Applications and Modeling of Non-Equilibrium Plasmas

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Non-Equilibrium Plasmas

Definition of non-equilibrium plasmas

- Low degree of ionization ($\delta$)
  - $n_e$ electron density, $N$ gas density
  - $\delta = \frac{n_e}{n_e + N} < 10^{-3} - 10^{-4}$
  - Gas density $>>$ plasma density

- Collisions between charged particles and neutrals are dominant
  - Transport equation = Boltzmann equation

- Non-equilibrium
  - Electron temperature $>>$ ion and neutral gas temperature
  - $T_e >> T_i \geq T_N$
Non-Equilibrium Plasmas

Electron Temperature (K)

Density n (cm⁻³)

1000 eV
100 eV
10 eV
1 eV

Non-Equilibrium Plasmas

RELATIVISTIC PLASMAS

CLASSICAL PLASMAS

QUANTUM PLASMAS

10¹⁰ 10⁻¹⁰ 10⁻²⁰ 10⁻³⁰

10¹⁰

10⁸

10⁶

10⁴

10²

1000 eV

100 eV

10 eV

1 eV

White dwarfs

Lightening

Solar Corona

Earth Magnetosphere

Solar Wind

Ionosphere

Magnetic fusion

Inertial fusion

Sun

White dwarfs

Thermal Plasmas

Non Equilibrium Plasmas

Mathematical Modeling and Computational Challenges in Plasma Physics - Cargese 2004
Non-Equilibrium Plasmas

Generation of non-equilibrium plasmas

- Current through a gas
  - For large enough applied electric field gas becomes conductor
  - Electron avalanches (ionization) + electron emission by surfaces $\rightarrow$ gas breakdown
  - Self-sustained plasma:
    $\rightarrow$ volume ionization + surface generation = losses to walls + recombination

- Various ways of generating a non-equilibrium plasma
  - DC or pulsed voltage
  - HF (high frequency AC voltage), capacitive or inductive coupling
  - Microwave source, microwave + magnetic confinement, ECR (electron cyclotron resonance)

- Large range of operating pressure
  - At low pressure: difficult to sustain the plasma $\rightarrow$ confinement by magnetic field or HF field
  - At high pressure: difficult to generate a large volume plasma $\rightarrow$ micro-plasma
Non-Equilibrium Plasmas

Applications

Electric Energy

Luminous Energy
Source of photons
- Lamps
  - Lighting
  - Water purification
- Visualization
  - Plasma displays
- Lasers

Kinetic Energy
Source of charged particles
- Ion sources
  - Ion implantation
  - Propulsion
  - Surface treatment
- Electron beams
  - X-ray source
- Switches

Chemical Energy
Source of active species
- Surface processes
  - Microelectronic
  - Surface treatment
  - Sterilization
- Volume processes
  - Pollution control
  - Exhaust gases
  - Waste destruction
- Material analysis
- Chemical synthesis
- Bio-medical applications

PLASMA

Applications

Surface processes
- Microelectronic
- Surface treatment
- Sterilization
Volume processes
- Pollution control
- Exhaust gases
- Waste destruction
Material analysis
- Chemical synthesis
- Bio-medical applications
Non-Equilibrium Plasmas

Specificity of non-equilibrium plasmas

- Generate active chemistry at low gas temperature (energy deposition by electrons)
- Non Maxwellian velocity distribution of charged particles
- Electron heating mechanisms can be complex
  Description of electron heating often needs a kinetic treatment. Examples:
  - Electron heating in a small region with high electric field (cathode sheath)
  - Non-collisional heating in a HF field at low pressure
  - Electron oscillations in a hollow cathode
- High non linearity of electron impact ionization
  - Ionisation depends exponentially on electric field or electron energy
Non-Equilibrium Plasmas

Applications in microelectronics industry: plasma etching and deposition

Plasma reactor for microelectronics
Low pressure plasma (1 mtorr-1 torr)

Plasma generates reactive species (due to high electron temperature) at low gas temperature (no damage of the substrate)
Non-Equilibrium Plasmas

