Benha University
Faculty of Science
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Plasma Propulsion Technologies

by:

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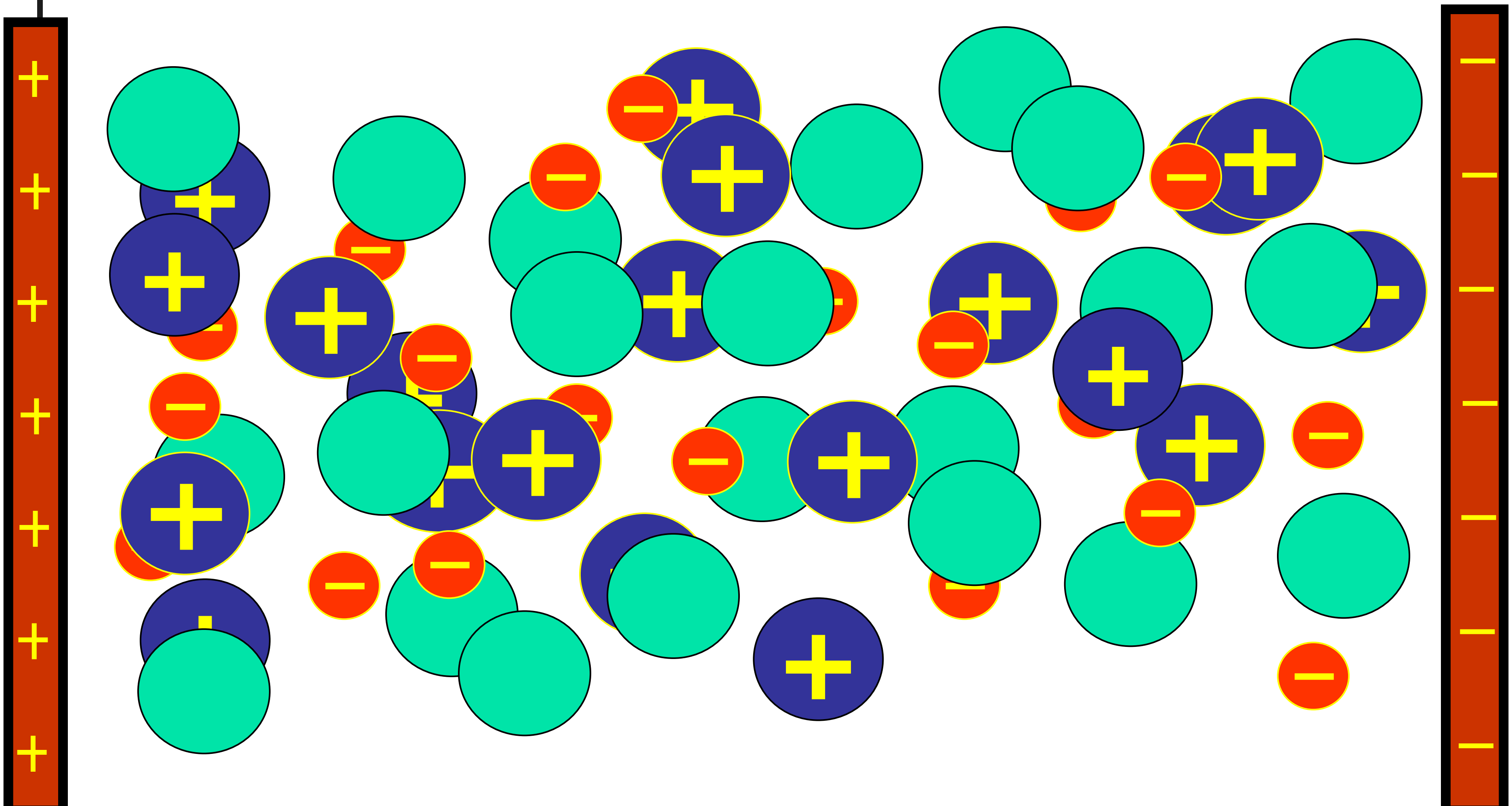
OUTLINES !!!

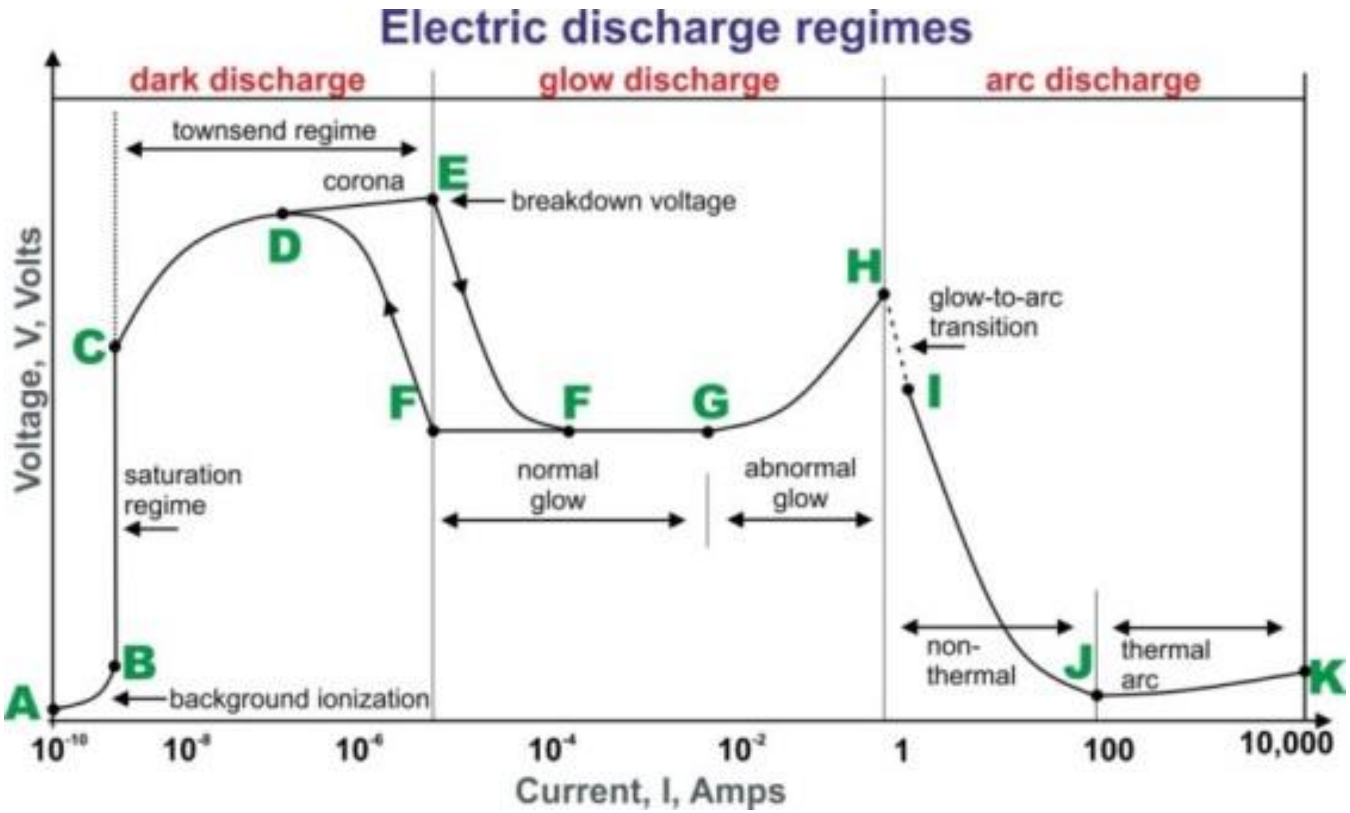
- Plasma Definition
- I-V Characteristic Curve
- Plasma Applications
- "PROPULSION" & "THRUSTERS" !?
- Main Types
- EM
- ET
- ES
- Plasma Propulsion around the world
- Conclusion

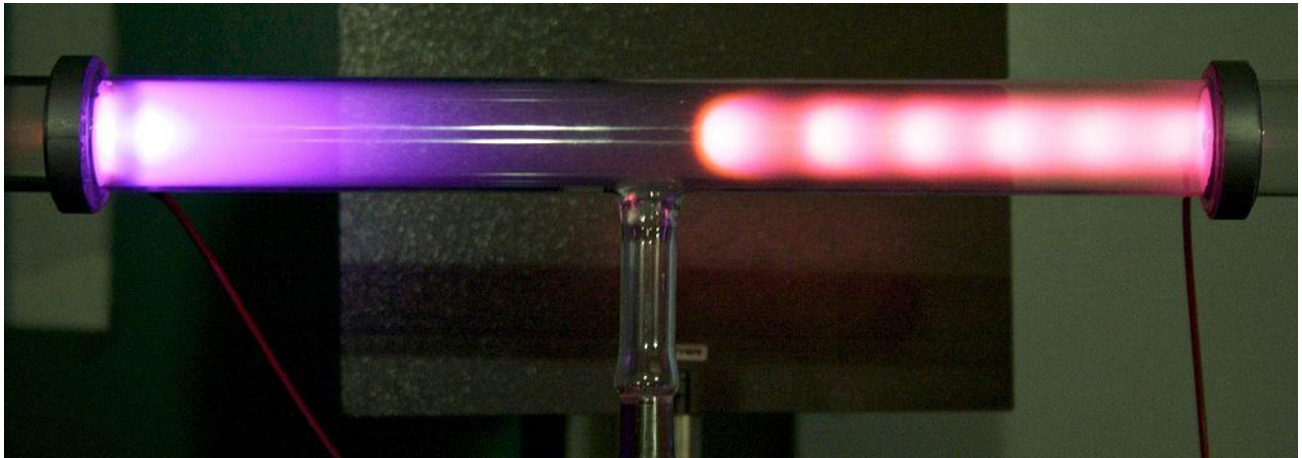
Plasma Physics

Plasma is energetically the forth state of the matter, It can be also defined as a quasi-neutral gas of charged and neutral particles characterized by a collective behavior.

