Jet and Rocket Propulsion

AE4451

LECTURE 27

Sedina Tsikata – March 13, 2023

Overview

- what we saw in Lecture 26
    - heat transfer
        - calculations
        - correlations between dimensionless numbers

- today
    - electric propulsion: introduction to basic concepts

Electric propulsion

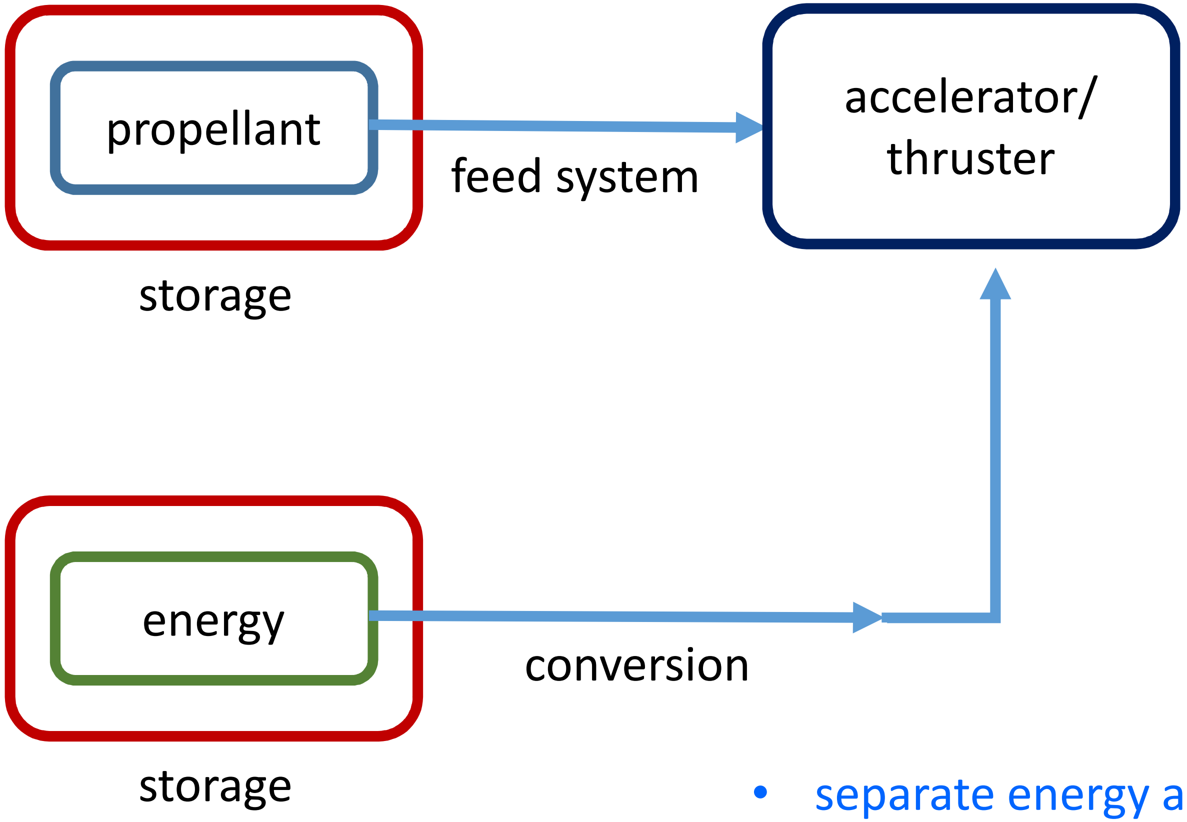
Definition

" The acceleration of gases for propulsion by electrical heating and/or by electric and magnetic body forces" – R. G. Jahn

- 2 important features:
  - how energy is supplied
  - how particles are accelerated
- the first ideas involving the use of charged particles for spaceflight appeared in 1906 (notebooks of Goddard) and independently in 1911 (Tsiolkovsky)
- Hermann Oberth formalized electric propulsion ideas in a later text in 1929

