilon}_{gain} = \dot{\epsilon}_{lost} \Rightarrow T_e = T_e(E/N)$



A. A. Fridman, Plasma Chemistry, Cambridge University Press, 2012

E/N ≡ reduced electric field.

E/N defines the chemistry



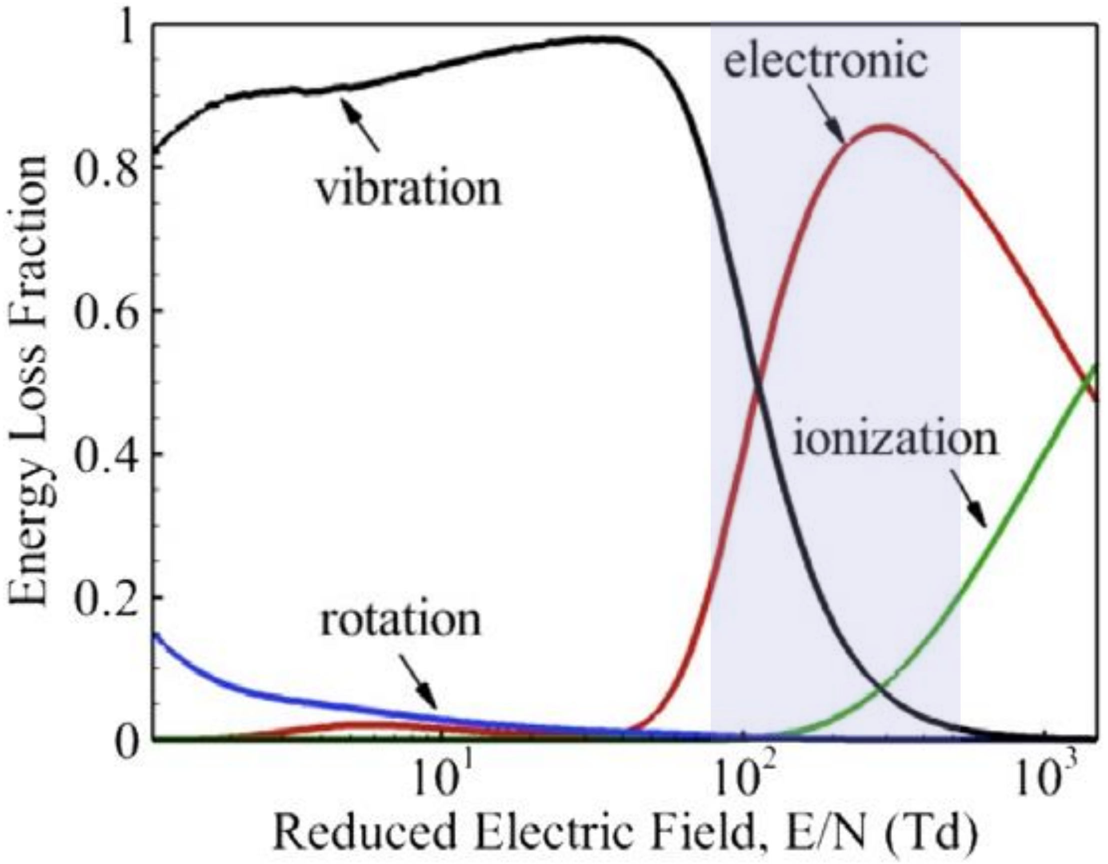
E/N < 100 Td

- Energy goes primarily into exciting rotational modes and low-energy vibration
- Rotational excitation rapidly equilibrates with gas temperature (τ_{RT}~0.1ns)
- Vibrational-translational (VT) relaxation times are much longer (τ_{VT}~100μs)

