Lecture 39

Electric Rocket Propulsion

Force and Impulse

Newton's 2nd Law: The rate of change of momentum of a body is equal to the net force acting on it

$$\mathbf{F} = \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = \frac{\mathrm{d}(m\mathbf{v})}{\mathrm{d}t}$$

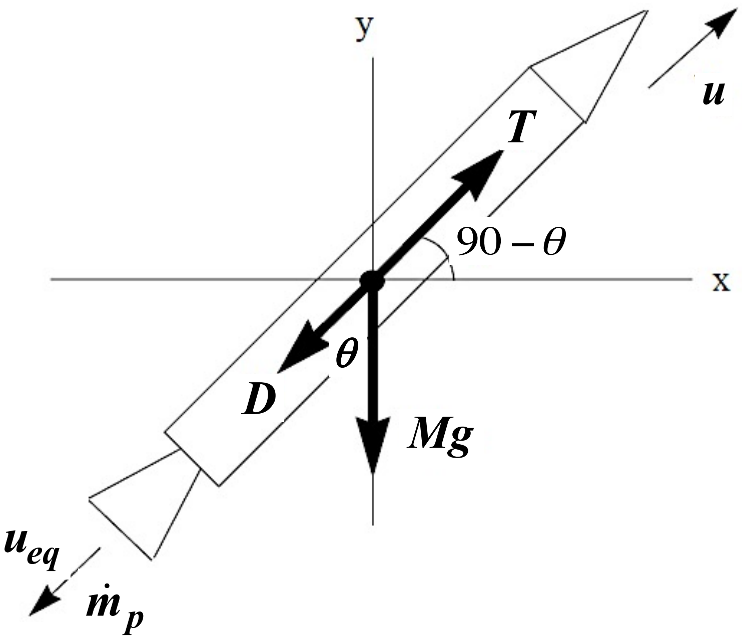
The impulse acting on a body is defined as $\int_{t_1}^{t_2} \mathbf{F}\,dt$

Or, $I = (mv)_2 - (mv)_1$

- Impulse is the net change in momentum imparted to a body due to a force acting on it over a period of time.
- The same impulse can be produced with a small force acting over a long time or a large force acting over a small time

The Tsiolkovsky Rocket Equation

(fundamental equation of rocketry)



$$m\bar{a} = \sum F_{axis}$$

$$M\frac{du}{dt} = T - D - Mg\cos\theta$$

$$\frac{du}{dt} = \frac{\dot{m}_p}{M}u_{eq} - \frac{D}{M} - g\cos\theta$$

$$\mathrm{u}_{\mathrm{eq}} = const$$

integrating from initial to burnout

$$\Delta u = u_{eq}\ln\left(\frac{M_0}{M_b}\right) - \int_0^{t_b}\frac{D}{M}dt - \int_0^{t_b} g\cos\theta\, dt$$

Delta-v only depends on exhaust velocity and mass of propellant and structure, not mass flow rate