Electric propulsion

Elements of an EP system



- propellant in solid/liquid/gaseous phase

- energy: chemical, nuclear, radiation
- conversion to electricity

- separate energy and propellant: no longer limited by chemical bond energy

Electric propulsion

Accelerators: 3 main classes

	Electrothermal	**Electromagnetic**	**Electrostatic**
accel. Force	Pressure, ∇p Electrically heat propellant and use nozzle expansion	Lorentz, $\vec{F}_m$ Magnetic and elec. fields accelerate charged particles	Electrostatic, $\vec{F}_e$ Static electric field alone accelerates charged particles
I_{sp}(s)	300-1,500	1,000-10,000	2,000-100,000+
$\frac{\text{Thrust}}{\text{Weight}}$	$<10^{-1}$	$<10^{-4}$	$<10^{-4}$–10^{-6}

- contrast with monopropellant (hydrazine) rocket, e.g. MR-107B:

  I_{sp} ~ 200 – 250 s

  T/W ~ 30

Electric propulsion

Advantages for in-space propulsion

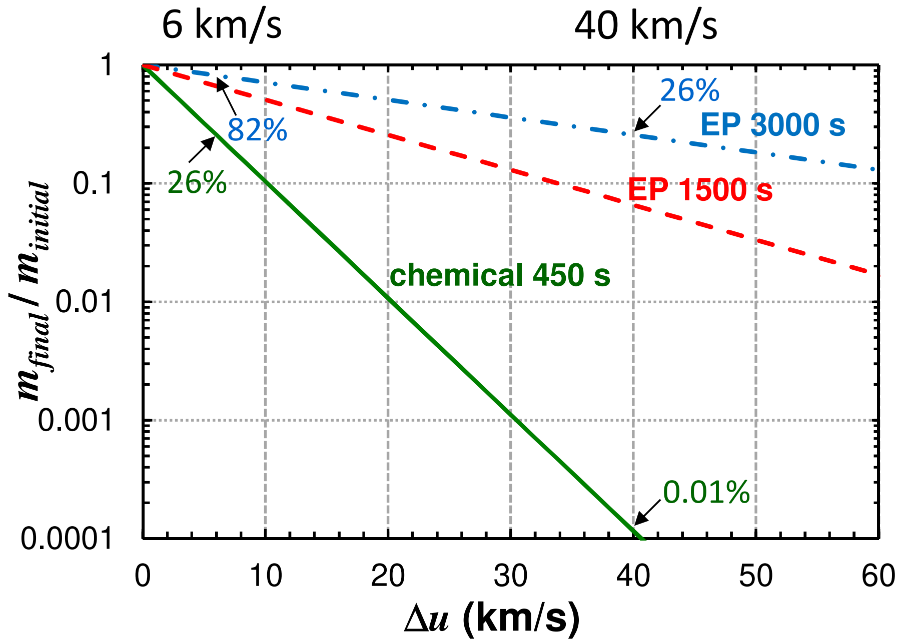
$$m_{final} / m_{initial} = e^{-\Delta u / u_e} = e^{-\Delta u / I_{sp} g_e}$$

rocket equation

In-space propulsion requirements

Mission	Typical Δu (km/s)
GEO stationkeeping (15 years)	1.0
LEO to GEO (< 1 day)	4.2
LEO to Mars (9 months)	5.7
LEO to GEO (8 months)	6.0
LEO to Jupiter (9 months)	50
LEO to Mars (1 month)	90
LEO to 1000 Aus (30 Yrs)	175

smaller exponent, larger fraction



- significant reductions in fuel fraction required for a given delta v
  - larger payloads
  - lower launch costs

Relevance to future missions

Example: Lunar Gateway

- NASA objectives – return people to the Moon, then Mars, and beyond

Artemis Program

key component is **Lunar Gateway**

- maneuverable outpost in cis-lunar space
- extension of human presence to deep space
- access to the surface of the Moon