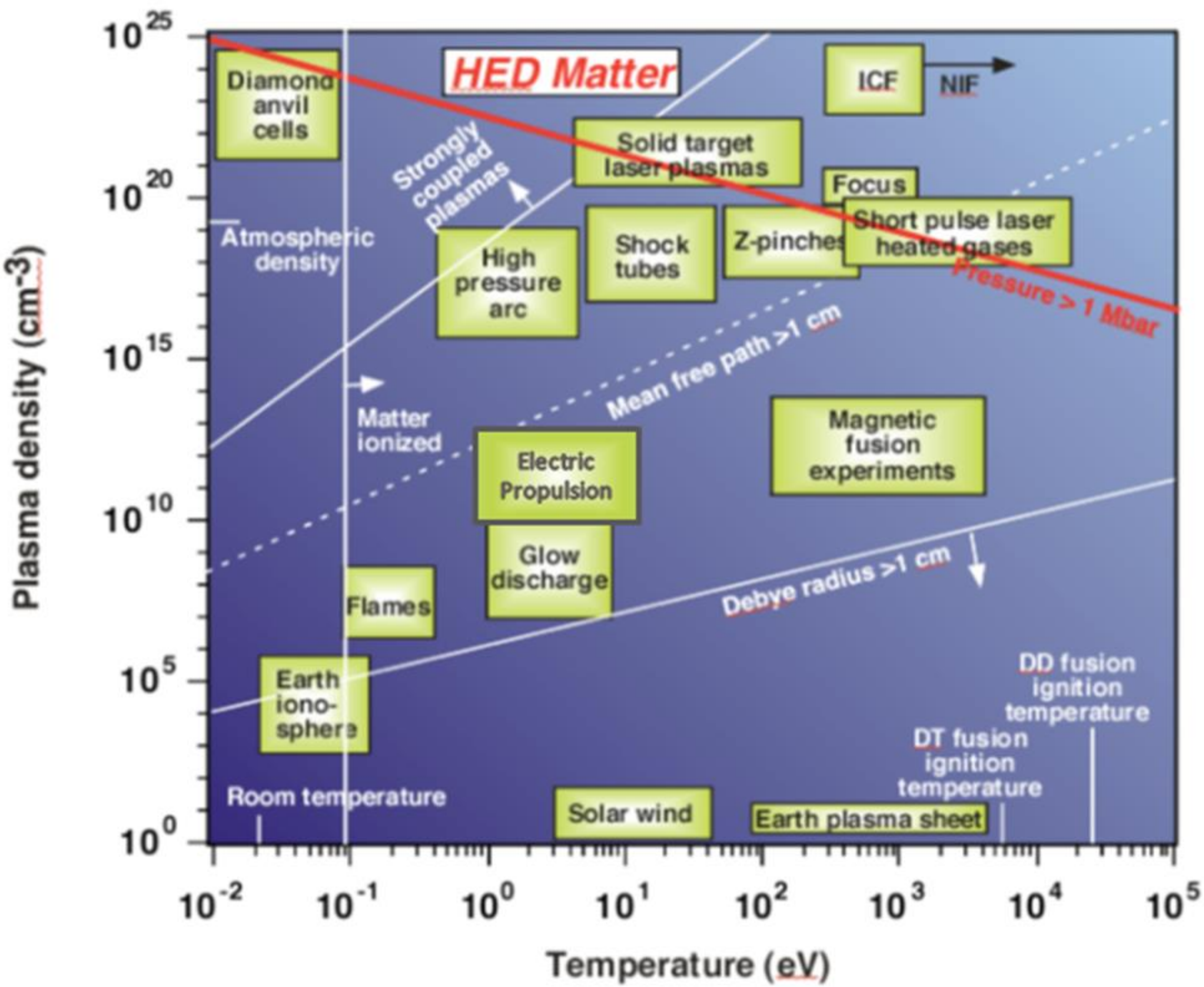


I-V Characteristic Curve



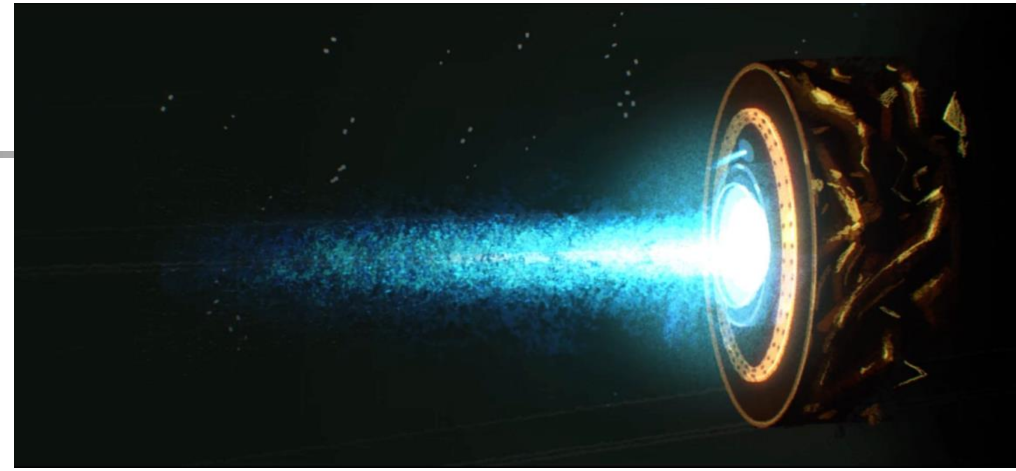
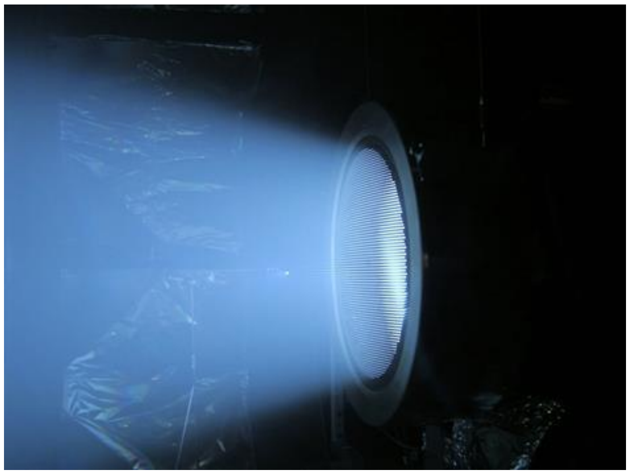
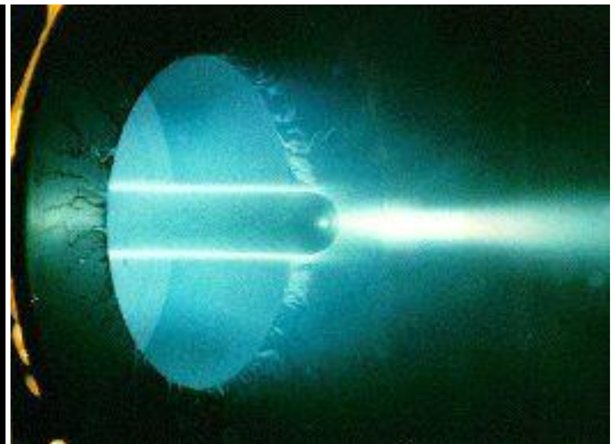
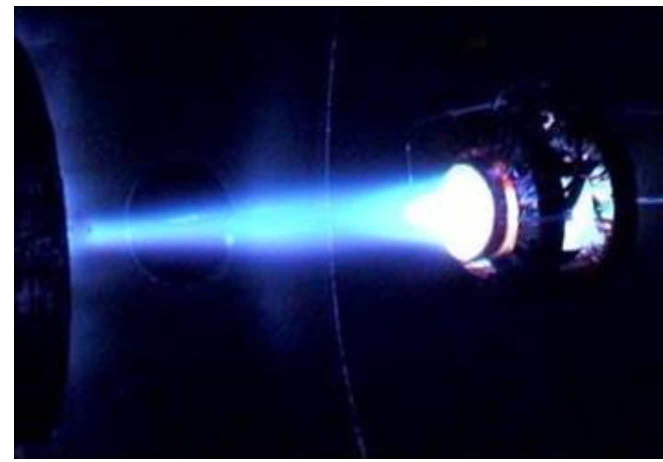


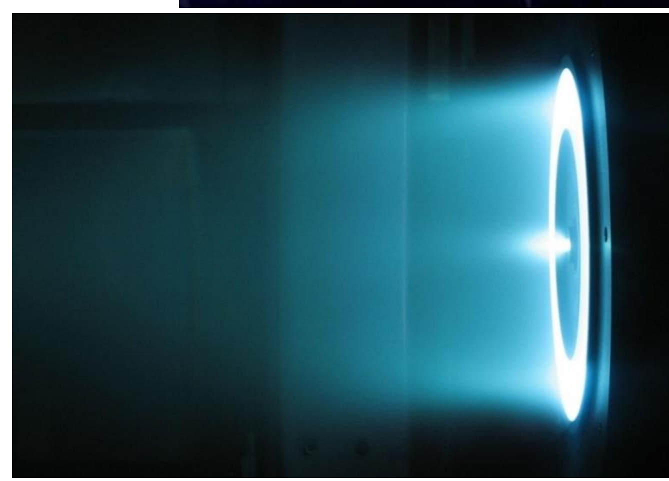
APPLICATIONS



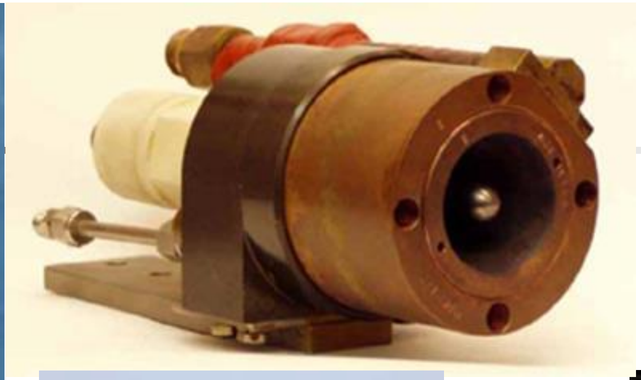
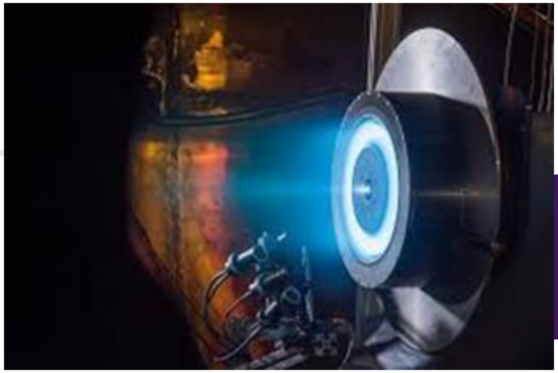
Plasma **Propulsion**