Plasma etching

The Etch Process

Photolithography

Patterned Wafer

Etching

Plasma

Electrode

Electrode

Plasma Reactor

Hwang & Giaquis, CALTECH
Pollution control – Destruction of NOx


- Reducing emissions in light-duty vehicles.
- Combine plasma treatment with specialized catalyst material to convert oxides of nitrogen (NOx) into components of clean air.
- 90% increase of NOx destruction by combining catalysis and non-equilibrium plasma.
Non-Equilibrium Plasmas

Diamond synthesis


All CVD techniques for producing diamond films require a means of activating gas-phase carbon-containing precursor molecules. This generally involves thermal (e.g. hot filament) or plasma (D.C., R.F., or microwave) activation, or use of a combustion flame (oxyacetylene or plasma torches).

Diamonds grown with 10% argon in the methane/hydrogen mixture

Microwave plasma source for diamond film deposition

about 50 hours to make a diamond film 0.1mm thick
Non-Equilibrium Plasmas

Atmospheric pressure plasma processing

http://www.surfxtechnologies.com/applications.htm

A plasma source may be viewed as an electrical switch that turns chemical reactions on and off. When it’s on, a high concentration of atoms and radicals are delivered to a surface to clean, remove, modify, or deposit a material of your choice. By using electricity instead of heat to turn reactions on and off, you can independently control the temperature of the surface. Atmospheric pressure plasma processing is already an established surface treatment method in several large industries. Traditionally, these plasma tools have been based on arc discharges, which can destroy many materials due to the extremely high temperatures generated inside the plasma. Surfx’s new products deliver a similar high density of reactive species to the working surface, but at very low temperature and under a control gas atmosphere that guarantees the desired change is made quickly, efficiently, and the same way every time.
Non-Equilibrium Plasmas

Sterilization - decontamination

http://www.odu.edu/engr/bioelectrics/research.html

« The technology of cold ionized gases has recently reached a level of maturity at which applications can be considered. Cold plasmas consist of electrons and ions in gases at high pressure, up to and even exceeding atmospheric pressure. The charged particles in these cold plasmas are successfully used to decontaminate surfaces ». 
Non-Equilibrium Plasmas

Bio-Medical applications


RadioFrequency « Plasma needle »

Potential Applications

- Cleaning of dental cavities
- Removal of unwanted cells/tissues
- Plasma induced modification of artery walls
- Treatment of cancer cells

1 millimetre plasma glow at 250V (about 0.1 W). The glow is cold enough to be touched (image credit: E Stoffels et al. 2003 J. Phys. D: Appl. Phys. 36 2908)
Non-Equilibrium Plasmas

Plasma Display Panels


Plasma Display Panel micro-discharge

adressing

UV light emitted by the discharge

sustaining
Non-Equilibrium Plasmas

Flow control by surface micro-plasmas

Flow Attachment at High Angle of Attack Using Plasma Actuators

Plasma Off  
Plasma On

J.R. Roth et al., Univ. Tennessee
Non-Equilibrium Plasmas

Ion thruster for satellite propulsion: Hall Effect thruster


European lunar probe SMART 1, launched by ESA on 09.27.2003 with Stationary Plasma Thruster from SNECMA: PPS1350

Smart 1 will arrive at the moon in January 2005

Will search for signs of water-ice in craters near the Moon's poles, provide data on the still uncertain origin of the Moon and reconstruct its evolution by mapping and the surface distribution of minerals and key chemical elements.
Non-Equilibrium Plasmas

Model

Charged Particle Transport
- Fluid
- Hybrid
- Particle-In-Cell Monte-Carlo

EM Field
- Maxwell
- Poisson

Photon Transport

Neutral Transport
- Fluid – Navier Stokes
- DSMC

Chemistry
- Volume
- Surface
Non-Equilibrium Plasmas

Choice of the model approximations

- Charged particle transport
  - Fluid
    - Closure relations?
  - Hybrid
  - Particle-In-Cell Monte Carlo Collisions