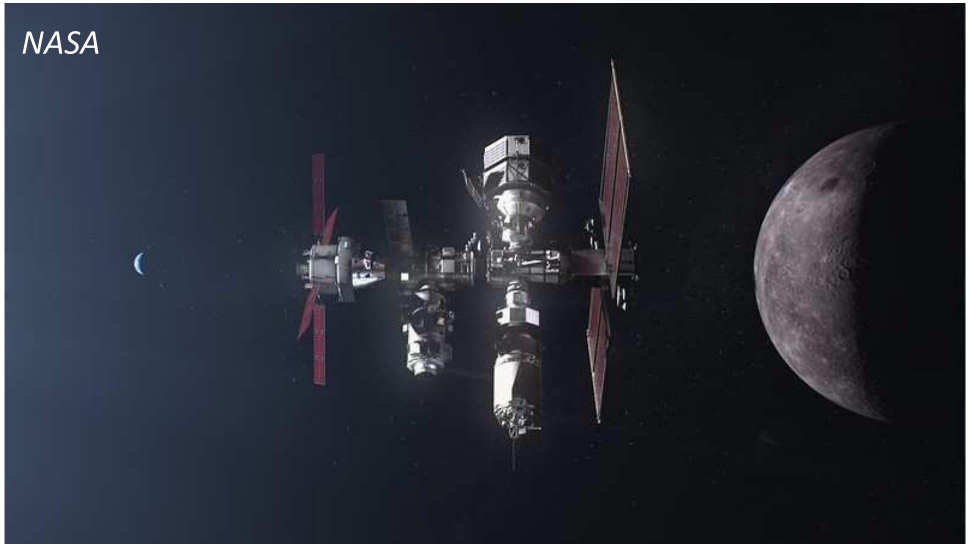
Power and Propulsion Element (PPE)

- reach and maintain lunar orbit
- solar electric propulsion (SEP) for (primarily) station-keeping and orbit transfer
- SEP also for attitude control

- 2 x 12.5 kW Hall thrusters (Aerojet Rocketdyne Advanced Electric Propulsion System, AEPS)
- 4 x 6 kW Hall thrusters (Busek)
- power processing unit (Maxar)

Hall thruster

Role in future missions: Lunar Gateway



orbiting outpost

electric propulsion systems

Electric propulsion

Power requirements

- minimum possible electric power required to operate EP device

$$P_j = \tfrac{1}{2}\dot{m}u_e^2 \quad = \tfrac{1}{2}\left(\dot{m}u_e\right)u_e$$

electrical power equal to jet power

jet power

$$P_j = \tfrac{1}{2}\tau u_e$$

$$P_j = \tfrac{1}{2}\tau\left(I_{sp}g_e\right)$$

if $u_{eq} = u_e$

- increase in Isp (or ue) requires increase in power
  - $\propto u_e^2$ for constant propellant flowrate
  - $\propto u_e$ for constant thrust

- comparison for rocket with moderate thrust of 4.5 kN
  - chemical rocket with I_{sp} = 350s : Pj ~ 7.7MW
  - EP rocket with I_{sp} = 3500s : Pj ~ 77 MW

→ EP devices power-limited

Electric propulsion

Power requirements

- note that in reality, electrical power required must account for the efficiency

$$P_e = \frac{\tfrac{1}{2}\,\dot{m}\,u_e^2}{\eta_T} \qquad \eta_T = \text{total efficiency of energy conversion}$$

electrical/supply power P_e

- 3 components in conversion efficiency

$$\eta_T = \eta_S \;\; \eta_{pp} \;\; \eta_{th}$$

energy conversion - of raw energy source to electricity

- ~100% for photovoltaics – direct conversion of photons (does NOT include fraction of solar radiation that can be converted to electricity by typical solar array, ~18-25%)
- 10-40% for nuclear thermal, thermodynamic cycle limits = large amount of waste heat

power preparation and conditioning electronics (losses in electronics)

- ~92% (electrostatic)
- ~98% (steady arc jets)

thruster efficiency - only part of delivered electrical energy converted to kinetic

- 30-75%

Electric propulsion

Mass requirements

$$m_{final}/m_{initial} = e^{-\Delta u/u_e} = e^{-\Delta u/I_{sp}g_e}$$

- what limits the available power to EP systems?
    - typically: mass of power plant and associated systems