Plasma **Thrusters**

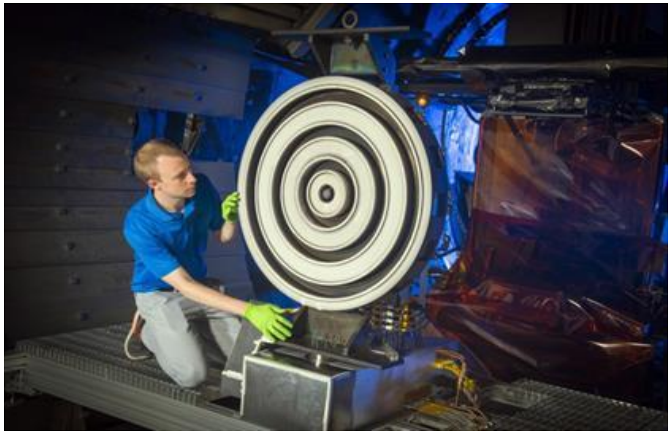
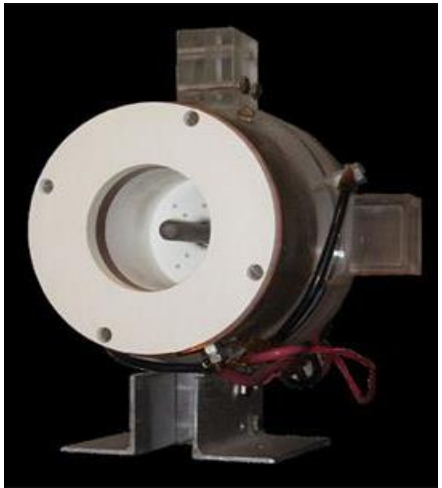
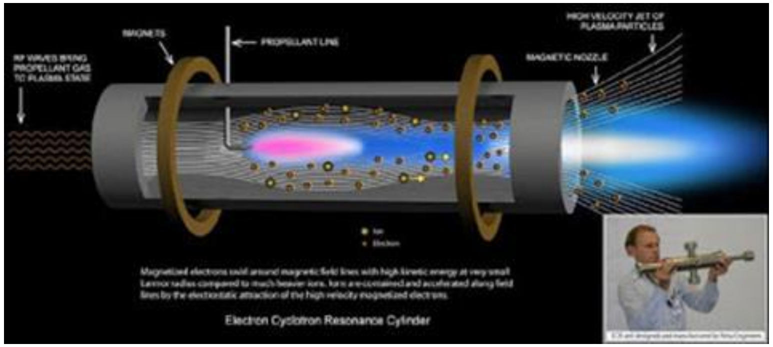






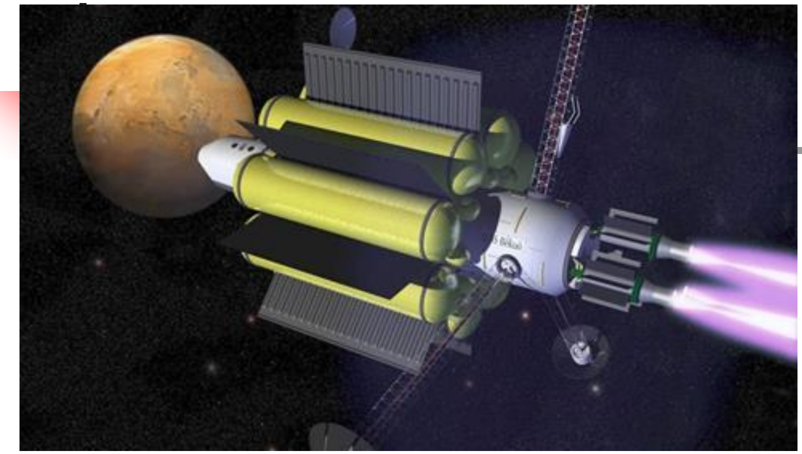


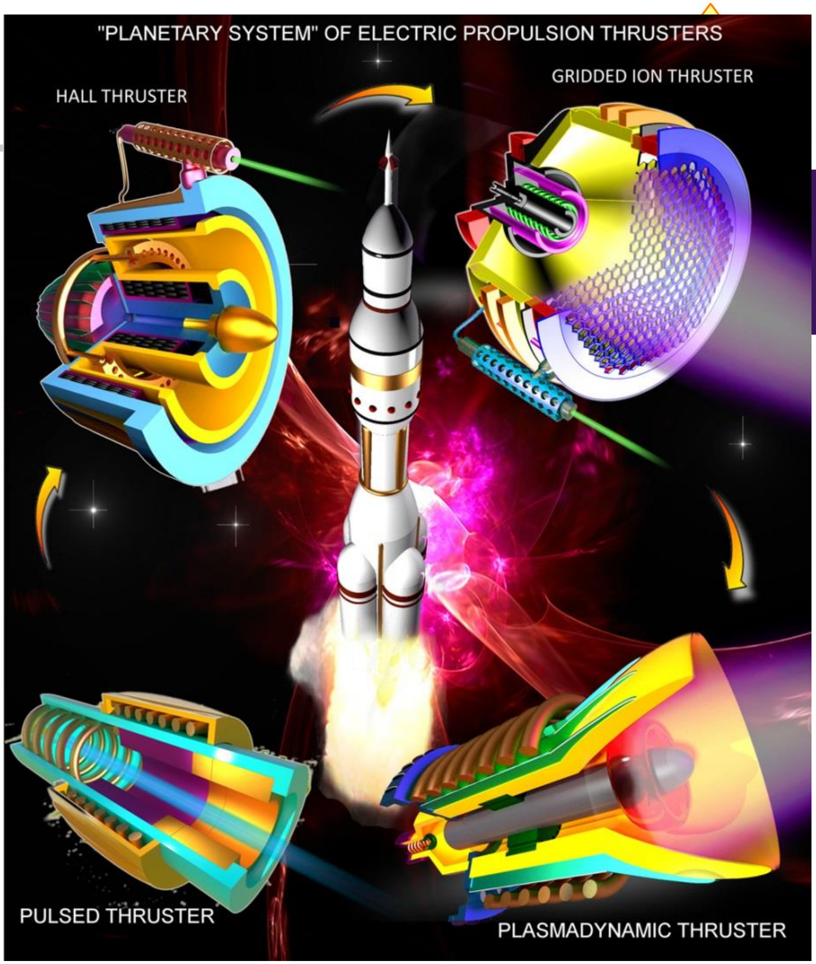


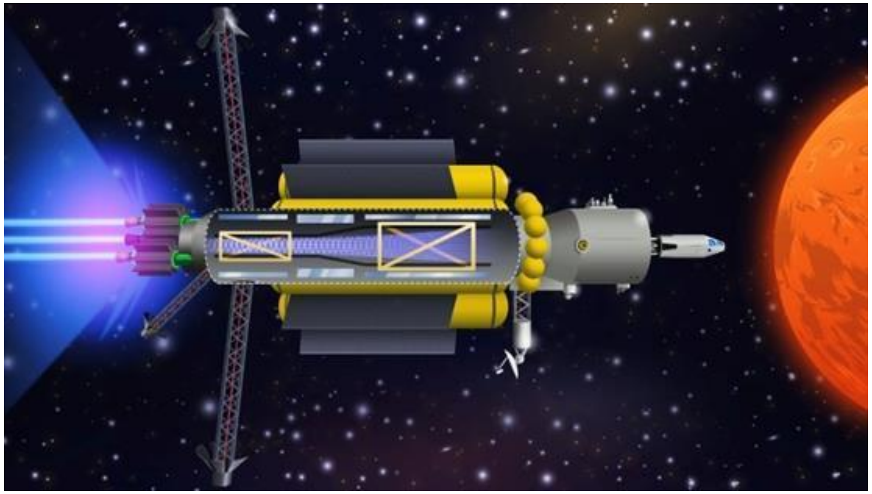



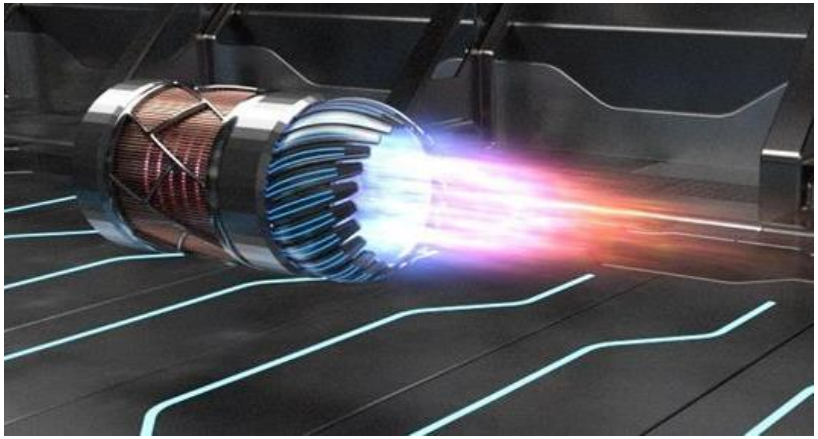

SPACEX





MAGNETS
PROPELLANT LINE
RF WAVES BRING PROPELLANT GAS TO PLASMA STATE
HIGH VELOCITY JET OF PLASMA PARTICLES
MAGNETIC NOZZLE
Ion
Electron
Magnetized electrons swirl around magnetic field lines with high kinetic energy at very small Larmor radius compared to much heavier ions. Ions are contained and accelerated along field lines by the electrostatic attraction of the high velocity magnetized electrons.
Electron Cyclotron Resonance Cylinder




"PLANETARY SYSTEM" OF ELECTRIC PROPULSION THRUSTERS
HALL THRUSTER
GRIDDED ION THRUSTER
PULSED THRUSTER
PLASMADYNAMIC THRUSTER





What Is Plasma Propulsion?

- **Propulsion**: Initiating or changing the motion of a body.

Propulsion moves things like spacecraft or jet planes forward by pushing something out of the back. Think of a balloon !!

- **Plasma propulsion** is a technology that the propellant is in an ionized, or plasma state. The temperature of the plasma ranges from room temperature to 5000 K and above.
- Plasma Propulsion can be achieved by one or more of the following methods:
  - **- Electromagnetic**
  - **- Electrothermal**
  - **- Electrostatic**

- **Propulsion Terminologies**

  -***Exhaust Velocity* (v_{ex})** – The velocity of any particle as it exits the diffuser.