- Coupling Charged Particle Transport – Electric Field
  - Solve Poisson’s equation? Constraint on time step
  - Quasineutrality assumption?

\[
\Delta t < \frac{1}{\omega_{ep}}
\]

\[
\Delta t < \frac{\varepsilon_0}{\sigma} \frac{V_{em}}{\omega_{ep}^2}
\]

PIC model

\[
\omega_{ep} = \sqrt{\frac{e^2}{\varepsilon_0 m_e} n_e}
\]

Fluid model

explicit integration of Poisson-transport equations: constraint on time step
Non-Equilibrium Plasmas

Quasineutrality or not?

« In a plasma, it is usually possible to assume \( n_e = n_i \) and \( \nabla \cdot E \neq 0 \) at the same time. This is a fundamental trait of plasmas, one which is difficult for the novice to understand.

*Do not use Poisson’s equation to obtain \( E \) unless it is unavoidable.*

*F.F. CHEN*

can assume quasineutrality if space charge sheath region do not play an essential role in sustaining the discharge
Non-Equilibrium Plasmas

Examples of models of non-equilibrium discharge plasmas

Outline

1. Hall effect thruster for satellite propulsion

2. Non equilibrium discharge plasma in collisional regime
   Atmospheric micro-plasmas and applications
Thrusters for Satellite propulsion

- **Electrothermal**
  - Heating of a gas + expansion through a nozzle
  - Arc Jet, resistojet

- **Magnetodynamic**
  - Plasma expansion due to Lorentz (Laplace) force
  - Pulsed Plasma Thruster
  - Lorentz Force Accelerator

- **Ion thrusters**
  - Plasma source + extraction and acceleration of ions by polarized grids
  - **Stationary Plasma Thruster (Hall Effect Thruster)**
  - No accelerating grids
Hall Effect Thrusters

Principles

- Cost reduction / chemical Prop
- Gridless Ion Engine
- High Thrust Efficiency > 50%
- Specific impulse ~1800 s
- Thrust to Power Ratio ~ 70 mN/kW
- Orbit Transfer – N/S Station Keeping
Hall Effect Thrusters

**Principles**

- Cost reduction / chemical Prop
- Gridless Ion Engine
- High Thrust Efficiency > 50%
- Specific impulse ~1800 s
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- Orbit Transfer – N/S Station Keeping

![Diagram of Hall Effect Thruster](image)

- xenon injection
- cathode
- electrons
- ions
- anode
- acceleration channel
- Coils
Hall Effect Thrusters

**Principles**

- Large radial B field at exhaust (200 G)
- Mean free paths >> dimensions
- Collisionless ions
- Collisional electrons (el confinement)
- Neutral flow ~ fully ionized

- Typical numbers
- Voltage 300 V
- Typical dimensions φ 10 cm, L 3 cm
- Xenon mass flow rate 5 mg/s
  - → ion velocity ~ 18 km/s
  - → thrust 80 mN
  - → current 4 A
Hall Effect Thrusters

**Principles**

- **radial B field**
- **trapped electrons**
- **low axial electron conductivity**

\[ J_e = \sigma_e E \]

low \( \sigma \) -> large \( E \)

\[ \sigma_e = en\mu_e = en \frac{e}{m} \frac{v}{\omega_B^2} \]
Hall Effect Thrusters

**Principles**

- radial B field
- trapped electrons
- low axial electron conductivity
- large axial electric field
- enhanced ionization

ION ACCELERATION

EXB configuration
Electron transport in SPT

Collisionless trajectories (specular reflexion on sheath)

\[ E_x = 100 \text{ V/cm} \]
\[ B_r = \frac{R_1}{r} \times 100 \text{ G} \]

No axial transport

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Mathematical Modeling and Computational Challenges in Plasma Physics - Cargese 2004
Electron transport in SPT