Limitations of Chemical Propulsion

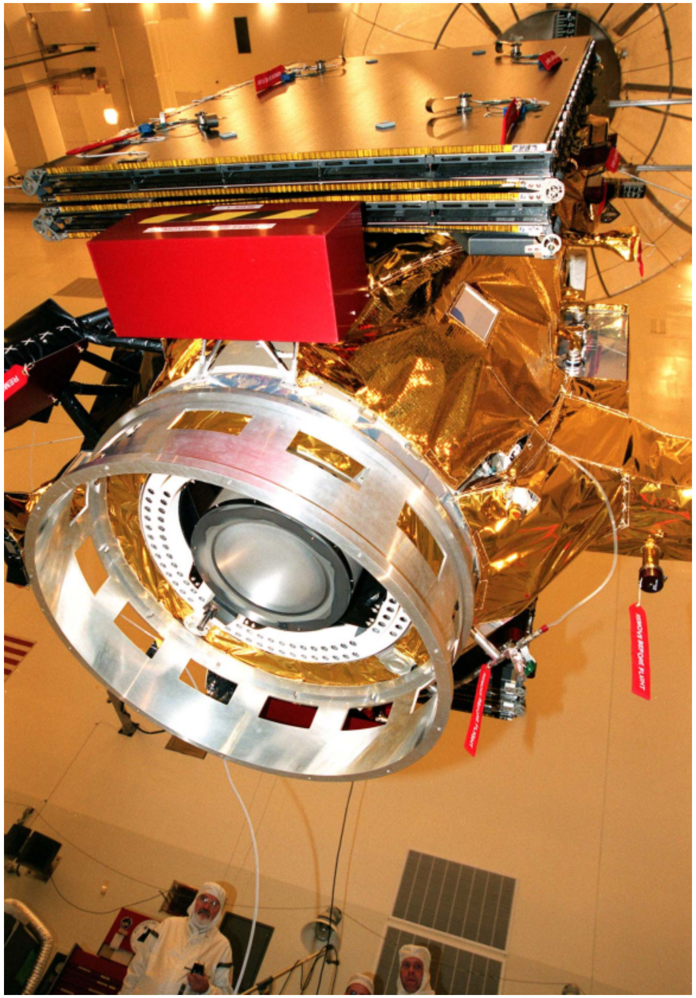
Mission	Required Δv*	$m_{initial} / m_{payload}$ (c_e = 5 km/s)	$m_{initial} / m_{payload}$ (c_e = 25 km/s)
Earth orbit to Mars and return	14 km/s	16	1.8
Earth orbit to Mercury and return	31 km/s	148	3.5
Earth orbit to Jupiter and return	64 km/s	3.6×10^5	12.9
Earth orbit to Saturn and return	110 km/s	3.6×10^9	81.5

*Assumes Hohmann transfer with no staging or gravity assists.

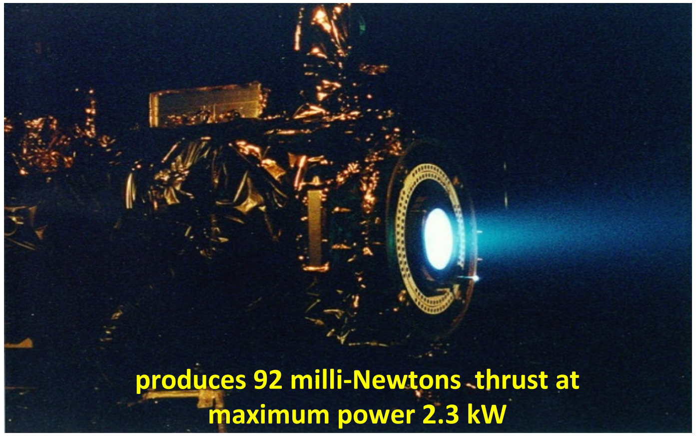
- Payload fractions are really small for chemical propulsion since the maximum exhaust velocity < 5km/s
- Significantly higher exhaust velocities are needed for long distance travel – that leads to electric propulsion for long distance travel

Deep Space 1, Ion Thruster

- Launched October 1998
- Payload platform for advanced, high risk technologies
- Flyby of Asteroid Braille; mission extended to include encounter with Comet Borrelly
- Travelled 263,179,600 km at speeds up to 4.5 km/s
- Engine: 30 cm beam, weight 8.3 kg; [w/81 kg of xenon] propellant



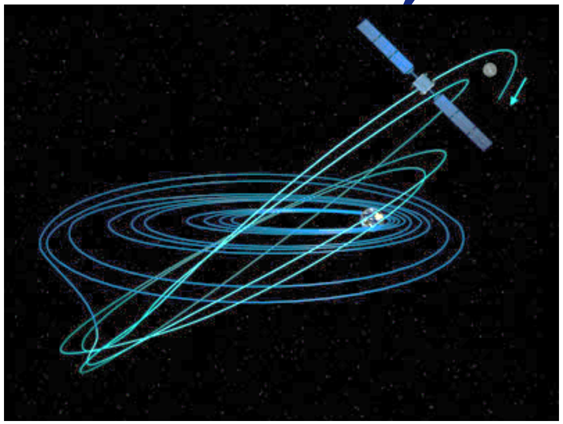
N-STAR solar powered, ion thruster for Deep Space 1 spacecraft