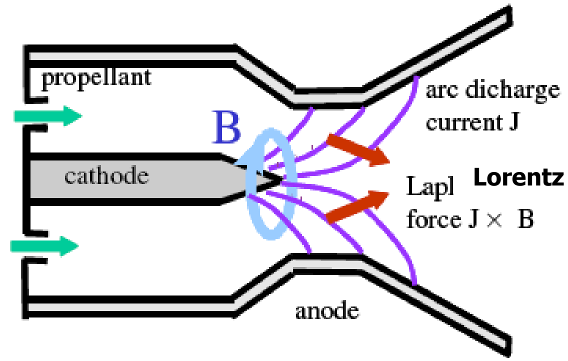
  -Thrust* (T)** is the amount of force generated by the engine, a **MOMENTUM.** -Specific Impulse* (I_{sp})** – The measurement of fuel efficiency in space engines. Specific impulse is the change in momentum per unit mass for fuels, or rather how much more push accumulates as you use that fuel.

Propulsion TYPES

1- Electromagnetic:

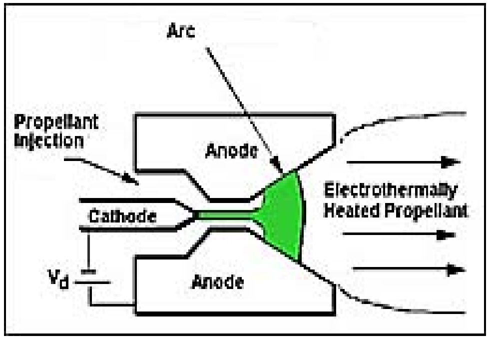
where an interaction between the plasma current and either self or applied magnetic fields accelerates the plasma via the J × B force.

- **Pulsed Plasma Trusters (PPT),**
- **Magnetoplasmadynamic Thruster (MPD),**
- **Variable Specific Impulse Plasma (VASIMR)**
- **Inductive Plasma, Helicon Plasma.**



2- Electrothermal:

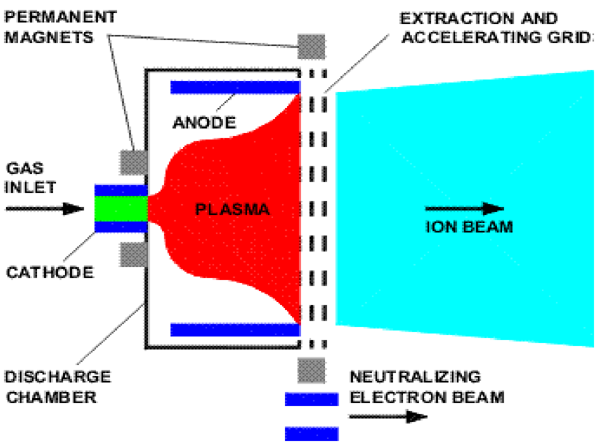
Involves heating the gas as resistively via the passage of current through it or the interaction of a gas with a hot element. Propellant is electrically heated through wall **(resistojet)** or by electrical arc discharge **(arcjet).**



3- Electrostatic:

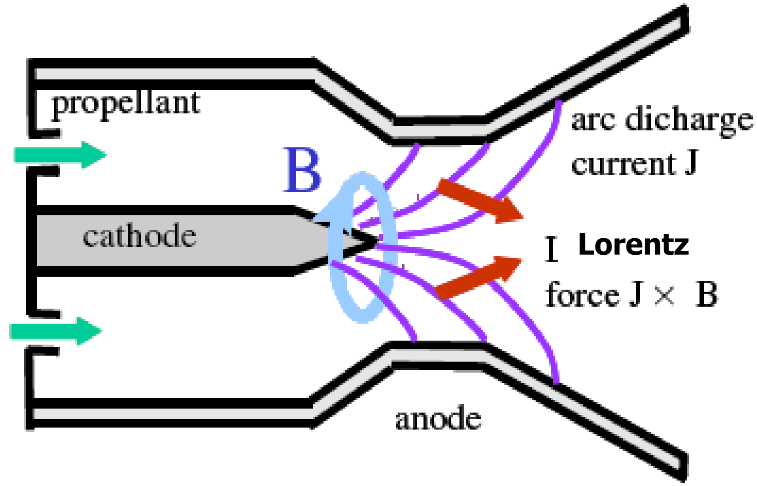
where the gas is ionized and accelerated via applied electric fields.

(Ion thrusters and Hall thrusters)



Electromagnetic Propulsion

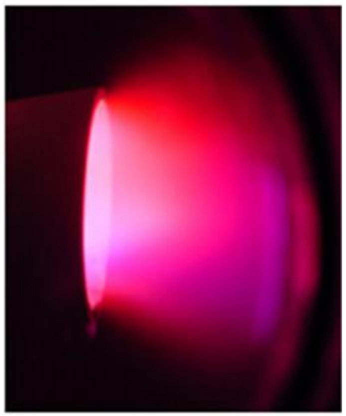
- Electromagnetic forces are used to accelerate a *plasma*
  - A gas consisting of positive ions, electrons
- Neutral beam is produced
- Higher thrust per unit area than electrostatic thruster



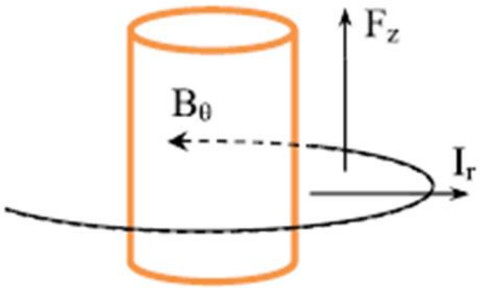
MPDT

$$\mathbf{F} = \int_V \mathbf{J} \times \mathbf{B} \, dV.$$

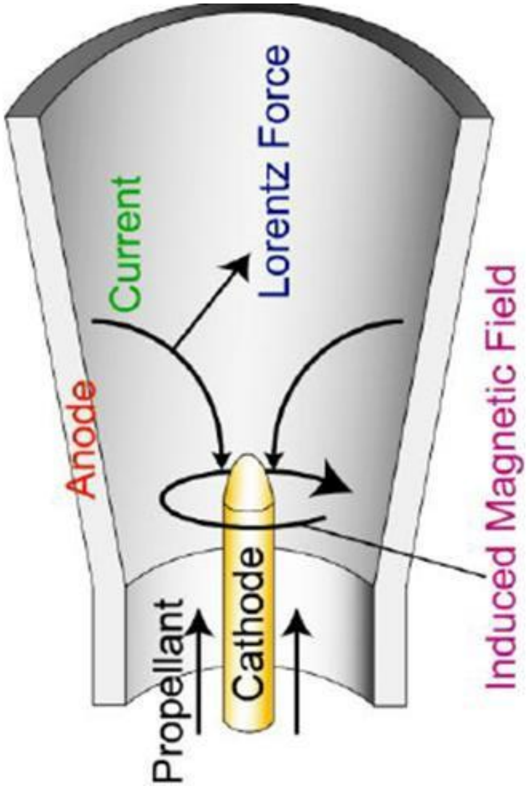
- **Classifications**
  - Magnetoplasmadynamic (MPD)
  - Pulsed plasma Thruster (PPT)

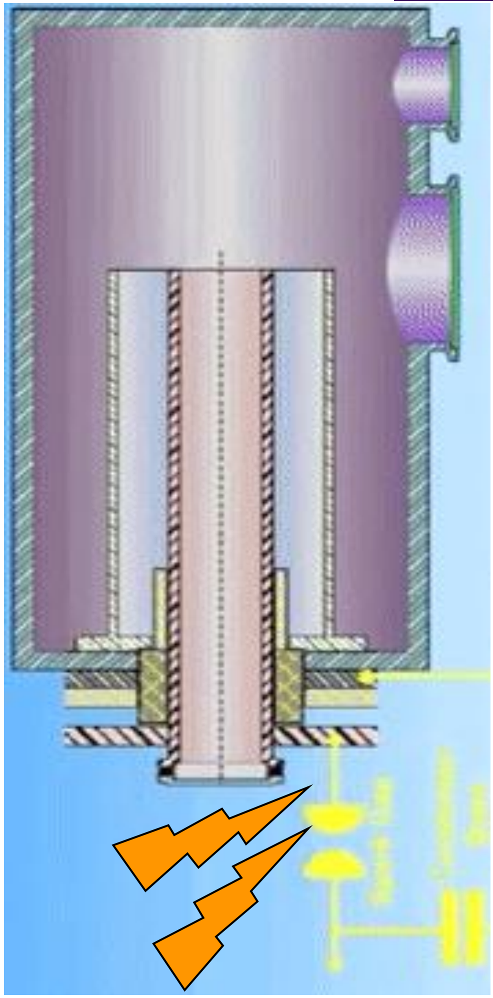


ELECTROMAGNETIC PROPULSION



$$\mathbf{F} = \int_V \mathbf{J} \times \mathbf{B}\, dV$$





$$\frac{d}{dt}\left[(L_o + L_a)I\right] + r_o I = V_o - \int \frac{Idt}{C_o}$$

Snow Plow Model

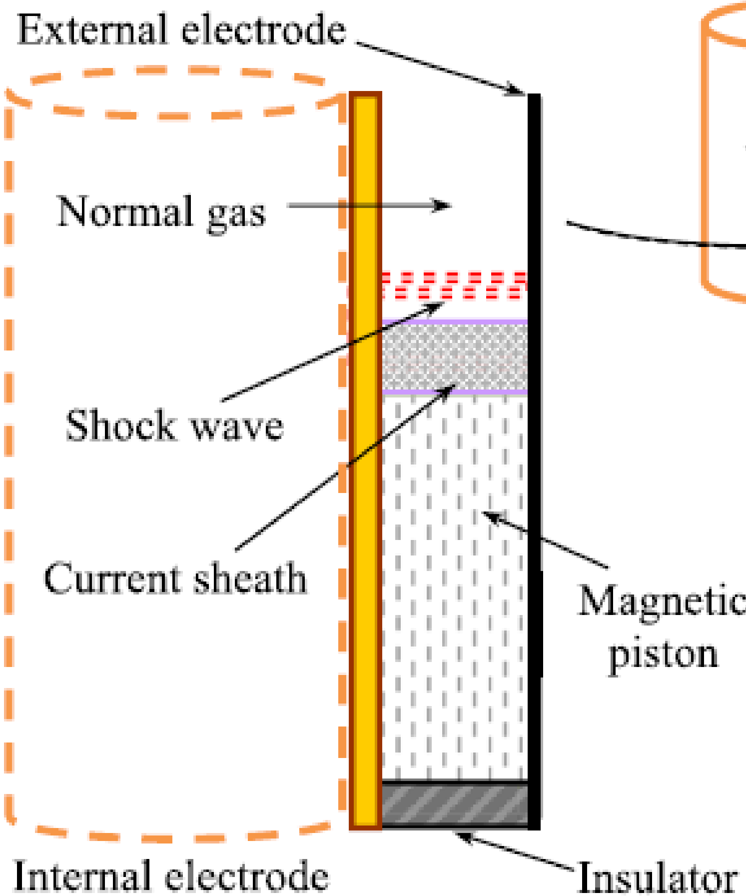
- The snow plow model assumes that all of the gas initially present in the implosion volume is accelerated and sweeps up all the encountered neutral gas by the radially imploding discharge which in turn is propelled inward by the JxB force involving the self azimuthal magnetic field.
- It assumes also that all of the fluid overtaken by the infinitely conducting current sheet is piled up in a very thin layer at the sheet and is moving at the same speed.