S Nagaraja et al. J. Phys. D: Appl. Phys. 46 (2013) 155205

$1\text{Td} = 10^{-17}\ Vcm^2$ ~250V across a 1cm gap at STP

E/N defines the chemistry



E/N ~ 100-400 Td

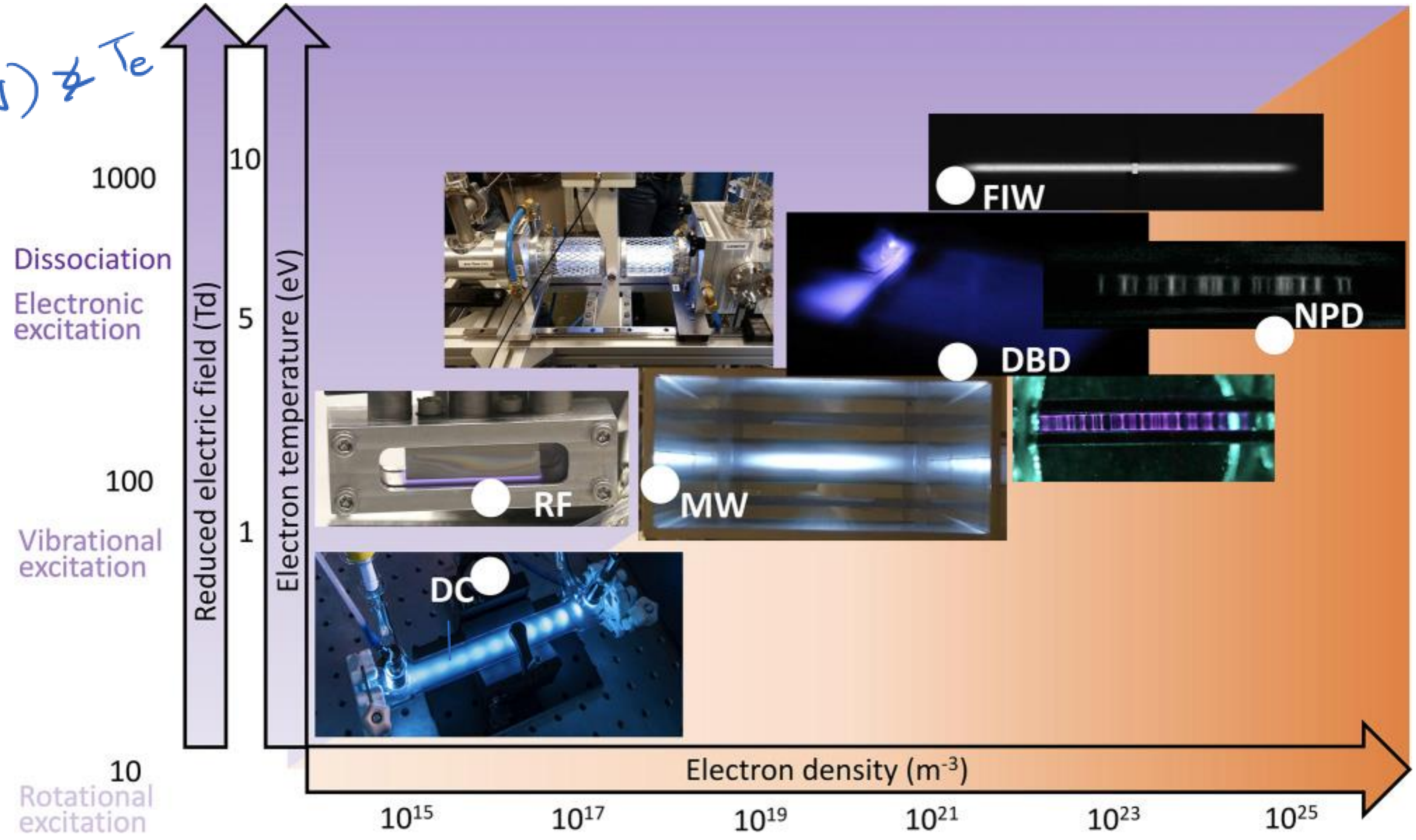
- Most energy goes into exciting electronic degrees of freedom
- Electronically excited states rapidly quench
- Quenching often results in dissociation/energy release
- Occurs much faster than VT relaxation ("fast gas heating")

$$N_2^{*}+O_2 \rightarrow N_2+O+O+\epsilon$$

S Nagaraja et al. J. Phys. D: Appl. Phys. 46 (2013) 155205

$1\mathrm{Td} = 10^{-17}\ Vcm^2$ ~250V across a 1cm gap at STP

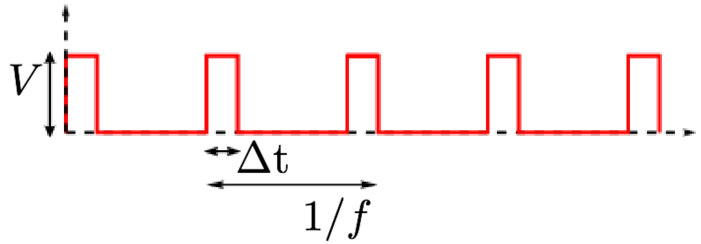
Different plasma sources can access different E/N



V Guerra et al. J. Appl. Phys. 132, 070902 (2022)

Nanosecond Pulsed Discharges (NPD)

- High E/N can be accessed using pulsed power → plasma shielding effects!
- To couple the energy to the electrons (nonequilibrium), current needs to be limited