Electron trajectories with collisions

\[ E_x = 100 \text{ V/cm} \]
\[ B_r = \frac{R_1}{r} \times 100 \text{ G} \]

collision with atom or scattering with wall

Axial transport

Azimuthal motion

Anode exhaust

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Hall Effect Thrusters

Principles

- radial B field
- trapped electrons
- low axial electron conductivity
- large axial electric field
- enhanced ionization

EXB configuration

ION ACCELERATION
Hall Effect Thrusters

Ionization and acceleration

- Collisional electrons – Collisionless ions
- Ionization zone upstream of acceleration zone → efficient ion acceleration
- Part of the potential drop outside the channel → effect on beam divergence

color = ionization rate
contours = potential
# Hall Effect Thrusters

**Orders of magnitude**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied voltage</td>
<td>300 V</td>
</tr>
<tr>
<td>Xenon mass flow rate</td>
<td>5 mg/s</td>
</tr>
<tr>
<td>Canal length</td>
<td>2.5 cm</td>
</tr>
<tr>
<td>Diameter of external cylinder</td>
<td>10 cm</td>
</tr>
<tr>
<td>Total current</td>
<td>4 A</td>
</tr>
<tr>
<td>Ion current</td>
<td>3 A</td>
</tr>
<tr>
<td>Ion beam energy</td>
<td>250-300 eV</td>
</tr>
<tr>
<td>Atom density at anode</td>
<td>$10^{13}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Atom density at exhaust</td>
<td>$10^{11} - 10^{12}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Max plasma density</td>
<td>$10^{12}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Max electron mean energy</td>
<td>30 eV</td>
</tr>
</tbody>
</table>
Hall Effect Thrusters

Characteristic times

- Inverse plasma frequency $1/\omega_{pe}$
- Inverse cyclotron frequency $1/\omega_{ce}$
- Electron-wall collision time
- Electron-atom collision time
- Ion transit time in acceleration zone
- Ion-atom collision time
- Atom transit time
Hall Effect Thrusters

Characteristic length

- electron Debye length
- electron cyclotron radius
- magnetic field gradient
- device length
- electron mean free path
- ion cyclotron radius

Length (cm)
Hall Effect Thrusters

Choice of model approximations

- Particle-In-Cell Monte Carlo simulation of Hall thruster is not practical
  Even implicit PIC model would need time steps less than $10^{-10}$ s
  1D PIC model in these conditions take several weeks of computation on fast computers

- Electric field is induced by a decrease of plasma conductivity
  Quasineutrality should be a good approximation
Hall Effect Thrusters

**Quasineutral hybrid model**

- **Neutral atoms transport**
  - injection at anode, collisions with walls, losses by ionization

- **Ion transport**
  - generation by ionization, collisionless transport
  - recombination at walls

- **Electron transport**
  - generation at cathode & by ionization
  - collisional transport (trapping by magnetic field)

- **Electric field**
  - quasineutrality is assumed
  - field deduced from electron momentum equation and current conservation equation
Hall Effect Thrusters

Quasineutral hybrid model

Time $t^k$, electric field & ionization rate $E^k, S^k$

- Ion & neutral transport (PIC) → plasma density $n^{k+1}$, ion current density $j_i^{k+1}$
- Electron momentum equation + quasineutrality → $\vec{j}_e = \vec{f}(n, \vec{E})$
- Current continuity $\vec{\nabla}.\vec{j}_T = 0$ → $\vec{\nabla}.\vec{j}_e = -\vec{\nabla}.\vec{j}_i$
- Electron energy equation → Electron energy + Ionization rate $S^{k+1}$

$E^{k+1}$ new field
Hall Effect Thrusters

Electron momentum equation

\[ n_e m_e \left( \frac{\partial \vec{u}_e}{\partial t} + \vec{u}_e \cdot \nabla \vec{u}_e \right) = -en_e \left( \vec{E} + \vec{u}_e \times \vec{B} \right) - \nabla p_e - m_e n_e v_{em} \vec{u}_e \]