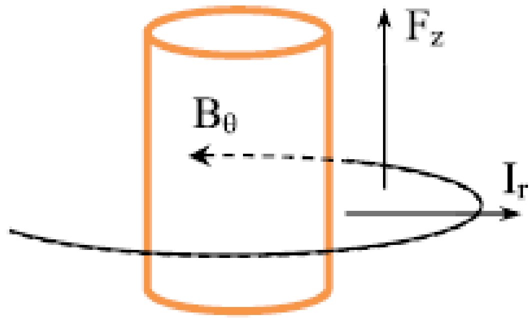
Slug Model

- The current density is assumed to be isotropic, azimuthally and radially symmetric. The only plasma sheath variation occurs as it is accelerated axially along the coaxial gun.
- Depends on the adiabatic relation (**PV^{γ} = constant**).
- Utilizes the shock relation as a function of the discharge current:

$$v_s = \frac{dr_s}{dt} = -\left[\frac{\mu(\gamma+1)}{\rho_o}\right]^{1/2} \frac{I}{4\pi r_p}$$

Governing Equations





$$F_1 = \frac{d(mv)}{dt}$$

$$F_2 = \int P\ dA = \int \frac{B^2}{2\mu} dA$$

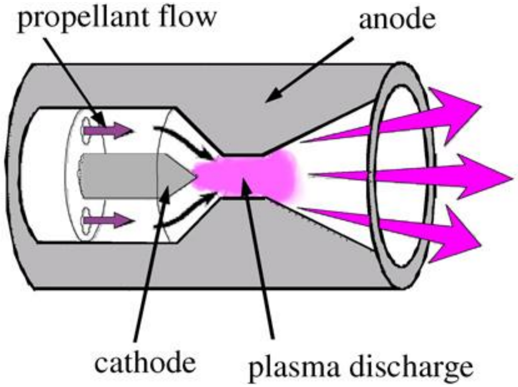
$$\frac{d(mv)}{dt} = \frac{d}{dt}\left(\left[\rho_o \pi (b^2 - a^2) z\right] f_m \frac{dz}{dt}\right)$$
$$= \rho\pi\left(c^2 - 1\right) a^2 f_m \frac{d}{dt}\left(z \frac{dz}{dt}\right)$$

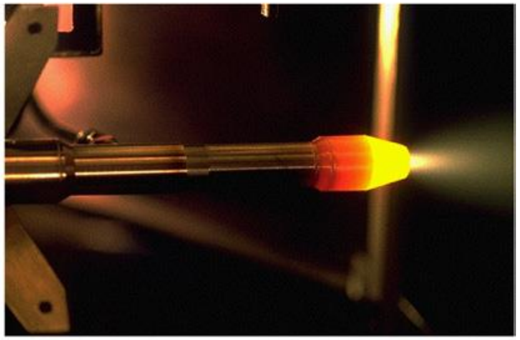
$$F_2 = \int_a^b \left[\left(\frac{\mu I f_c}{2\pi r}\right)^2 /(2\mu)\right] 2\pi r dr = \frac{\mu f_c^{\ 2}}{4\pi} \ln\left(\frac{b}{a}\right) I^2$$

Effects !!

ELECTROTHERMAL PROPULSION

Electro-thermal propulsion systems are those systems in which electrical energy is used to heat propellants, which produce gases. The gases are then sent through a supersonic nozzle to produce thrust.

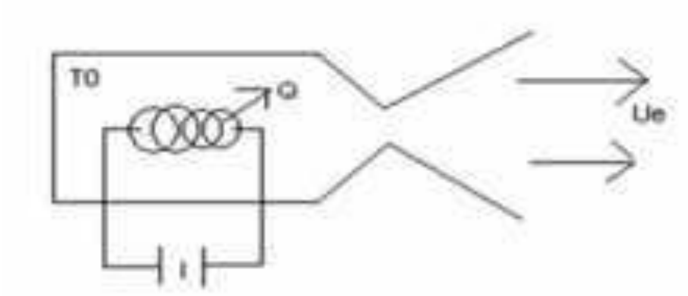




- ## Resistojet

▪Catalytic decomposition of propellant is augmented with high power electric heater

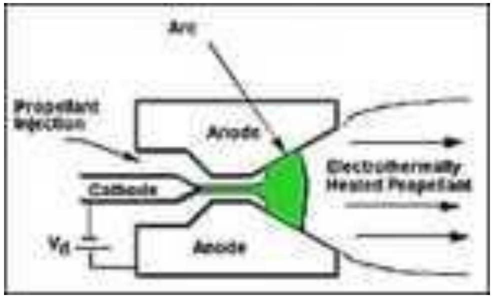
▪800 – 5,000 W



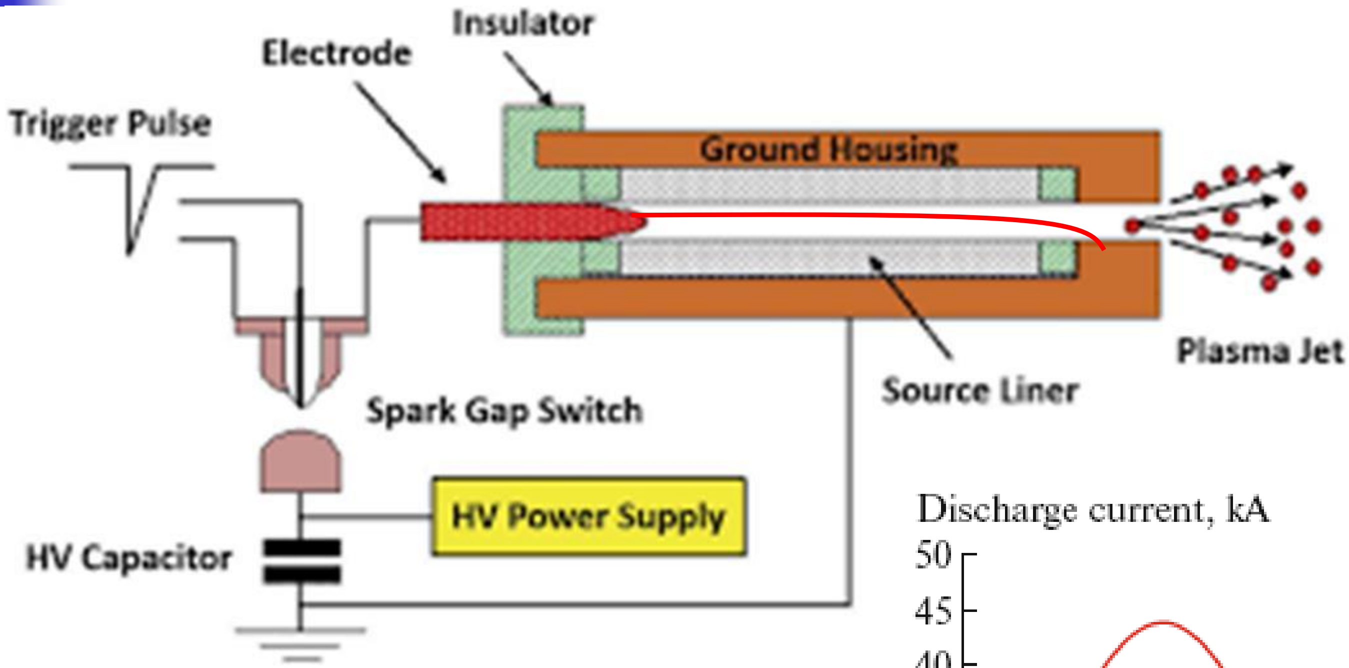
- ## Arcjet

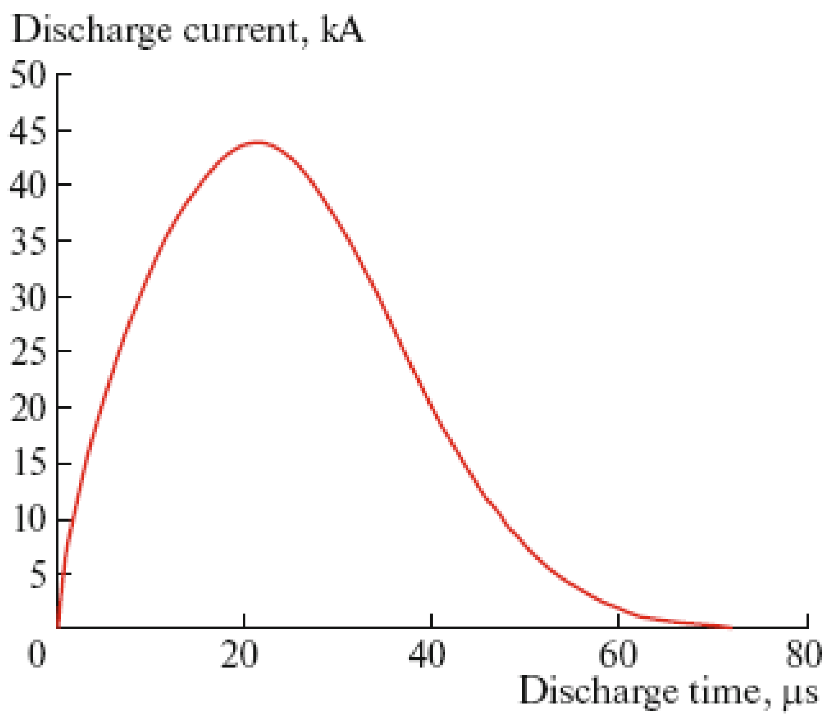
▪High voltage arc at nozzle throat adds thermal energy to exhaust

▪Various gaseous or vaporized propellants can be used.