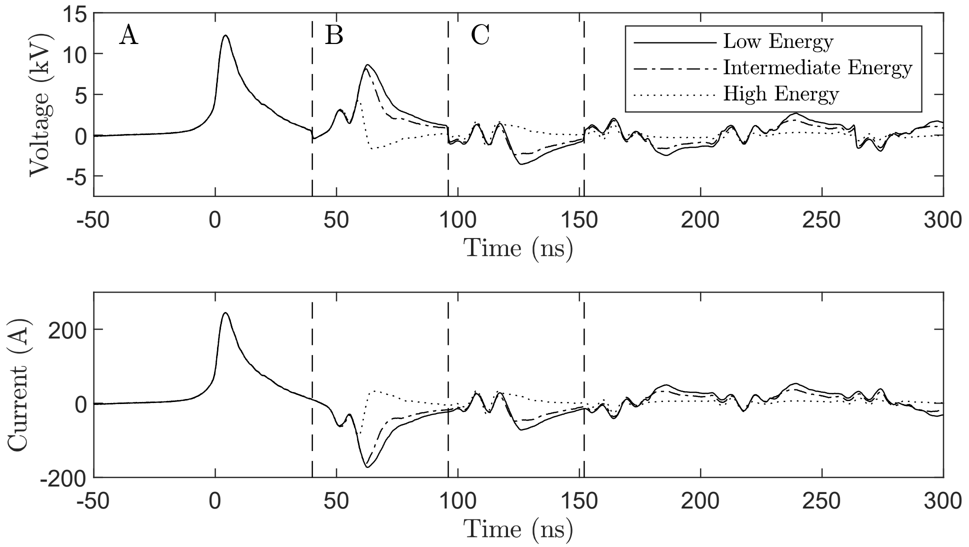


Nanosecond Pulsed Discharges (NPD)

- Short duration pulses: Non-equilibrium, high E/N
- High frequency: Sustain plasma

Eectrical parameters

- Gas gap: ~1-10mm
- Electrical: ~10kV, ~20ns, 1-50kHz
- Energy per pulse: ~100μJ-10mJ
- Power: 0.1-500W
- **E/N ~ 180-500 Td**



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From Kinetic Theory to Fluid Models

- Fluid models are derived by taking moments (< averages >) of the Boltzmann equation

$$[BE]: \quad \frac{Df_s}{Dt} = \frac{\partial f_s}{\partial t} + w_i \frac{\partial f_s}{\partial x_i} + \frac{F_i}{m_s}\frac{\partial f_s}{\partial w_i} = \left(\frac{df_s}{dt}\right)_{\text{coll}}$$

- Yield macroscopic conservation equations for:
  - mass, $\iiint_{-\infty}^{\infty} m_s [BE]\, d^3w \longrightarrow \frac{\partial n_s}{\partial t} + \nabla_x \cdot (n_s \vec{u}_s) = \dot{S}_s$
  - momentum, $\iiint_{-\infty}^{\infty} [BE]\, m_s \vec{w} \longrightarrow$ momentum conservation
  - energy $\iiint_{-\infty}^{\infty} [BE]\, \frac{1}{2} m_s w^2 \longrightarrow$ energy conservation

(s) = electrons, ions, atoms, molecules ...

- The general equations are very complicated and still need to be combined with Maxwell's equations for $\vec{E}$ and $\vec{B}$!

Drift-diffusion approximation typically used in LTP

- Fluid models should be simplified given the specific problem of interest
- For LTP a multi-fluid model is needed
- In the case of LTP, a common approximation is the ‘drift-diffusion’ model
- Combines all 3 conservation equations into 1

mass conservation

momentum information

$$\frac{\partial n_p}{\partial t} + \nabla \cdot \vec{\Gamma}_p = S_p,$$

$$\nabla \cdot (\epsilon_r \varepsilon_0 \nabla V) = -e(n_i - n_e),$$

Poisson eq.

drift. diffusion.

$$\vec{\Gamma}_p = \mathrm{sign}(q_p) n_p \mu_p \vec{E} - D_p \nabla n_p,$$

p = electrons, ions

Where is the momentum equation?

$$\frac{\partial n_p}{\partial t} + \nabla \cdot \vec{\Gamma}_p = S_p,$$

$$\vec{\Gamma}_p = \text{sign}(q_p) n_p \mu_p \vec{E} - D_p \nabla n_p,$$

$$\nabla \cdot (\epsilon_r \varepsilon_0 \nabla V) = -e(n_i - n_e),$$

Electrons: assume negligible inertia

$$\nabla p_e + n_e e \vec{E} = - m_e n_e \nu_{en} \vec{u}_e$$

Locally uniform T_e: $\nabla p_e = kT_e \nabla n_e$

$$\vec{\Gamma}_e = n_e \vec{u}_e = - \frac{kT_e}{m_e \nu_{en}} \nabla n_e - n_e \frac{e}{m_e \nu_{en}} \vec{E}$$