- if power plant mass is significant fraction of propellant mass, then some advantages of higher specific impulse operation are lost
    - i.e. expected fuel economies reduced

- delivered "payload" may consist mostly of power plant/electronics for propulsion system

- not a problem if power plant part of desired payload

Electric propulsion

Power source mass

$$M_{ps} \cong \beta_s P_s$$

mass of power source

β_s = specific mass (kg/kW)

specific power (kW/kg) also used $\frac{1}{\beta_s}$

- β_s ~ 7 - 25 kg/kW$_{elec}$ for solar arrays (depends on cell design, substrate)
- β_s ~ 2 - 4 kg/kW$_{thermal}$ for nuclear reactors (depends on shielding)
  - to reject waste heat, also require additional mass for radiators β_R ~ 0.1 - 0.4 kg/kW$_{waste\ heat}$

Electric propulsion

Power preparation and conditioning mass

$$M_{pp} \cong \underbrace{\beta_{pp}}_{\text{specific mass}} \overset{\text{power}}{P_{pp}}$$

- large variation with type of EP device (especially if need high voltage or power, and short pulse forming electronics/switches)

β_{pp} ~ 0.2 kg/kW$_{elec}$ for typical arcjets
β_{pp} ~ 20 kg/kW$_{elec}$ for PPT (pulsed plasma thrusters)

Physics of EP systems

Terms

V – potential or voltage (sometimes ϕ) ($Volts$)

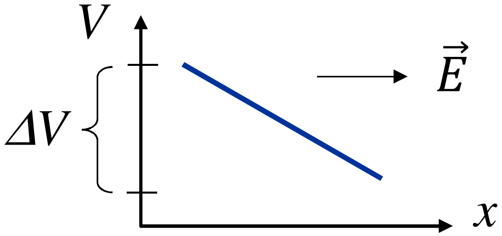
E – electric field (V/m, N/C)

q – charge (C) ($q_{e^-}=1.602\times10^{-19}\ C$)

Force, $\vec{F} = \vec{E}q$

Potential Energy $\int F dx = \int qE dx = q\Delta V$

$$\vec{E} = -\nabla V \text{ e.g.,} = -\frac{dV}{dx}$$



J – current (A, C/s)

j – charge current density (A/m^2, C/sm^2) = J / A

$$\underline{j = n_q q u_q}$$

n_q – number density charged part. ($1/m^3$)

u_q – velocity of charged particles (m/s)

Physics of EP systems

Electrical heating

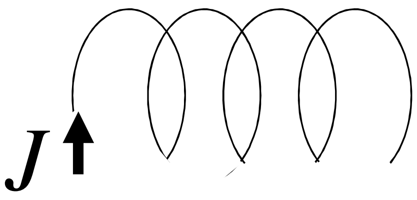
- current passing through conductor heats it by amount proportional to its resistance: ohmic heating

current (A = C/s)

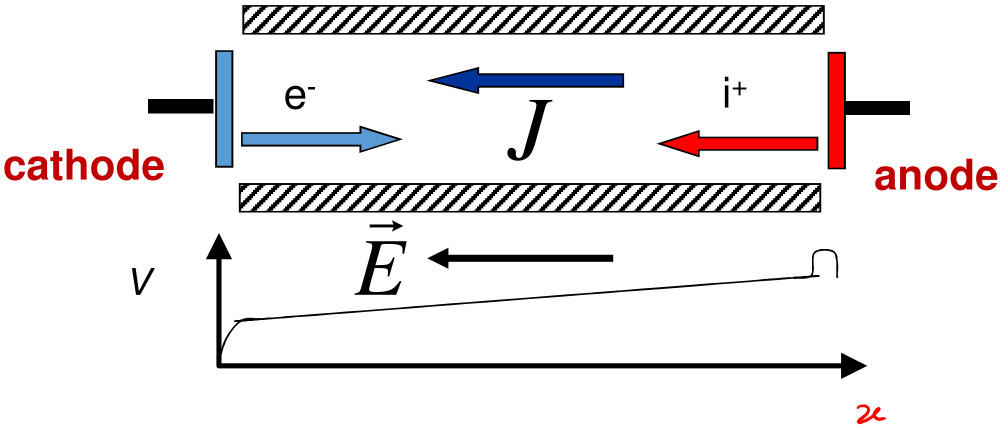
resistance (Ohms)