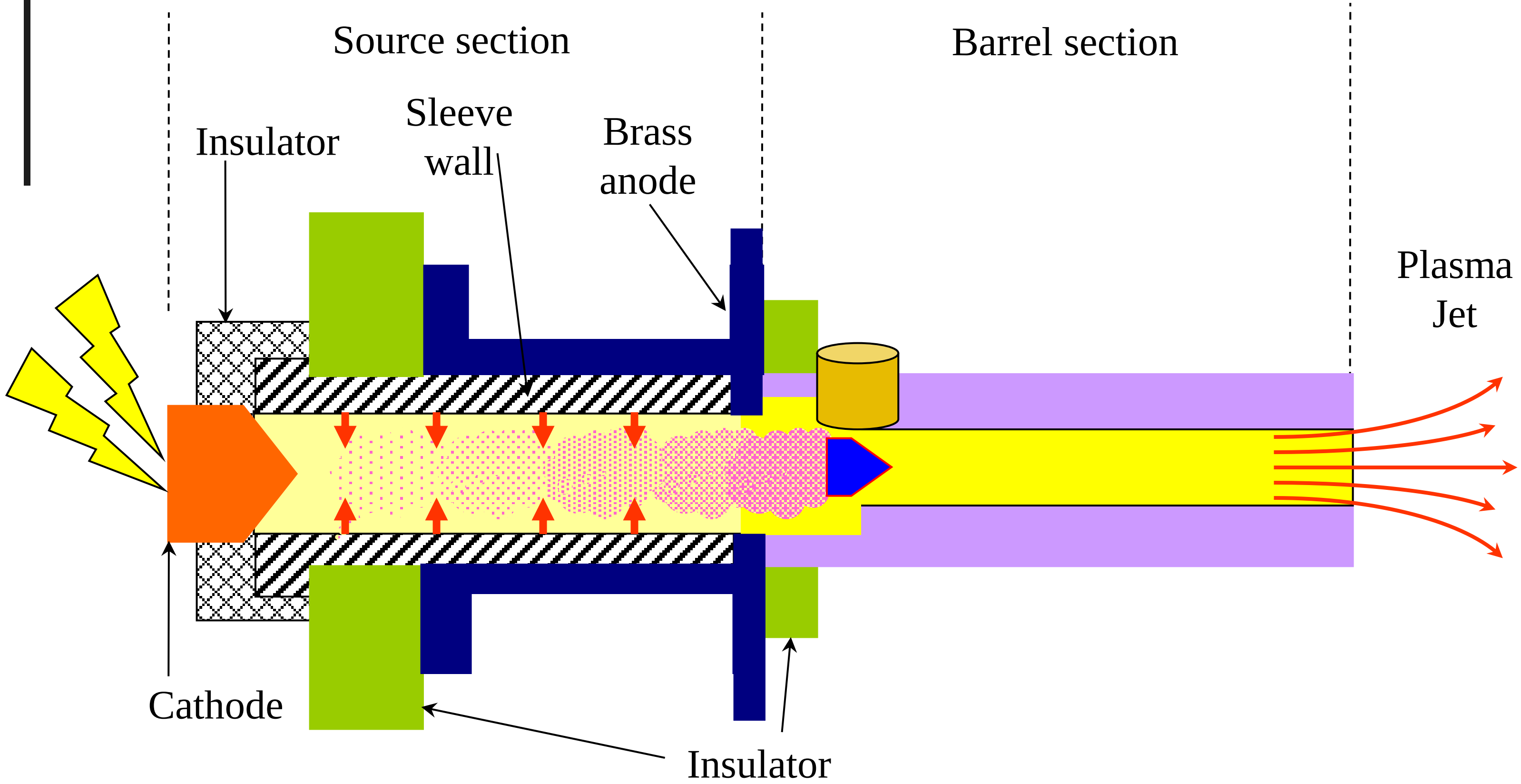


Main Design and applications





ELECTROTHERMAL PLASMA SOURCES



GOVERNING EQUATIONS

- **Modified Saha–Boltzmann equation**

a relation between the effective charge state Z_{eff} and the ionization potential, I_z ,

- $$I_Z(Z_{eff}+\tfrac{1}{2}) = kT\ln\left(\frac{AT^{3/2}}{Z_{eff}\, n}\right)$$

- where A = 4.834 x l0^{21} K$^{-3/2}$ m^{-3} is a constant,
- k is Boltzmann's constant,
- n is the number density of plasma particles, and
- T is the plasma kinetic temperature.

Conservation of mass

The continuity equation:

$$\frac{\partial n}{\partial t} = \dot{n}_a - \frac{\partial (vn)}{\partial z}$$

$$\dot{n}_a = \frac{Q A_w N_A}{V H_{sub} M_p} = \frac{2Q}{H_{sub} M_p R}$$

$\partial n / \partial t$ the time rate of change of the particle density in each cell

$\dot{n}_a$ the change in the number density introduced by ablation

$\frac{\partial (vn)}{\partial z}$ the rate of particles entering and leaving the cell , where v is the plasma velocity.

Conservation of momentum

$$\frac{\partial v}{\partial t} = -\frac{1}{\rho}\frac{\partial P}{\partial z} - \tfrac{1}{2}\frac{\partial v^2}{\partial z} - \frac{v\dot{n}_a}{n} - \frac{2\tau_w}{\rho R}$$

$\partial v/\partial t$	the rate of velocity change in each cell
$\partial P/\partial z$	the axial pressure gradient,
$\partial v^2/\partial z$	kinetic energy gradient,
$\frac{v\dot{n}_a}{n}$	loss due to the increase of the number density due ablation,
$\frac{2\tau_w}{\rho R}$	the loss due to the viscous drag occurs at the capillary wall.

ρ is the plasma density and $\tau_w = \frac{1}{2} C_f \rho v^2$ is the viscous drag at the capillary wall and C_f is the friction factor.

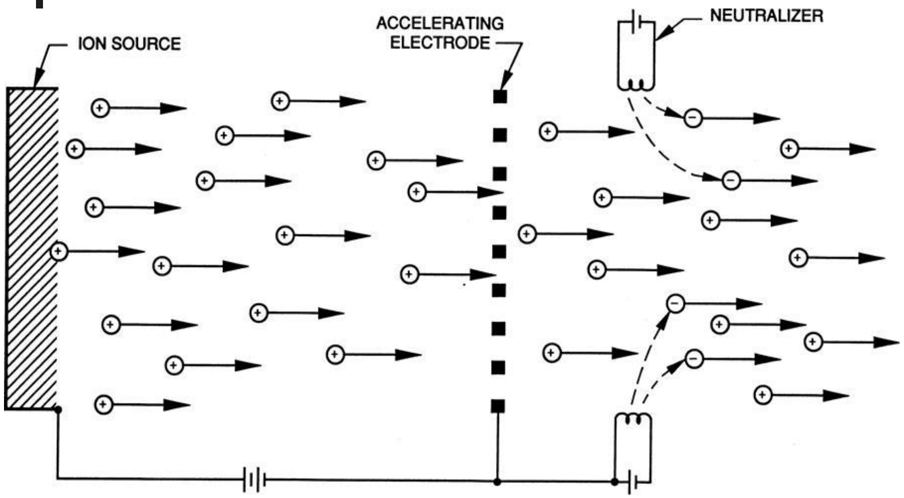
Conservation of energy

$$n\frac{\partial U}{\partial t}=\eta J^2-\frac{2Q}{R}-P\frac{\partial v}{\partial z}+\tfrac{1}{2}\dot{\rho}_a v^2-\dot{n}_a U-v\frac{\partial(nU)}{\partial z}$$

ηJ^2	The increase in internal energy due to joule heating is determined by where η is the plasma resistivity, and J is the discharge current density.
2Q/R	The loss in internal energy due to thermal radiation
$P\ \partial v/\partial z$	the change due to plasma flow work,
$\tfrac{1}{2}\dot{\rho}_a v^2$	the increase due to friction from ablation,
$\dot{n}_a U$	the loss due to plasma cooling from ablated mass,
$v\,\partial(nU)/\partial z$	the change in internal energy due to particles entering and leaving the cell.

The internal energy of ideal plasma is composed of the internal energy due to thermal motion $\tfrac{3}{2}kT\left(1+\overline{Z}\right)$, where $\overline{Z}$ is the average charge state, the dissociation energy E_{diss}, and the internal energy due to effective ionization state I_i : $U=\tfrac{3}{2}kT\left(1+\overline{Z}\right)+I_i+E_{diss}$

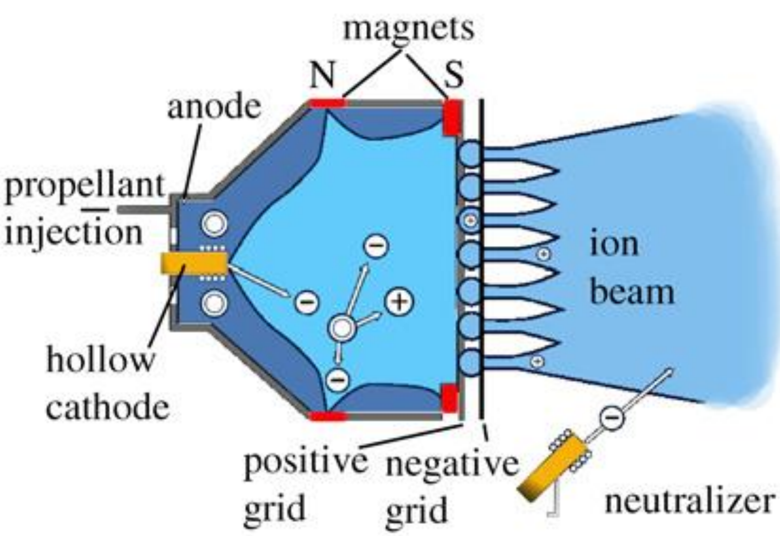
Electrostatic Propulsion



Ion Thruster

All **ion thrusters** have these key elements: generation chamber, two electrodes and a neutralizer. The two electrodes, screen and acceleration, create a high **potential difference** between them. The ions drift into the orifices of the electrodes and are then accelerated. The ions are neutralized once out of the thruster to prevent charging. The exhaust velocity of the ion thruster is measured as:

- Xenon Ion Thruster



$$v_e = \left(\frac{2qV}{M}\right)^{1/2}$$

$$j = \frac{4\epsilon}{9}\left(\frac{2q}{M}\right)^{1/2}\frac{V^{3/2}}{d^2}$$

$$\frac{T}{A} = \frac{\dot{m}v_e}{A} = \frac{jMv_e}{q} = \frac{8\epsilon}{9}\left(\frac{V}{d}\right)^2$$