D_e = diffusion

μ_e = mobility

drift

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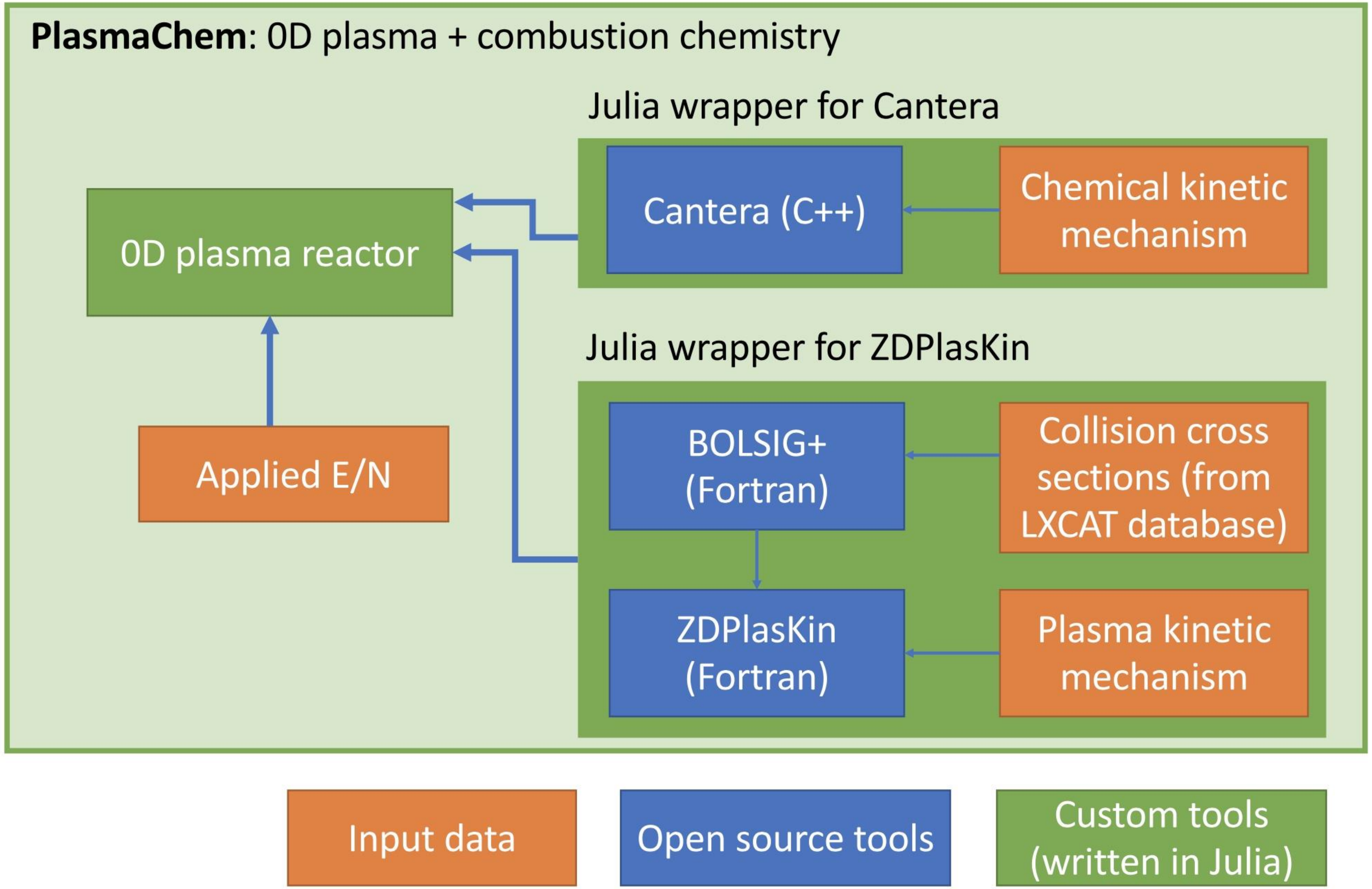
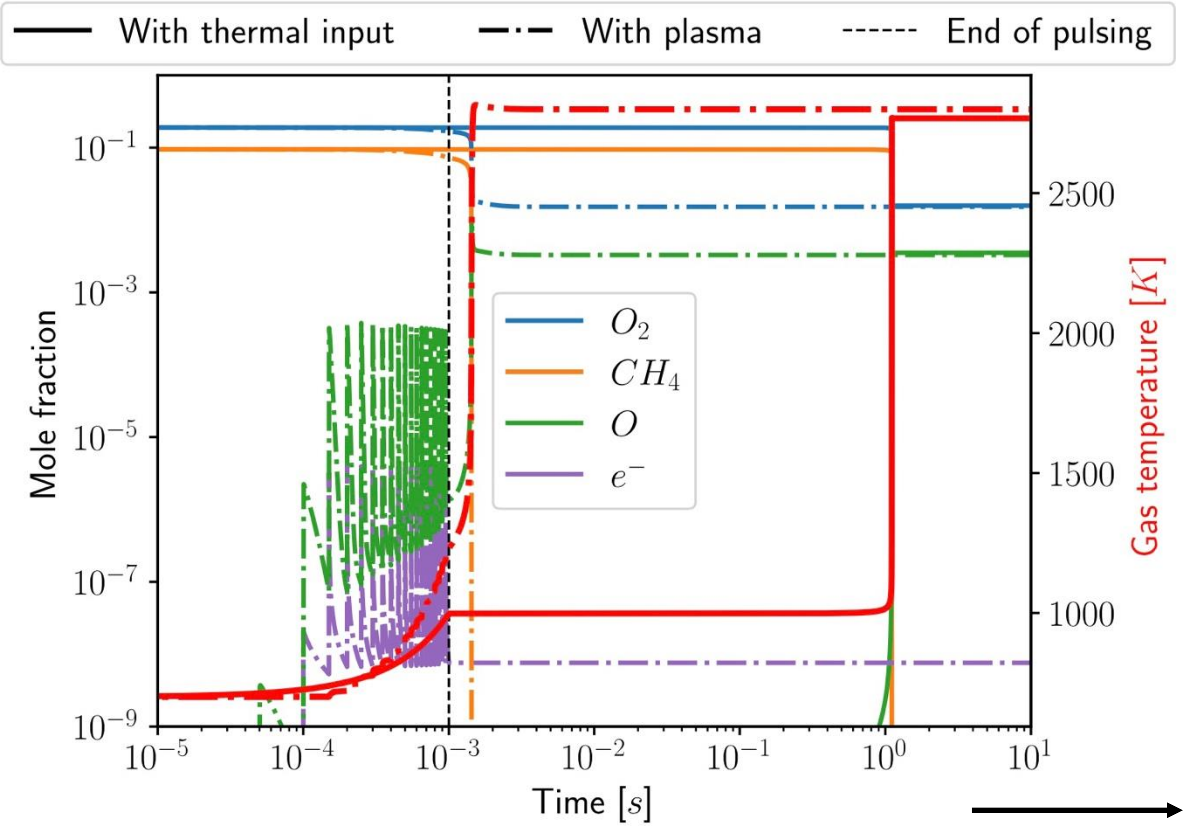
How do we bring this together in research?