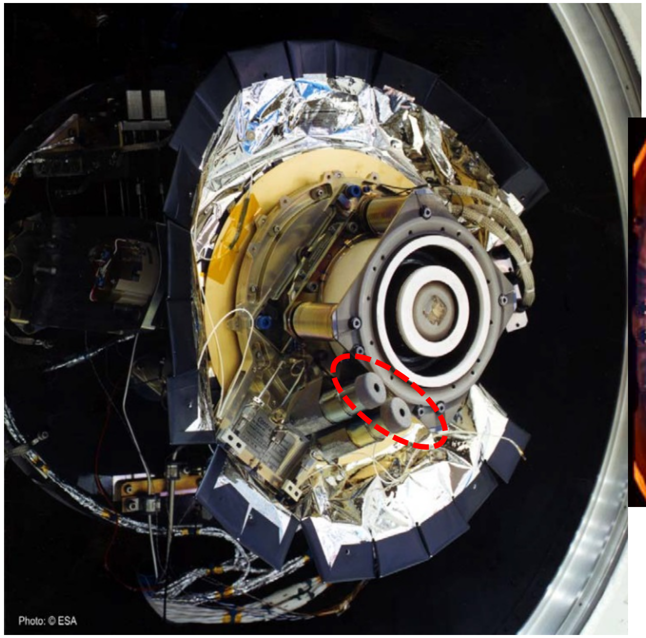
NASA's 2.3 kW N-STAR ion thruster during hot fire test at JPL

ESA Smart-1, Ion Thruster

Artist's depiction of SMART-1 mission to the Moon in 2003; impacted in 2006



Circuitous route to the Moon
13 ½ months



SMART-1 ion bombardment ion engine
Note the "neutralizer"

- Xenon is ionized by electron bombardment
- electrostatic grid used to accelerate charged particles to very high velocities
- electrons routed to second anode and injected into beam to neutralize charge
- allows for a reduction in propellant mass of up to 90% in a satellite designed for 12-15 years of operation

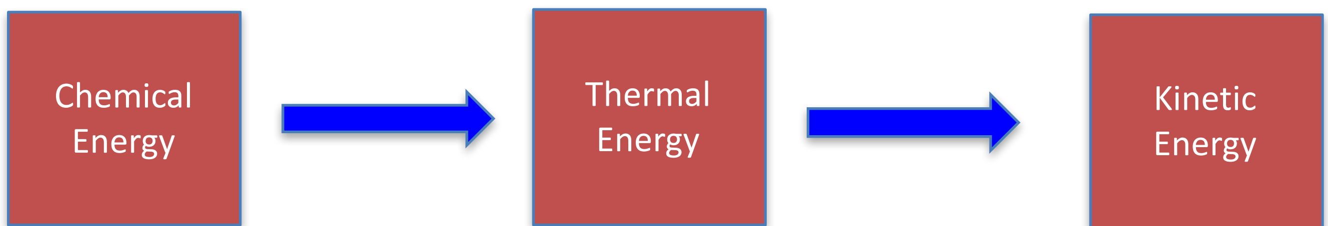
- Solar powered
- 7 g (~ 70 mN) thrust
- 50 liters (~ 13 gallons) of Xenon to the Moon