$$\dot{Q} = J^2 R$$

- in plasma discharge, resistance heating occurs due to collisions



wire current



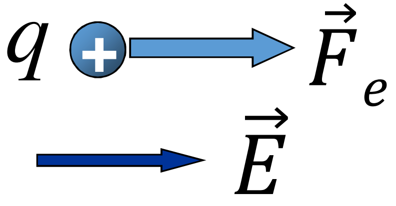
Physics of EP systems

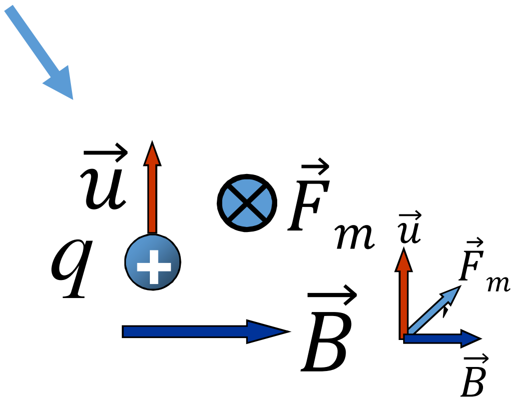
Forces on a charged particle

- to use electrical energy to accelerate a propellant, consider acceleration of a particle with mass ***m*** and charge ***q***

$$m\frac{d\vec{u}}{dt} = \underbrace{q\vec{E}}_{\text{electrostatic Force}} + \underbrace{q\left(\vec{u}\times\vec{B}\right)}_{\text{Lorentz Force}} + \vec{p}$$

collisional force (momentum transfer)





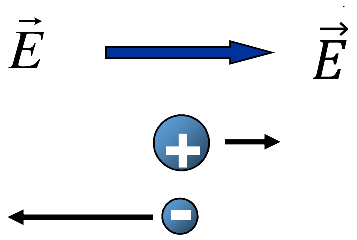
Physics of EP systems

Motion of charged particle in electric and magnetic fields

Electric field only

electron lighter, higher acceleration

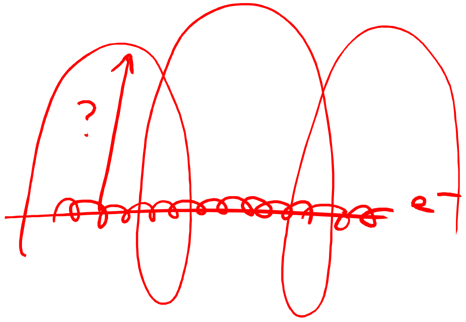
$$\frac{d\vec{u}}{dt} = \frac{q}{m}\vec{E}$$