C. Pavan, MIT PhD Thesis 2023

Examples – Plasma-assisted combustion

Performance metric for ignition: ignition delay time (IDT)

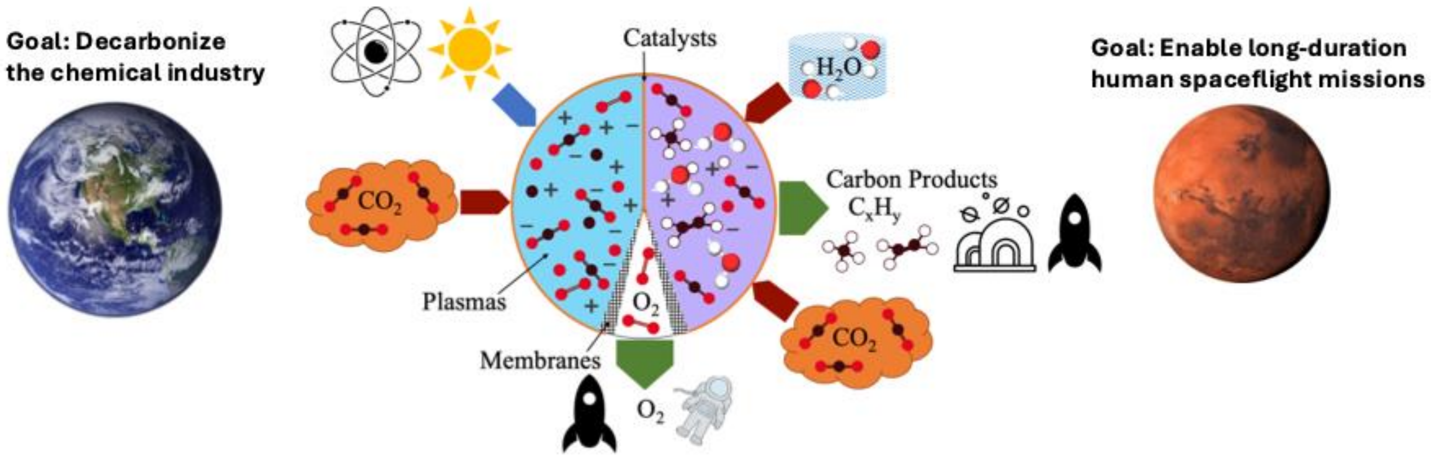


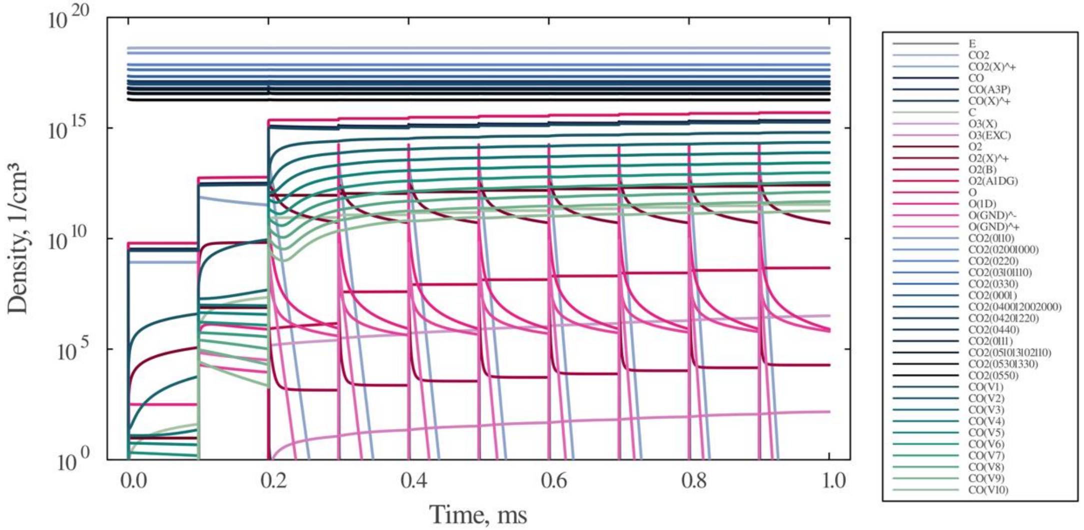
Non-equilibrium effects

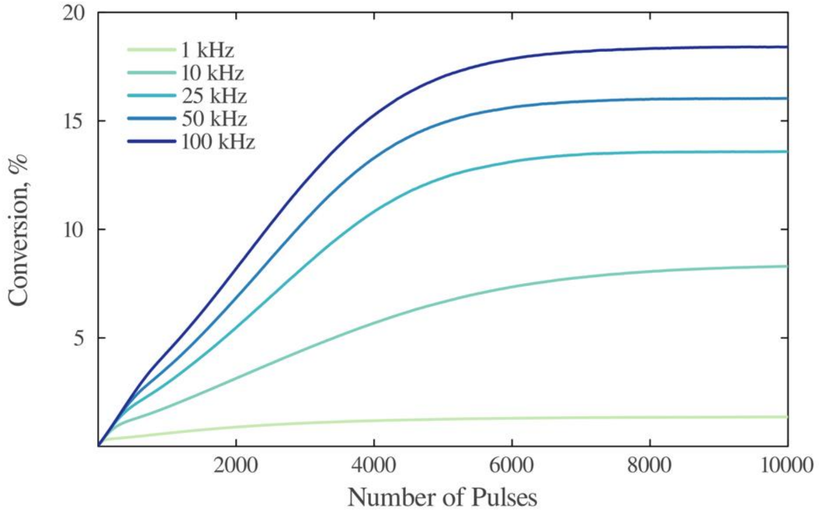
W/o plasma > 10^3 s

R. Dijoud, N. Laws, and C. Guerra-Garcia. Mapping the performance envelope and energy pathways of plasma-assisted ignition across combustion environments. *Combustion and Flame*, 2024.
https://www.sciencedirect.com/science/article/pii/S0010218024005029