http://smart.esa.int/science-e/www/object/index.cfm?fobjectid=40127

Energy Transformation in Rocket Propulsion

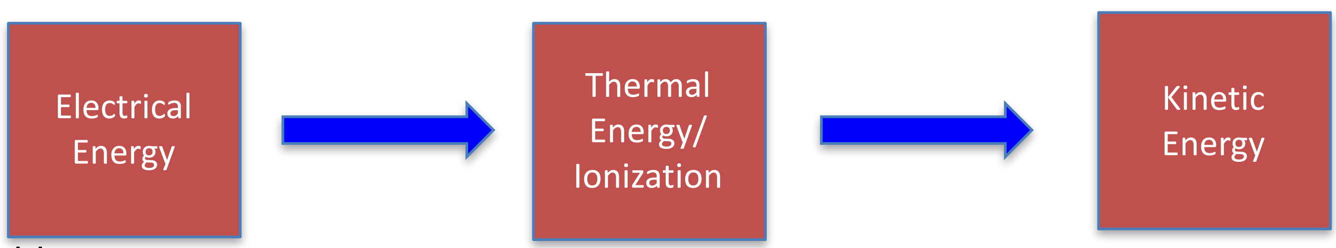
- Accelerate propellant in one direction to provide thrust in the opposite direction
- The energy transformation process to accelerate air is different in chemical propulsion compared to electric propulsion

Chemical Propulsion



- Stored in a propellant
- Typically not re-chargeable
- Energy release is quick
- Low efficiency

Electric Propulsion



- Solar power/Rechargeable
- Energy release is slow
- High efficiency

ELECTRIC PROPULSION OVERVIEW

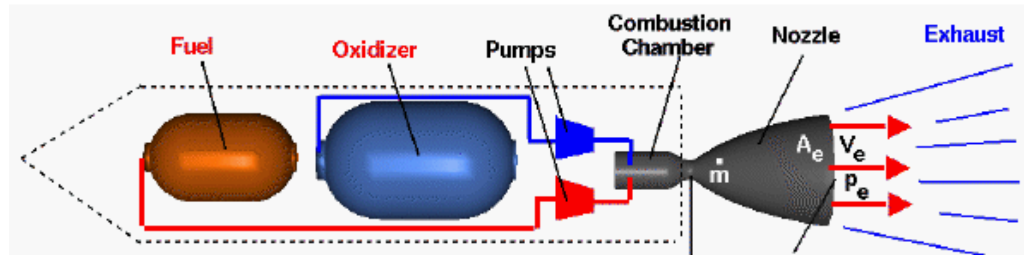
- Electric propulsion broadly defined as acceleration of propellants by:
  - Electrical heating
  - Electric body forces
  - Magnetic body forces

- Electric systems: **Power limited**
  - No limit to energy added to propellant (in theory)
  - However, power limited by mass of conversion equipment which must be carried, $M_{electrical}$
  - Possible to achieve very high exhaust velocities at cost of high power consumption
  - Efficiency ~ 90%
  - Fraction of propellant compared to chemical rockets

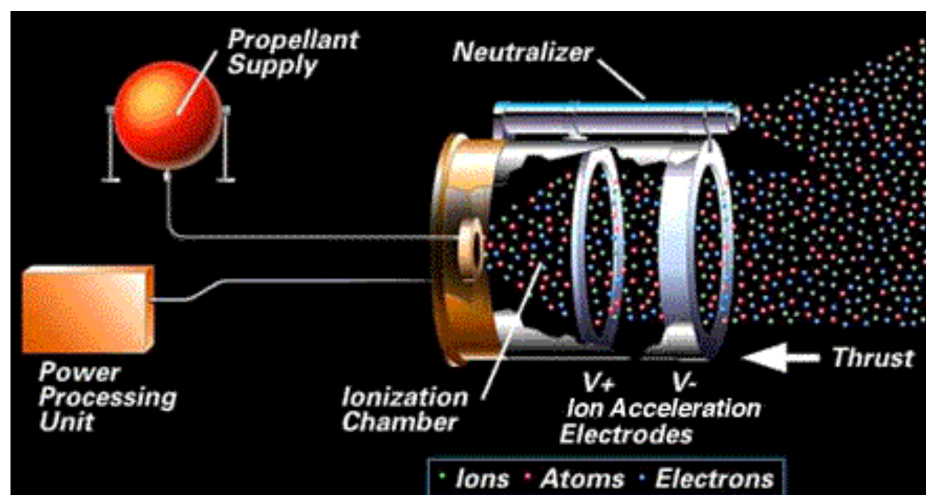
- Chemical rockets: **Energy limited**
  - Limited to energy contained within propellants they carry
  - High power (W=J/s) due to rapid conversion of energy
  - Efficiency ~ 35%