Magnetic field only

particle gyrates around field

$$\frac{d\vec{u}}{dt} = \frac{q}{m}\left(\vec{u} \times \vec{B}\right)$$

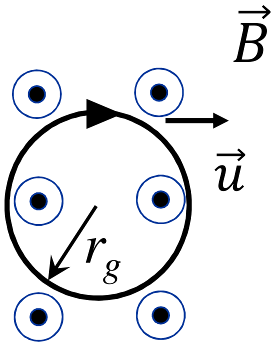


radius of gyration

electron / ion

Larmor radius

$$r_g = \frac{m\left|\vec{u} \times \vec{B}\right|}{qB^2}$$



electron / ion

frequency of gyration — cyclotron frequency

$$\omega_g = \frac{qB}{\underline{m}}$$

no work; B and F perpendicular

Physics of EP systems

Motion of charged particle in crossed electric and magnetic (E x B) fields

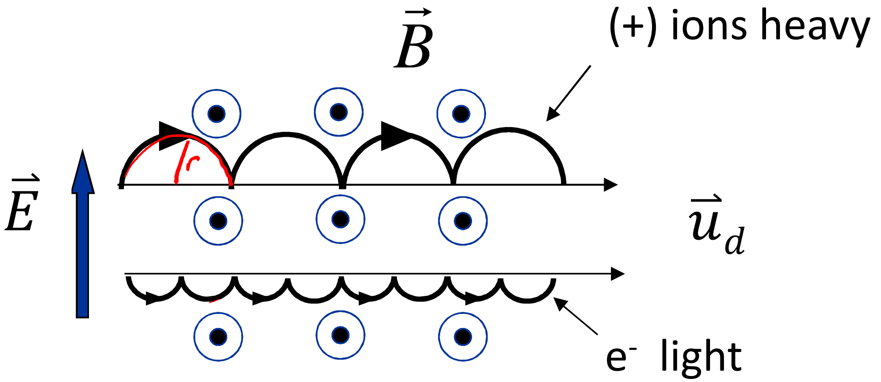
Crossed E and B fields

$$m\frac{d\vec{u}}{dt} = \underline{q\vec{E} + q\left(\vec{u}\times\vec{B}\right)}$$

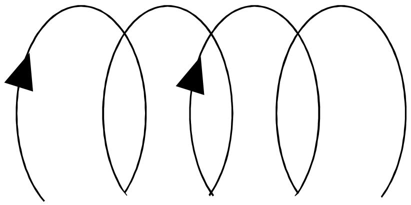
- E field accelerates (+) particle upward