Examples – Plasma-based CO_2 conversion



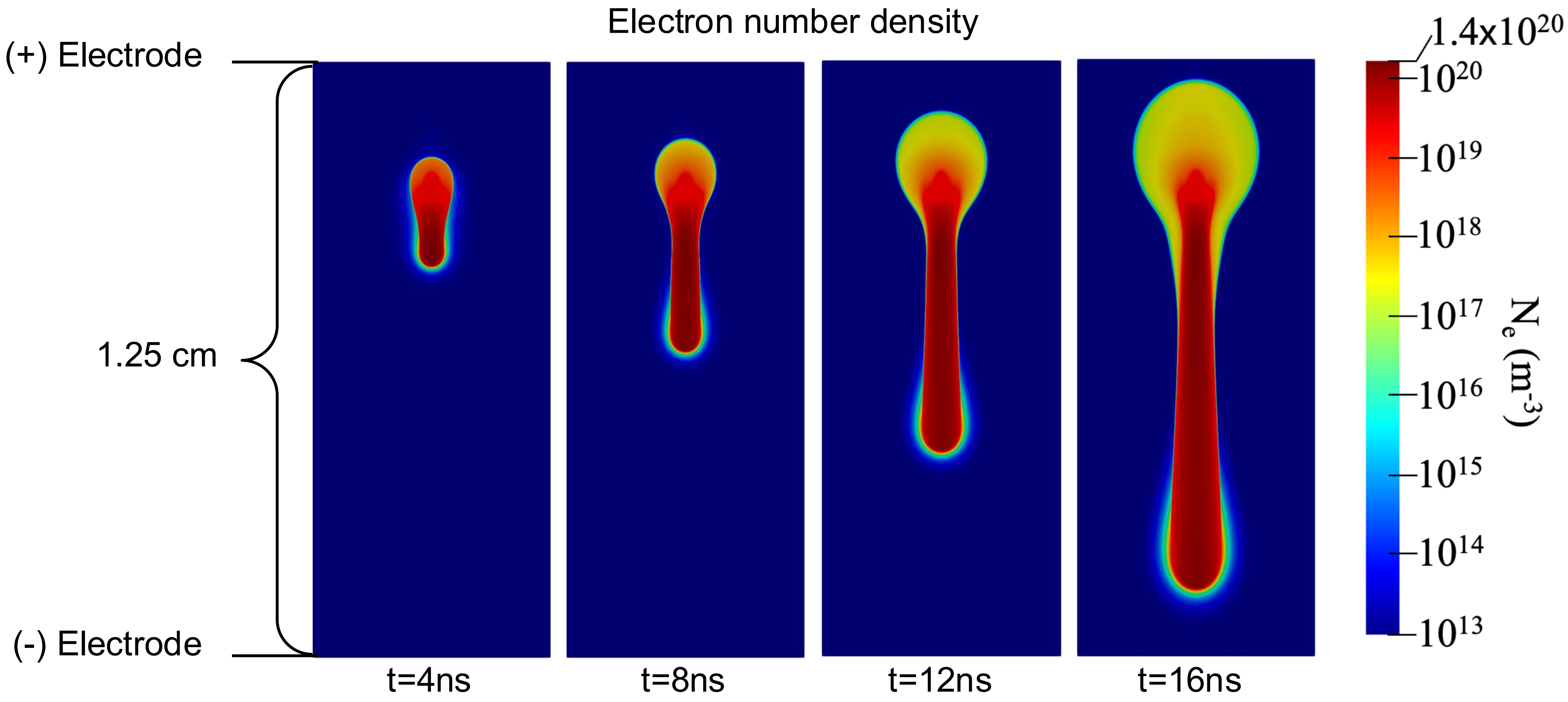




$CO_2 \rightarrow CO, O_2$

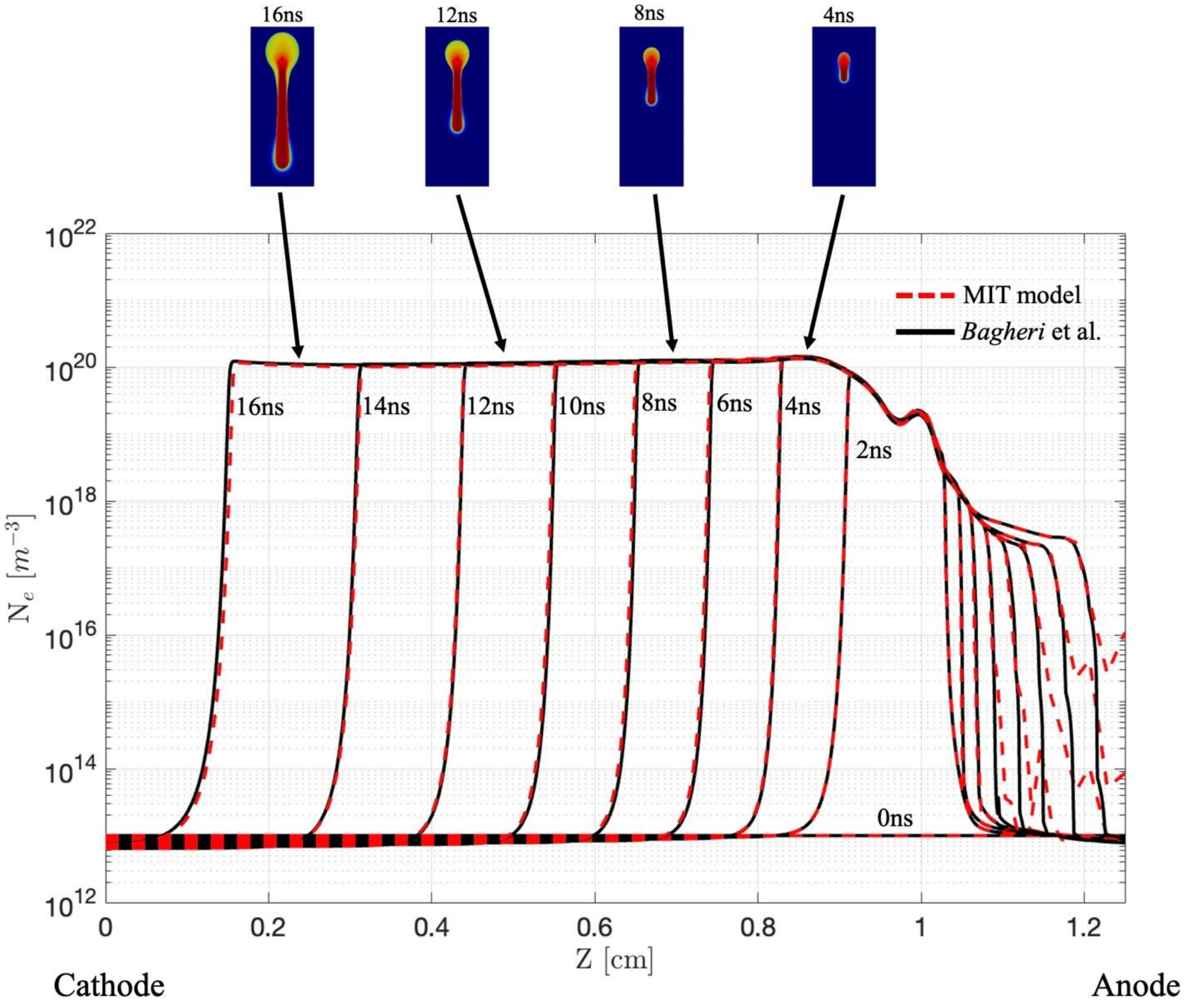
L. McKinney, T. Silva, V. Guerra, and C. Guerra-Garcia. Kinetic modeling of CO2 nanosecond pulsed discharges: insights for reactor design. *In preparation*, 2025