COMPARISON EXAMPLE: ORDER OF MAGNITUDE

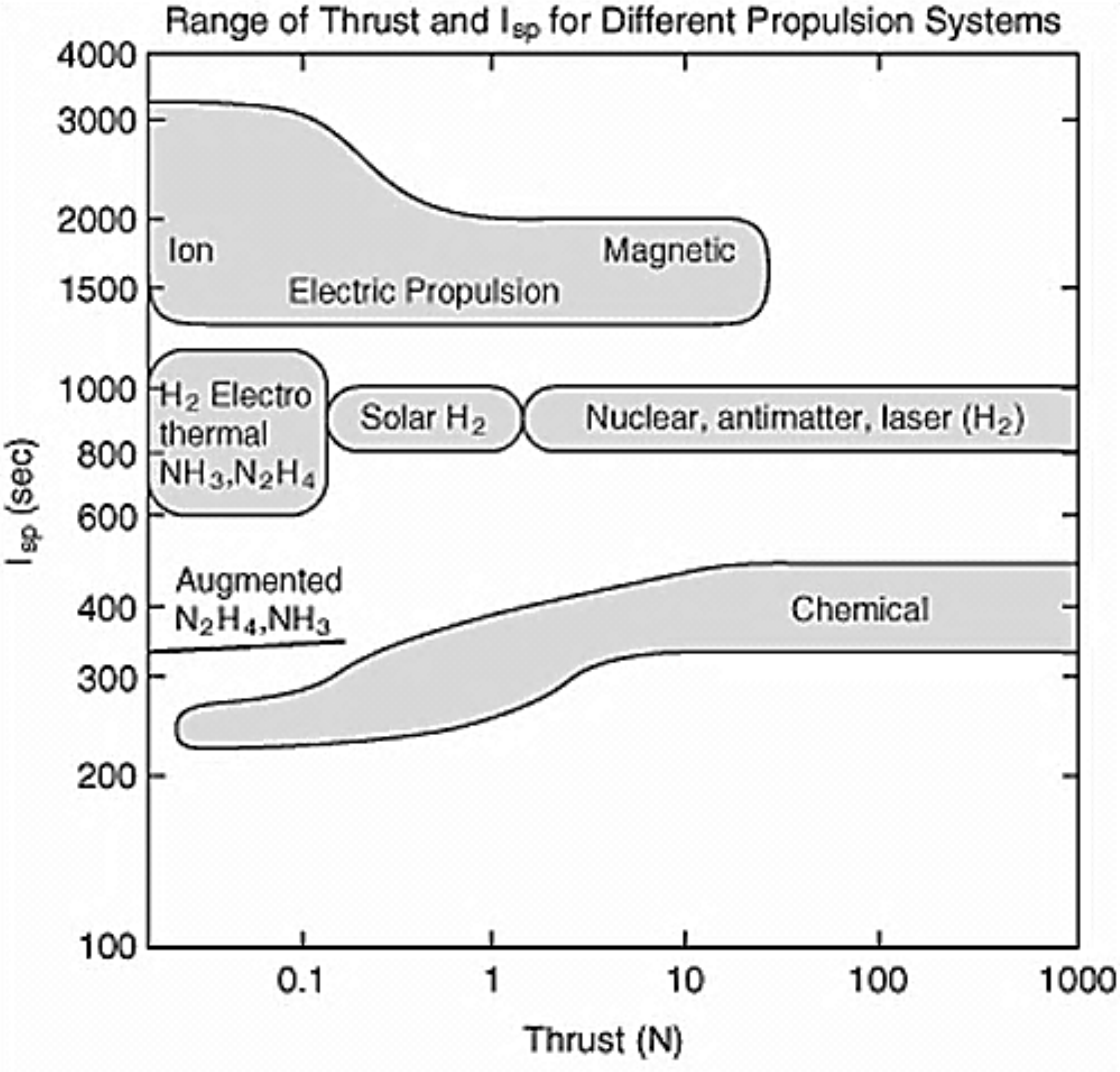
- **Liquid Rocket: Energy Limited**
  - Ue ~ 4,000 m/s
  - Isp ~ 450 s
  - Energy ~ 100 GJ
  - Power ~ 300 MW
  - Thrust ~ 2,000,000 N