- B field causes acceleration perpendicular to *u*

- overall result is drift velocity normal to *E* and *B*



$$\underline{\vec{u}_d = \frac{\vec{E}\times\vec{B}}{B^2}}$$

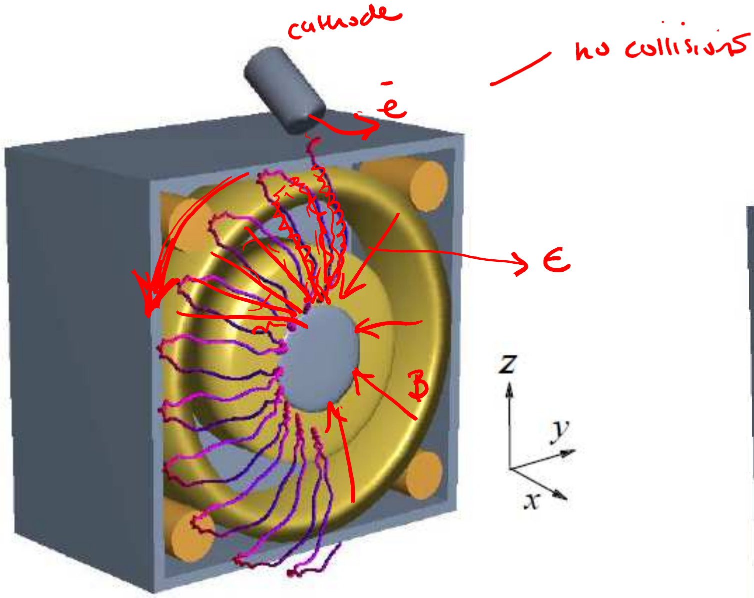


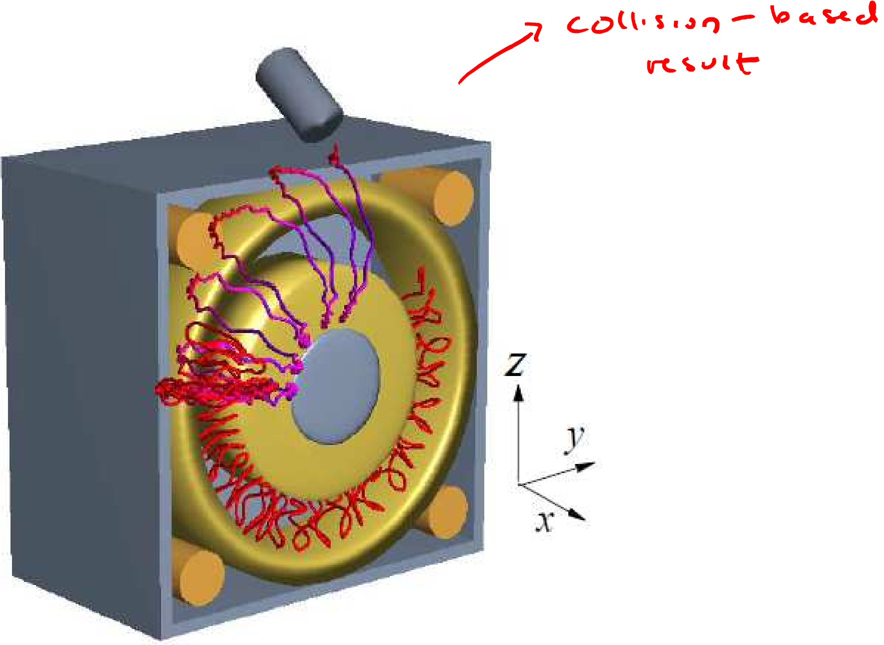
$$r_g \propto m$$

$$\omega_g \propto 1/m$$

Physics of EP systems

Motion of charged particle in crossed electric and magnetic (E x B) fields





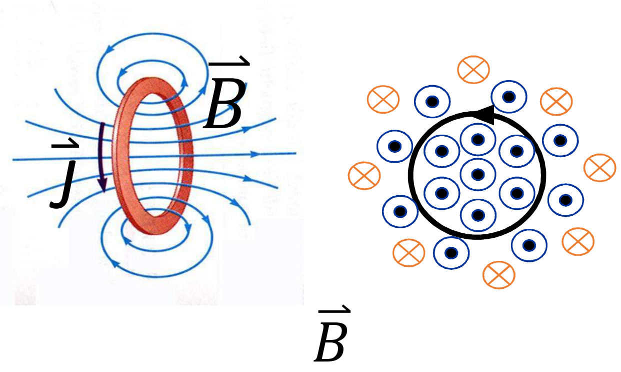
Hall thruster electron modelling (J. Perez-Luna)

- very complex, often unpredictable, particle trajectories result

Physics of EP systems

Induced magnetic fields

- in general, current flow induces a B field
  - can be induced by a linear current
  - can be induced by a coil



- we can exploit this to generate self fields in propulsion

Physics of EP systems

Plasma properties

- gas composed of equal “amount” of negatively and positively charged particles
  - electrically neutral
  - negative particles usually e- ✓ $\underline{SF_6^-}$ $\underline{SF_6^+}$
  - positive particles are usually positive ions

- most of gas molecules often remain neutral (in weak plasma, or partially ionized gas)

ionization ~ few %
rate

Momentum equation for plasma

$$\rho\left(\frac{\partial\vec{u}}{\partial t}+\vec{u}\cdot\nabla\vec{u}\right)=-\nabla p+\underline{\vec{j}\times\vec{B}}$$

current density (A/m^2)

$$\nabla\vec{u}\equiv\left(\nabla u_1,\nabla u_2,\nabla u_3\right)$$

Physics of EP systems

Plasma classifications

"cold"

$T_e \approx T_i \approx T < 2\times10^4\,\mathrm{K}$

low-temperature thermal cold plasmas
e.g. high pressure arc plasmas

$T_i \approx T \approx 300\,\mathrm{K}$

$T_i << \underline{\underline{T_e}} \leq 10^5\ \mathrm{K}$

low-temperature non-thermal cold plasmas
e.g. low pressure glow, arc plasmas

propulsion

"hot"