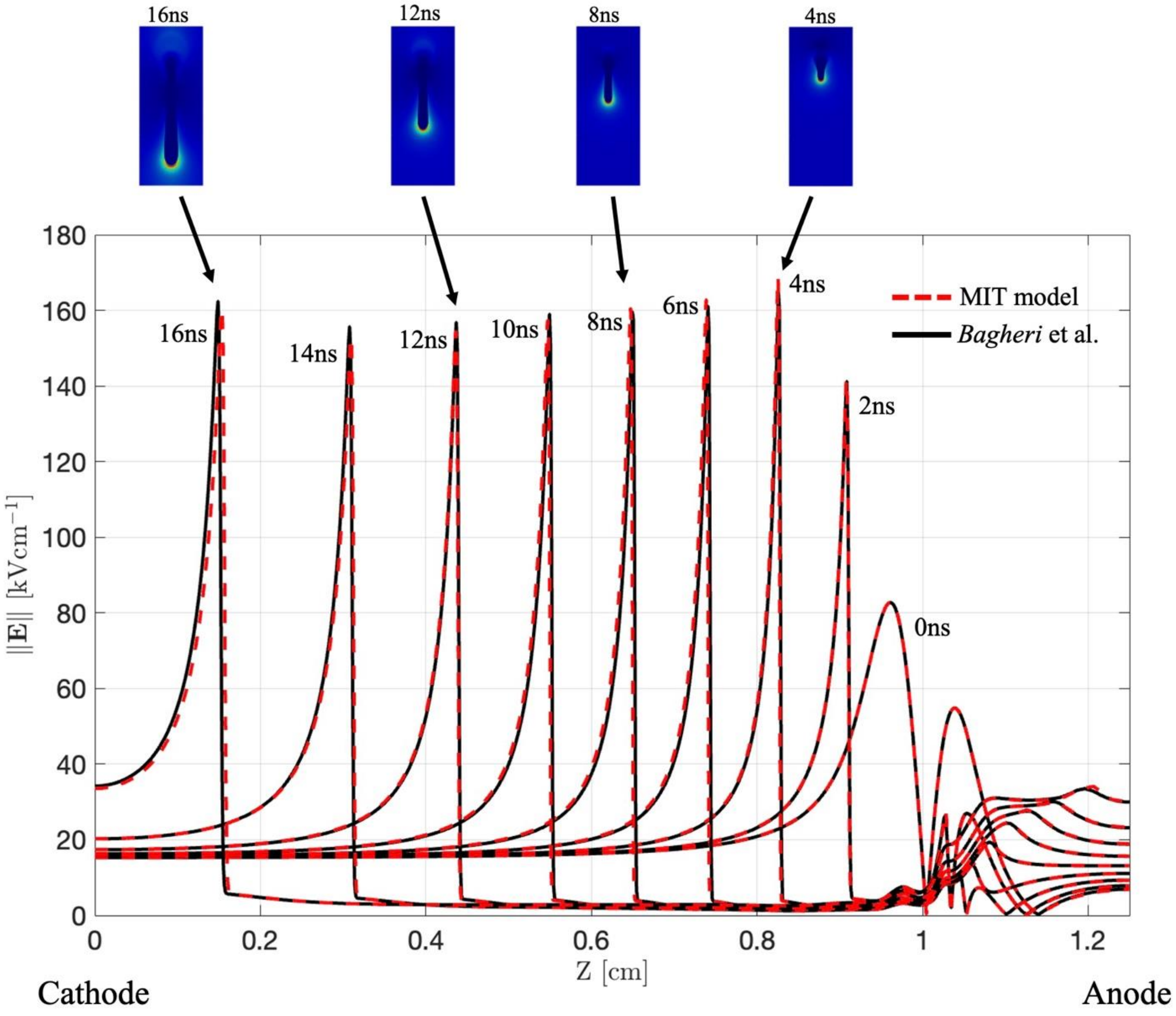
The drift-diffusion approximation to model streamers



Simulated by Sam Austin, MIT Aerospace Plasma Group

The drift-diffusion approximation to model streamers





Simulated by Sam Austin, MIT Aerospace Plasma Group

Bagheri, Behnaz, et al. Plasma Sources Science and Technology 27.9 (2018): 095002

Summary of concepts

QUESTIONS?

- Common to all LTP is their non-equilibrium
  - Thermal: Electrons are much hotter than the heavy species in the gas
  - Energy distribution functions often non-Maxwellian
  - Chemical non-equilibrium is an asset for numerous applications
- The reduced electric field, E/N, is critical to describe these plasmas
- Fluid models for these multi-species plasmas are complex, and simplifications are needed, the drift-diffusion approximation is the most common modelling approach
- The numerous applications of LTP benefit from *dual* scientific backgrounds (e.g. Aerospace + Plasma!)