- **Ion Rocket (Electrostatic): Power Limited**
  - Ue ~ 40,000 m/s
  - Isp ~ 3,000 s
  - Energy ~ 1,000 GJ
  - Power ~ 1 kW
  - Thrust ~ 0.1 N



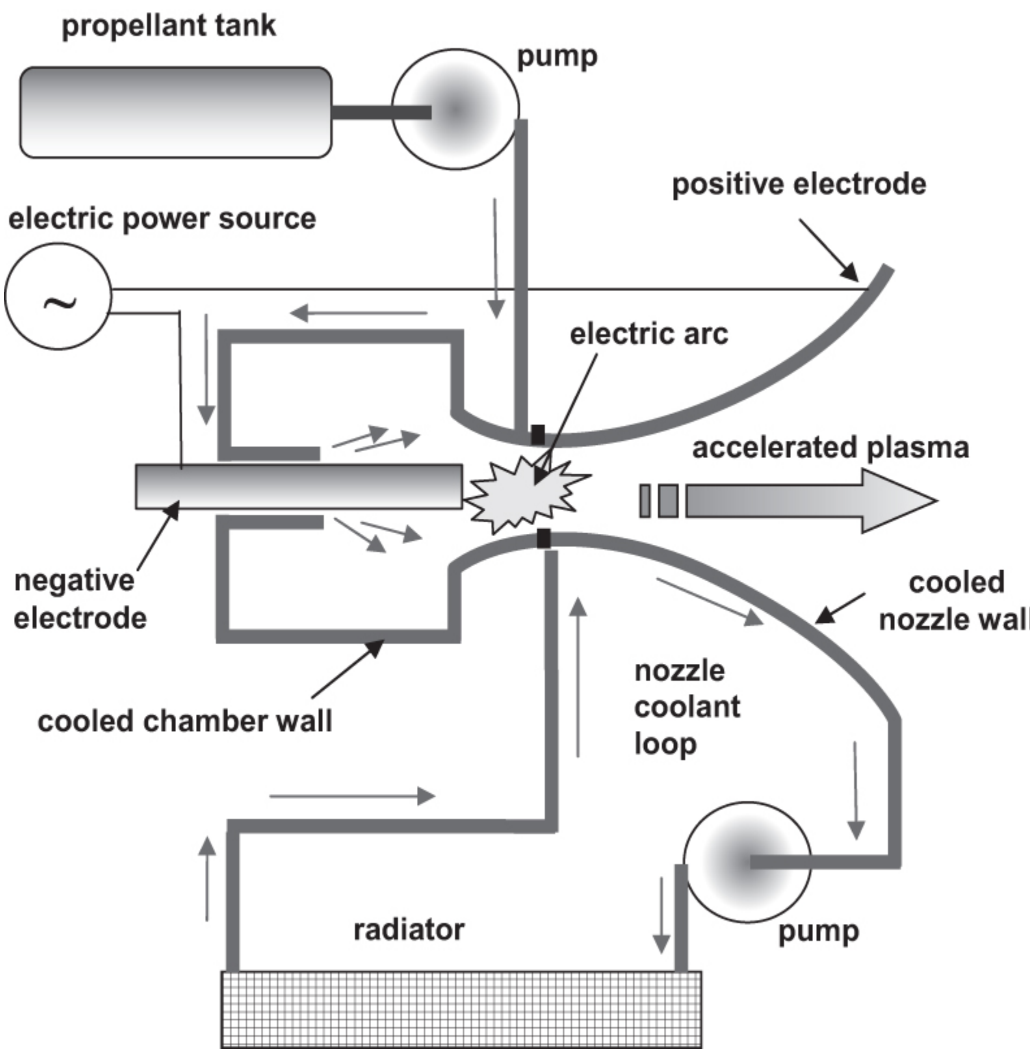
Thrust and Isp Ranges



Electric Propulsion Classification

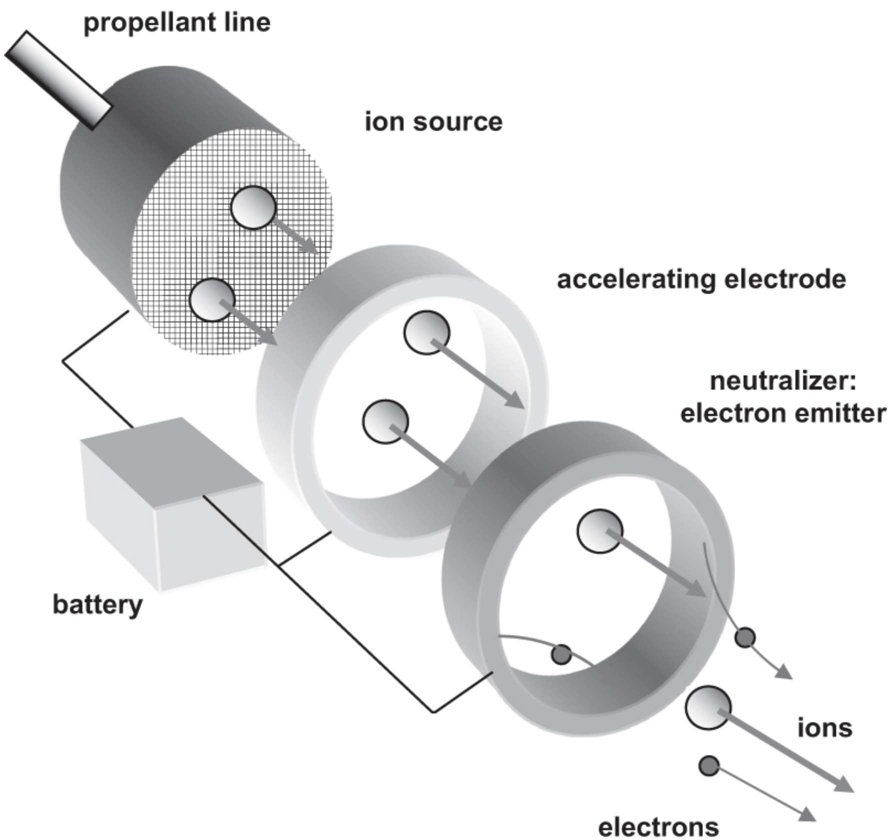
- Electro-Thermal
  - Propellant is electrically heated through wall (resistojet) or by electrical arc discharge (arcjet)
  - then expand through a C-D nozzle; high thrust, high I_{sp}
- Electro-Static
  - accelerate a stream of electrically charged particles
  - very high exhaust velocities (5-10 times chemical) $\Rightarrow$ high I_{sp}
  - low fuel flow, low thrust, long burn time $\Rightarrow$ long term missions
- Electro-Magnetic
  - create magnetic body force on conducting gas or plasma
  - extremely high jet velocities (~ 50 km/sec)

Electro-thermal Thruster



- Electrical energy generates hot plasma to increase the energy of bulk propellant.
- Thermal energy converted into kinetic energy in a C-D nozzle formed from solid material or magnetic fields.
- *ArcJet*
  – high voltage arc at nozzle throat adds thermal energy to exhaust
  – various gaseous or vaporized propellants may be used
  – typically hydrazine, ammonia, H_2
  – operating temp ~ 2500 K
- *ResistoJet*
- *RF/EM/radiative heating*
- Typically 1-5 kW Power req'd:
  – hottest parts are electrodes → HT issues
- All limited by:
  – material temperatures; erosion - abrasion
  – losses similar to chemical rockets and the nature of rapidly expanded, high speed flows