$T_i \approx T_e > 10^6\ \mathrm{K}$

e.g. fusion plasmas

kinetic theory of gases (Boltzmann)

average kinetic
energy per particle

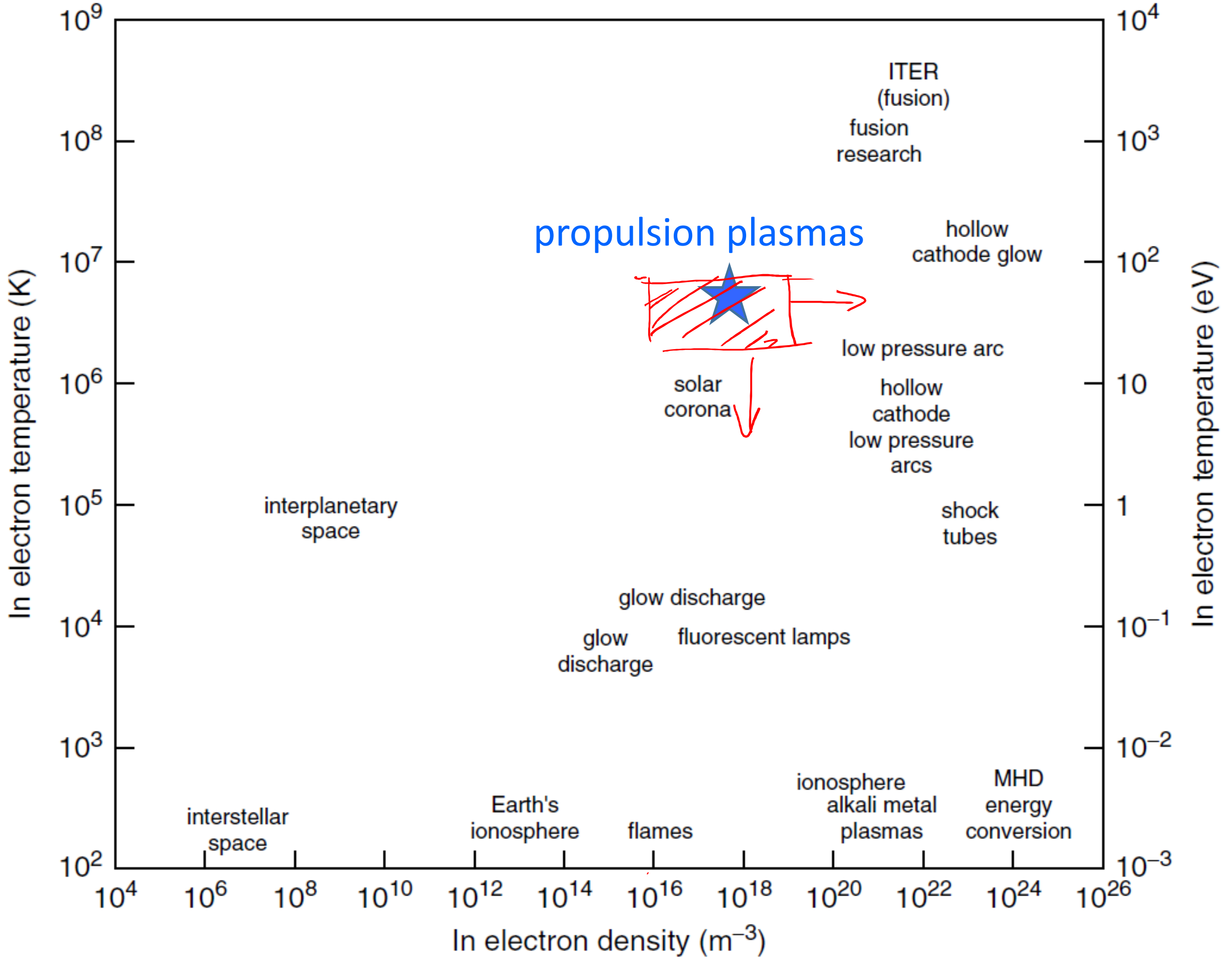
$$E_k = \frac{1}{2} m u^2{}_{rms} = \frac{3}{2} k_B T$$

considers individual atoms impinging on walls
of a container each with translational energy

Physics of EP systems

Plasma classifications

1 eV = 11600 K



Harry 2010