- **electric force**
- **electron-neutral collisions**
- **electron kinetic pressure**

\[ p_e = n_e kT_e \]

\[ T_e = \text{electron temperature} \]
Hall Effect Thrusters

**Electron momentum equation**

\[
\frac{m_e n_e \nu_{em}}{m_e \nu_{em}} \vec{u}_e = -en_e \left( \vec{E} + \vec{u}_e \times \vec{B} \right) - \vec{\nabla} p_e
\]

\[
n_e \vec{u}_e = \frac{en_e}{m_e \nu_{em}} \left[ -\vec{E} + \vec{u}_e \times \vec{B} - \frac{\vec{\nabla} (n_e kT_e)}{en_e} \right]
\]

**Hall current**

\[
\vec{j}_e = \sigma_{e0} \left[ \frac{\nu_{em}^2 \vec{E}_\perp^* + \vec{E}_\parallel^*}{\omega_{ec}^2} \right] - en_e \frac{\vec{E} \times \vec{B}}{B^2}
\]

\[
\vec{E}_\perp^* = \vec{E} + \frac{\nabla n_e kT_e}{en_e}
\]

\[
\sigma_{e0} = \frac{e^2 n_e}{m_e \nu_{em}}
\]
Hall Effect Thrusters

Electron momentum equation

![Diagram of a Hall thruster with electron fluxes](image)

\[
\begin{align*}
\mathbf{j}_{e,\perp} &= \sigma_e \frac{V_{em}^2}{\omega_{ec}} \mathbf{E}_\perp \\
\mathbf{j}_{e,\parallel} &= \sigma_e \mathbf{E}_\parallel \\
\mathbf{j}_{e,H} &= -en_e \frac{\mathbf{E} \times \mathbf{B}}{B^2}
\end{align*}
\]

In a Hall thruster:

\[10^{-1} < \frac{V_{em}}{\omega_{ec}} < 10^{-4}\]
Hall Effect Thrusters

Calculation of electric field from electron momentum equation

\[ \vec{j}_e = f(n_e, \vec{E}) \]

electron momentum transport equation

(1) \[ n_e = n_i = n \]

(quasineutrality) known from ion transport

(2) \[ \nabla \cdot \vec{j}_e = -\nabla \cdot \vec{j}_i = -S \]

(current continuity) known from ion transport

+ boundary condition: total current

(1) + (2) \[ \rightarrow \] equation for the electric field \( \vec{E} \)
Hall Effect Thrusters

Calculation of electric field from electron momentum equation

\[ \vec{\nabla} \cdot \vec{j}_e = -\vec{\nabla} \cdot \vec{j}_i = -S \]

\[ \vec{\nabla} \cdot \vec{j}_e = \vec{\nabla} \cdot \left[ \sigma_{e0} \left( \frac{V_{em}^2}{\omega_{ec}^2} \vec{E}^*_{\perp} + \vec{E}^*_{\parallel} \right) \right] \]

\[ \vec{\nabla} \cdot \left[ \sigma_{e0} \left( \frac{V_{em}^2}{\omega_{ec}^2} \vec{V}^* \right) \vec{V}^* \right] = S \]

\[ \vec{E}^* = -\vec{\nabla} V^* \]

\[ V^* = V - \frac{kT_e}{e} \ln \frac{n}{n_0} \]

- Simple elliptic equation for \( V^* \)
  - but coefficient in one direction >> coefficient in the perpendicular direction

- Difficult to solve numerically
Hall Effect Thrusters

Calculation of electric field from electron momentum equation

Approximation:

Boltzmann equilibrium along the B filed lines

$$\vec{j}_{e,\parallel} = \sigma_e e_0 \vec{E}^* = \sigma_e e_0 \left[ -\nabla || V + \frac{\nabla n_e kT_e}{en_e} \right] \sim \vec{0}$$

$$V(x, r) = V^*(\lambda) + \frac{kT_e(\lambda)}{e} \ln \left[ \frac{n_e(x, r)}{n_0} \right]$$

\(\lambda\) stream function, constant along B field lines

\(V^*(\lambda)\) obtained by integrating the current equation along a B field line
Hall Effect Thrusters