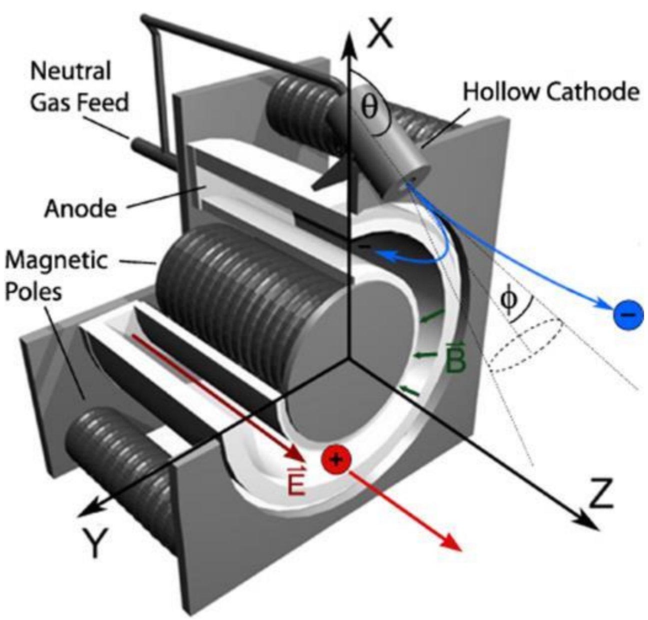
Electrostatic Propulsion

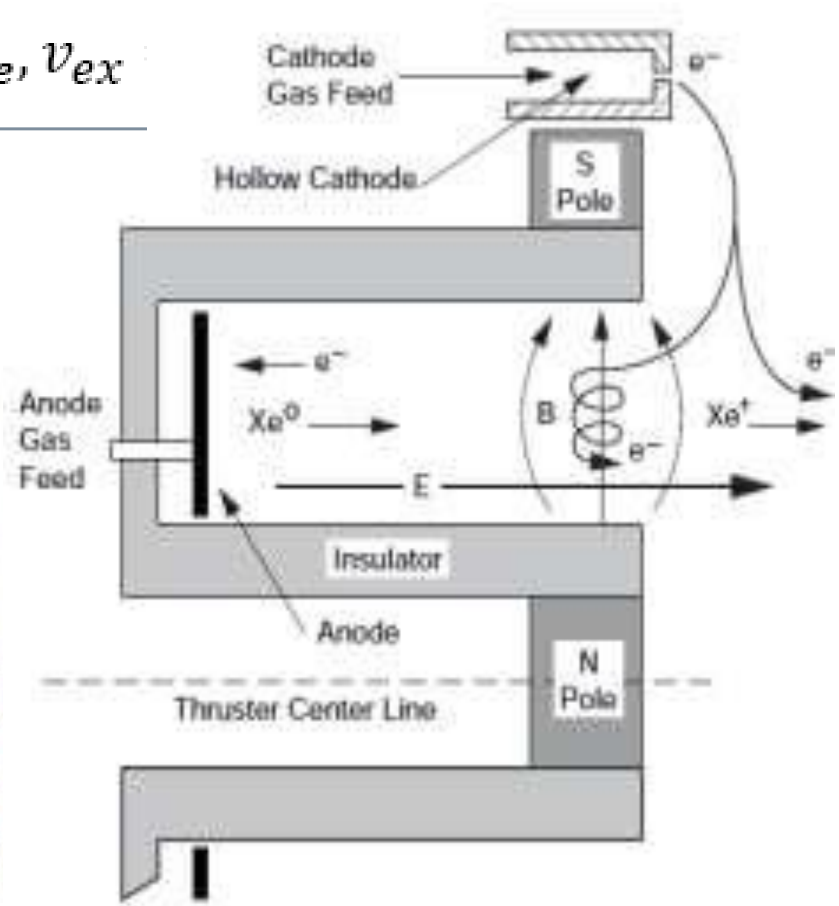
Hall thrusters operate in a different manner than ion thrusters. They are operating by using the neutralizer as an ionizer. The electrons are trapped in a magnetic field, freely rotating around. The incoming gas bombards the electrons, causing ionization. The concluding exhaust velocity is determined by **the drift velocity** of the electron and the **magnetic field**

$$v_e = \frac{\mathbf{E}\times\mathbf{B}}{B^2},$$

$$= \frac{F}{\dot{m}} = \frac{1}{\dot{m}}\int_V \mathbf{J}_\theta \times \mathbf{B}_\mathbf{r} dV$$

$$\mathbf{J}_\theta = e n_e v_e, v_{ex}$$





GOVERNING EQUATIONS

XP4

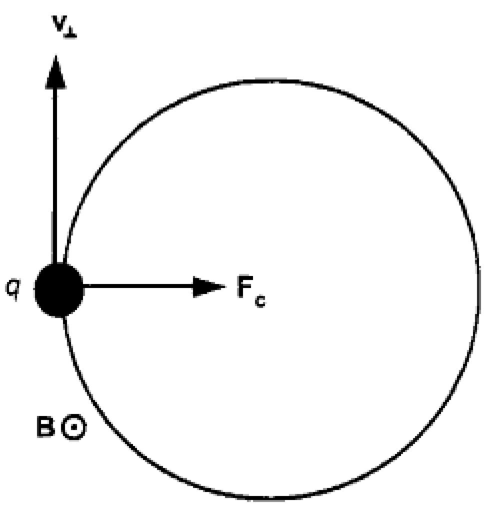
EGY Plasma

Lorentz force

$$\mathbf{F} = q\mathbf{v}_\perp \times \mathbf{B}\,.$$

$$\mathbf{F_c} = q\mathbf{v}_\perp \times \mathbf{B} = \frac{mv_\perp^2}{r}\,,$$

$$\mathbf{v} = \frac{\mathbf{E}\times\mathbf{B}}{B^2} \equiv \mathbf{v}_E\,,$$



MAXWELL EQUATIONS

$$\nabla\cdot\mathbf{E} = \frac{\rho}{\varepsilon_o}$$

$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}$$

$$\nabla\cdot\mathbf{B} = 0$$

$$\nabla\times\mathbf{B} = \mu_o\left(\mathbf{J} + \varepsilon_o\frac{\partial\mathbf{E}}{\partial t}\right),$$

Single Particle Motions

$$\mathbf{F} = m\frac{d\mathbf{v}}{dt} = q\left(\mathbf{E} + \mathbf{v}\times\mathbf{B}\right).$$

$$\omega_c = \frac{|q|\,B}{m}\,. \qquad r_L = v_\perp / \omega_c$$

Electron Cyclotron frequency

Larmor Radius

Thrust

The thrust is proportional to the beam current times the square root of the acceleration voltage

$$T = \sqrt{\frac{2M}{e}}\, I_b \sqrt{V_b} \ \text{[newtons]}.$$

$$v_i = \sqrt{\frac{2qV_b}{M}}, \qquad \dot{m}_i = \frac{I_b M}{q}.$$

Momentum Conservation

$$\mathbf{F}_L = m\frac{d\mathbf{v}}{dt} = q(\mathbf{E} + \mathbf{v}\times\mathbf{B}).$$

$$mn\frac{d\mathbf{v}}{dt} = mn\left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v}\right] = qn(\mathbf{E}+\mathbf{v}\times\mathbf{B}) - \nabla\cdot\mathbf{p} - mn\nu(\mathbf{v}-\mathbf{v}_o),$$

Utilizing conservation of momentum, it is possible to valuate how the electron fluid behaves in the plasma

$$mn_e\left[\frac{\partial v_z}{\partial t} + (v\cdot\nabla)v_z\right] = qn_eE_z - \frac{\partial p}{\partial z},$$

Boltzmann relationship for electrons $\quad n_e = n_e(0)\, e^{(e\phi/kT_e)}$

Performance Calculations

- Thrust & Specific Impulse
  - *Thrust* is the amount of force generated.
  - *Specific impulse* is a measure or engine performance (analogous to miles per gallon)
    - Units are *seconds*

$$I_{sp} = \frac{F}{w}$$

$$\mathrm{Isp} = \frac{T}{\dot{m}_p g},$$

T = Thrust

$w =$ weight flowrate of propellant

- Main Equation

$$\Delta V = g I_{sp} \ln \frac{m_i}{m_f}$$

$g = 9.8 \text{ m/s}^2$

$m_i =$ mass of vehicle before burn

$m_f =$ mass of vehicle after burn

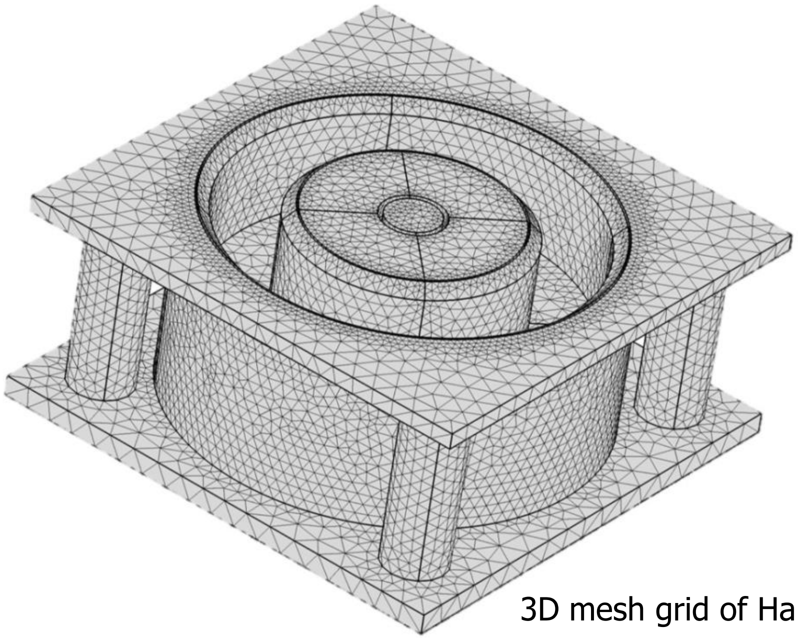
$m_p =$ mass of propellant for ΔV

$= m_i - m_f$

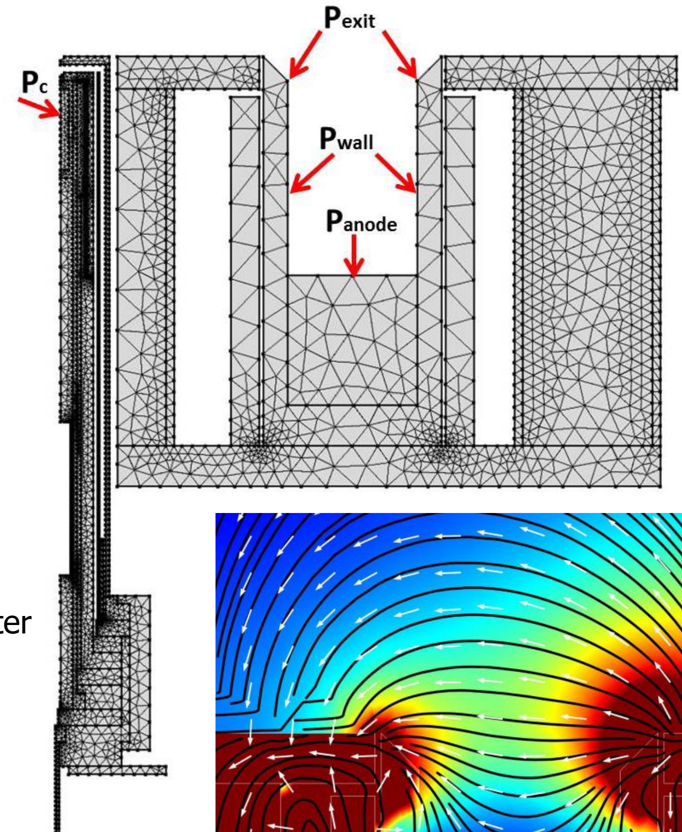
$$m_p = m_i \left(1 - e^{\frac{-\Delta V}{g I_{sp}}} \right)$$

