Physics of low-temperature plasmas

Amy Wendt
University of Wisconsin - Madison
Dept. of Electrical and Computer Engineering

SULI - Introduction to Fusion Energy and Plasma Physics, June 24, 2021
Introduction: setting the stage
PHYSICS of low temperature plasmas

- thermodynamics
- statistical mechanics
- fluid dynamics
- classical mechanics
- waves
- electricity and magnetism
- atomic physics
- quantum
- chemistry

https://gfycat.com/gifs/search/plasma+globe
Low temperature plasmas at work
What is a low temperature plasma?

- What is a plasma?
- What is temperature?
- In what sense is the temperature low?

Peeling back the “layers of the onion”
Plasma as the 4th state of matter

Solid | Liquid | Gas | Plasma

Deformable | Compressible | Conductive

http://www.grinp.com/plasma/physics.html
What is a low temperature plasma?
Temperature: elastic collisions thermalize populations

- **elastic collisions** - particles “bounce” off one another; kinetic energy is conserved
- energy becomes randomly distributed among the particles over time - this is *thermal equilibrium*
Thermal Equilibrium

- System energy is randomly distributed among particles through collisions.
- Pairs of particles exchange energy in collisions, but for the system as a whole, the relative numbers of particles for each energy does not change.
- The shape of the distribution can be represented by a single parameter - temperature $T$.
- Called “Maxwell-Boltzmann” or “Maxwellian” distribution.

\[
g(E) = 4\pi n (2\pi\kappa T)^{-3/2} \sqrt{2E} \exp \left( -\frac{E}{\kappa T} \right)
\]

- $\kappa = 8.6 \times 10^{-5}$ eV/K is the Boltzmann constant.
- Electron volts (eV) are units of energy.
- $1$ eV $\simeq 1.6 \times 10^{-19}$ J.
- $\kappa T = 1$ eV corresponds to $T \sim 11,600$ K.
Temperature case study: inductively coupled plasma

- AC currents in spiral antenna produce high frequency electric fields inside plasma volume
- Electrons (low mass!) are preferentially accelerated by electric fields:
  - Lorentz Force
  \[ \vec{a} = \frac{\vec{F}}{m} = \frac{q}{m} \left( \vec{E} + \vec{v} \times \vec{B} \right) \]
  - and heated
- Electrons thermalize to \( kT_e \sim 1 - 10 \text{ eV} \)
- Atoms and ions remain near room temperature
- Many low temperature plasmas are NOT in thermal equilibrium: \( T_e > T_{\text{ion}} \approx T_{\text{gas}} \)
Elastic collisions: low-temp plasmas are often *not* in thermal equilibrium

Unequal masses: kinetic energy transfer is weak

Equal masses: kinetic energy transfer is very efficient
High and low temperature (it’s all relative!) plasmas
# High temperature vs. low temperature plasmas

<table>
<thead>
<tr>
<th></th>
<th>High T</th>
<th>Low T</th>
</tr>
</thead>
<tbody>
<tr>
<td>usually fully ionized?</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>collisions with neutrals?</td>
<td>rare</td>
<td>frequent</td>
</tr>
<tr>
<td>plasma waves</td>
<td>likely</td>
<td>damped by collisions</td>
</tr>
<tr>
<td>surface boundaries?</td>
<td>rare</td>
<td>common</td>
</tr>
<tr>
<td>fusion reactions</td>
<td>maybe</td>
<td>no</td>
</tr>
</tbody>
</table>
Low temperature plasma superpowers: #1 Electron-neutral collisions
Low-temperature plasmas are often *partially* ionized.

**Partially ionized plasma**

**Fully ionized plasma**
Partially ionized plasmas

- Collisions between electrons and neutral particles play *really, really* important roles

- Electron-neutral inelastic collisions:
  - ionization - sustains plasma
  - excitation - results in photon emission
  - dissociation - exotic chemistries

![Diagram of positive ion, electron, neutral atom, or molecule]
Where does the energy go in partially ionized plasmas??

- kinetic energy \( = \frac{1}{2}mv^2 \)

- acceleration in EM fields:
  \[
  \vec{F} = m\vec{a} = m\frac{dv}{dt} = q\left( \vec{E} + \vec{v} \times \vec{B} \right)
  \]

- electrons gain energy more readily from electric fields
- electron mass is smaller, but velocity is bigger
- electrons have high kinetic energy
- elastic collisions thermalize electron population
- *inelastic* electron-neutral collisions consume electron kinetic energy with important outcomes
Inelastic electron-neutral collisions

• If free electron kinetic energy is sufficiently high, it may be utilized in several ways upon collision
Electron-neutral inelastic collisions: what happens to electron kinetic energy?

- Ionization
- Electronic excitation
- Molecular dissociation
- Photon emission

Products may be highly chemically reactive.
Low temperature plasma superpowers: #2 Surfaces and plasma sheaths
Potential (voltage) profile across plasma - sheaths form next to surfaces

- Contrast plasma to resistor

\[ V_0 \]

- Resister voltage axial profile is *linear*.

\[ V \]

Positive and negative charges respond to electric field, forming sheaths at electrodes. Ions accelerate into negative electrode
What is a plasma sheath?

- Plasma sheath is a boundary layer between plasma and solid surface:
  - container wall, electrodes, substrate, etc.
- **Interior** of plasma volume:
  - Charges shift position to maintain charge balance
  - electric field weak due to shielding by plasma
- **Sheath region**
  - Strong electric field
  - plasma density low
  - unequal positive and negative charge densities
  - **ions accelerated** into surfaces
    - removal of surface material
    - ion implantation
Low temperature plasma superpowers: #3 Magnetic fields and low-T plasmas
Partially ionized plasmas: charged particles in magnetic field

• In the absence of collisions
  • charges in magnetic field undergo helical orbits
  • “guiding centers” follow magnetic field lines - magnetic confinement
Charged particles in magnetic fields

• Lorentz Force equation

• smaller mass, smaller orbit radius

• higher kinetic energy, higher orbit radius

• collisions with neutrals disrupt orbital motion - interfere with magnetic confinement

• plasmas at low gas pressures are better confined by magnetic field due to reduced collision frequency
Case study: planar magnetron sputter deposition
Case study: planar magnetron thin film deposition

- Magnetic field
  - electrons confined
  - ion orbit too big
- Electric field
  - negative voltage applied to electrode
  - sheath forms above “target”
    - strong electric field
    - ions accelerated into surface
      - target atoms sputtered
      - electrons released - “secondary emission”
    - secondary electrons enter plasma with high energy due to acceleration in sheath
- Diffusion
  - uncharged target atoms traverse the plasma
  - some reach substrate and stick to form thin film

http://nabis.fisi.polimi.it/equipments/aja-atc-orion-8-sputtering-system/
Parting comments
PHYSICS of low temperature plasmas

- thermodynamics
- statistical mechanics
- fluid dynamics
- classical mechanics
- waves
- electricity and magnetism
- atomic physics
- quantum
- chemistry

https://gfycat.com/gifs/search/plasma+globe
Final thoughts

• Stop and smell the roses - savor the richness of plasma physics; no need to rush.
• Delve into the various physics sub-disciplines relevant for plasmas - a great foundation for understanding plasmas.
• Plasma physicists use an odd collection of units - get to know them and relevant conversion factors. Seek out shortcuts in plasma formulary and/or textbook appendices.
• Embrace opportunities - the skills you acquire will benefit you in ways you cannot imagine now.
• UW-Madison is home to world-renowned experts in a breadth of plasma research areas - it is a great place for graduate degrees in plasmas!