Calculation of electric field from electron momentum equation

stream function $\lambda$

\[
\begin{align*}
\frac{\partial \lambda}{\partial x} &= rB_x \\
\frac{\partial \lambda}{\partial r} &= -rB_x
\end{align*}
\]

integrating the current equation along a B field line

\[
\iint j_x ds = I_T - \iint j_t ds
\]

\[
\iint j_e ds = \iint \sigma_e \left[ \frac{V_{em}^2}{\omega_{ec}^2} \bar{E}_\perp^* \right] ds
\]

$\bar{E}_\perp^* = -\nabla_{\perp} V^* + \left( 1 - \ln \frac{n}{n_0} \right) \nabla_{\perp} \frac{kT_e}{e}$

\[
\alpha \frac{\partial V^*}{\partial \lambda} + \beta \frac{\partial kT_e}{\partial \lambda} = I_T - \iint j_t ds
\]
Hall Effect Thrusters

Ionization and acceleration

- Collisional electrons – Collisionless ions
- Ionization zone upstream of acceleration zone → efficient ion acceleration
- Part of the potential drop outside the channel → effect on beam divergence
Hall Effect Thrusters

New concepts of Hall thrusters

- **Need for versatile thrusters** for GEO and probes
  - orbit top up – orbit raising
    - high thrust (reduction of mission duration)
    - high mass flow rate/low voltage (enhance ionization)
  - North/South Station Keeping – probes
    - high Isp to minimise gas consumption
    - high voltage/low mass flow rate to enhance acceleration

- **Single Stage Hall Effect Thruster**
  - ionization/acceleration strongly connected
  - difficult to optimize thruster for several operation modes

- **Double Stage Hall Effect Thruster**
  - Separation of ionization and acceleration processes
  - promising candidate for multi-mode operation
Hall Effect Thrusters

Double Stage Hall Effect Thruster (DSHET)

- Ionization Chamber
- Hall acceleration

- RF source ?
- Helicon ?
- Magnetic confinement ?

- cathode
- electrons
- ions
Hall Effect Thrusters

SNECMA Patent 03 08384, Authors: Secheresse Olivier, Bougrova Antonina, Morozov Alexei filled: 9 July 2003

- Xenon injection
- Ion trap
- Anode 1: 350 V
- Anode 2: 300 V
- Coils
- Cathode 0 V
- Electrons
- Ions
Hall Effect Thrusters

Double Stage Hall Effect Thruster (DSHET)

- Anode 1: 350 V
- Anode 2: 300 V
- Cathode 0 V
- Zero magnetic field

myxina
separatrix
Hall Effect Thrusters

DSHET: Electron trajectories

350 V

300 V

0 V
Hall Effect Thrusters

Simulations based on

- quasineutral plasma assumption
- Particle-In-Cell ions and neutral atoms
- electric field from Ohm’s law
- electron energy and ionization from fluid model or Monte Carlo simulation
Potential Distribution

Hybrid simulations CPAT

Ions

- trapped in the potential well
- bounce back & forth
- are guided to the channel where they are accelerated out
Hall Effect Thrusters

Other questions

1. Anomalous electron transport
   - Classical (collisional) conductivity not sufficient in the exhaust region
   - Need to account for « anomalous » conductivity due to plasma turbulence
   - Experiments and PIC models can help quantify anomalous conductivity

2. Electric field calculation
   - Assumption of Boltzmann equilibrium along field lines not good for small B
   - Not good in the 0 B region of the Double Stage Hall Effect Thruster
   - Need for improvement of electric field calculation
(\(x, \varphi\)) Particle-In-Cell Model

J.C. Adam et al., Physics of Plasmas 2003

\[ E_x \]

\[ E_\varphi \]

\(x\) (cm)  x100 V/cm  \(r\) (cm)  \(\varphi\) (cm)

\(X\) (cm)  x100 V/cm
Hall Effect Thrusters

References

- **Hybrid, quasineutral model**

- **Kinetic model of electron transport**

- **PIC model and anomalous conductivity**

- **Attempts to develop quasineutral PIC models**