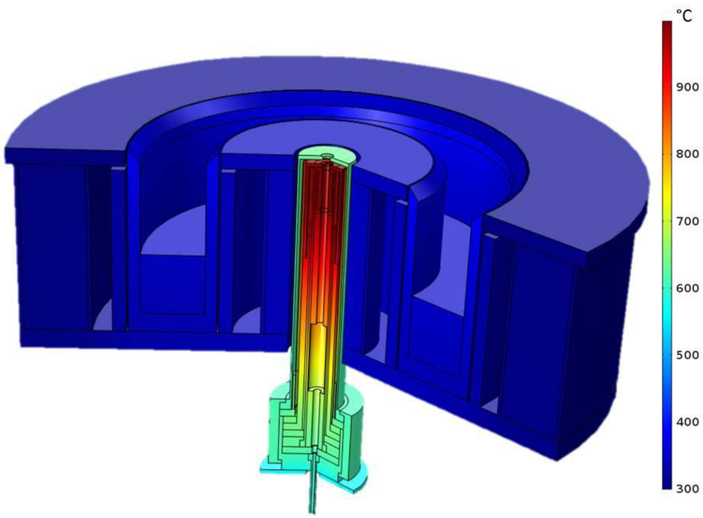
The main equation assumes no losses (gravity effects, aerodynamic drag). Actually very accurate for short burns in Earth orbit or in deep space!

Analysis of the Hall thruster is conducted using COMSOL Multiphysics

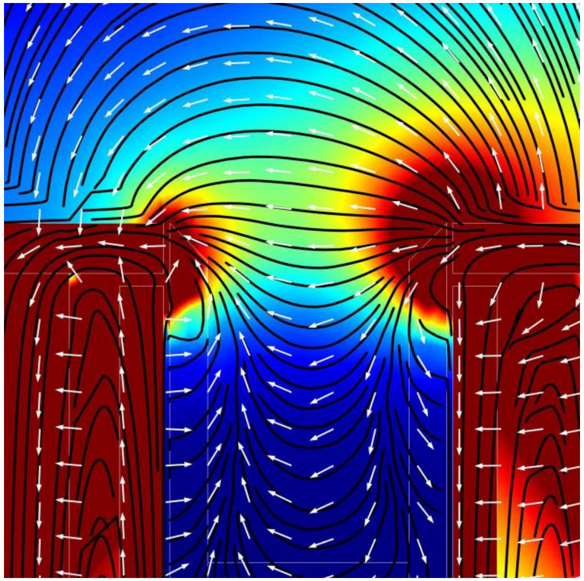


3D mesh grid of Hall thruster

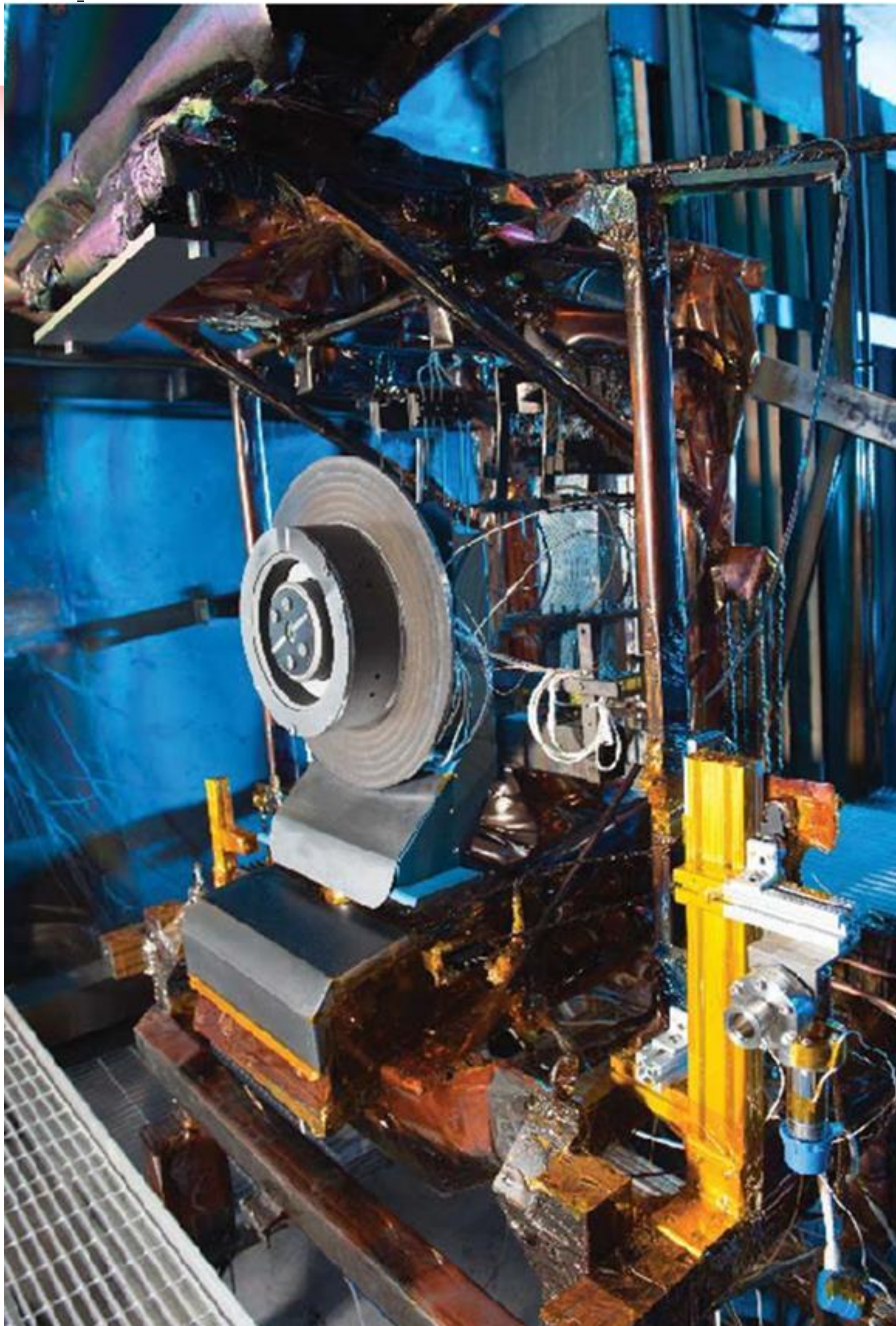




Temperature distribution



Parametric sweep of the gap between magnetic shields and BN channel






Performance of some electric thrusters

Thruster	Missions	Electric power (kW)	I_{sp} (s)	T (N)	Physical principles
Electrothermal					
Arcjets					
Hydrazine[a]	NSSK[b]	0.3–2	500–600	10^{-3}–0.2	$v_{ex} \sim \sqrt{\frac{T}{M}}$
Ammonia[c]	Orbit raising	30	800	2	
Hydrogen[d]	NSSK/orbit transfer	1–100	900–2000	0.1–5	
Electrostatic (Xe gas)					
Hall effect thrusters[a]	NSSK	0.5–5	500–3000	10^{-2}–0.4	$v_{ex} \sim \sqrt{\frac{2\,e\,V_{ac}}{M_i}}$
Gridded ion engines[a]	NSSK	0.3–5	1000–4000	10^{-3}–0.2	
Electromagnetic					
Magnetoplasmadynamic					
Lithium[d]	Large Δv	200–1000	2000–5000	2–15	$v_{ex} \sim \frac{J}{\dot{m}}$
Hydrogen[d]	Large Δv	1000	5000	15	

https://pstlab.engin.umich.edu/electric-propulsion-activities/

COMMENTS / CHALLENGES

- How to ignite !
- Homogeneous ignition …
- Plasma wall interaction – wall ablation/erosion.
- Time of operation.
- Fuel type for highest energy and longest time..
- Increasing the thrust and the specific impulse.

Plasma Propulsion in Egypt and around the world

Helium 3

^3He can be used in fusion reactions by either of the reactions

$$^2H + {}^3He \rightarrow {}^4He + {}^1p + 18.3\ MeV,$$

Or

$$^3He + {}^3He \rightarrow {}^4He + 2\,{}^1p + 12.86\ MeV.$$

Russia 2001, China 2015, India 2008 and 2018

There are approximately 1 million metric tons of Helium-3 embedded in the moon (one expert estimated Helium-3's value at about five billion US dollars a ton).

The amounts of helium-3 needed as a replacement for conventional fuels are substantial by comparison to amounts currently available. The total amount of energy produced in the 21H + 32He reaction is 18.4 MeV, which corresponds to some 493 megawatt-hours (4.93×10^8 W·h) per three grams (one mole) of ^3He. If the total amount of energy could be converted to electrical power with 100% efficiency (a physical impossibility), it would correspond to about 30 minutes of output of a gigawatt electrical plant per mole of 3He. Thus, a year's production (at 6 grams for each operation hour) would require 52.5 kilograms of helium-3. The amount of fuel needed for large-scale applications can also be put in terms of total consumption: electricity consumption by 10^7 million U.S. households in 2001 totaled 1,140 billion kW·h (1.14×10^{15} W·h). Again assuming 100% conversion efficiency, 6.7 tonnes per year of helium-3 would be required for that segment of the energy demand of the United States, 15 to 20 tonnes per year given a more realistic end-to-end conversion efficiency.

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Questions?

Thank you

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