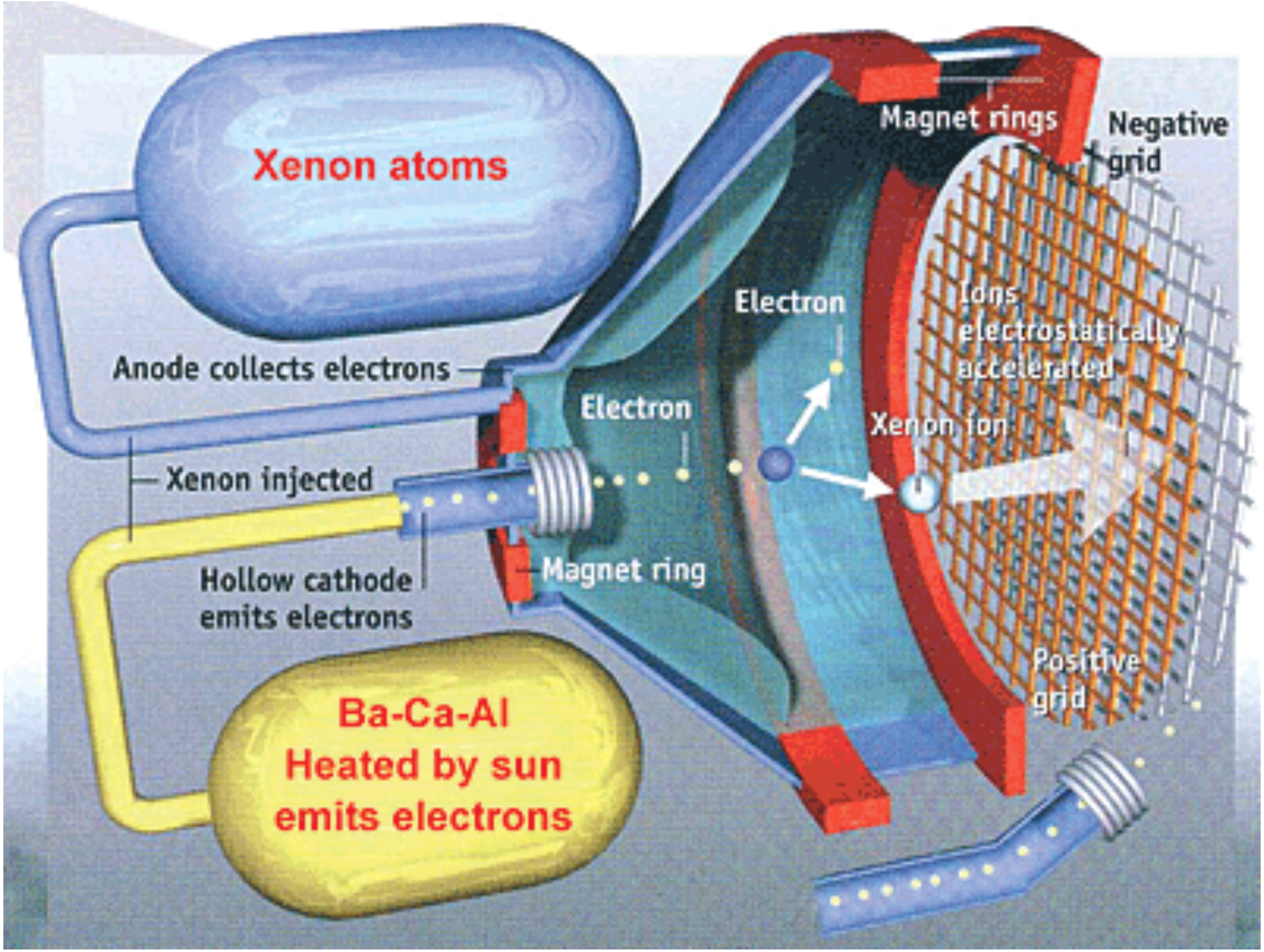
Electrostatic Ion Thruster



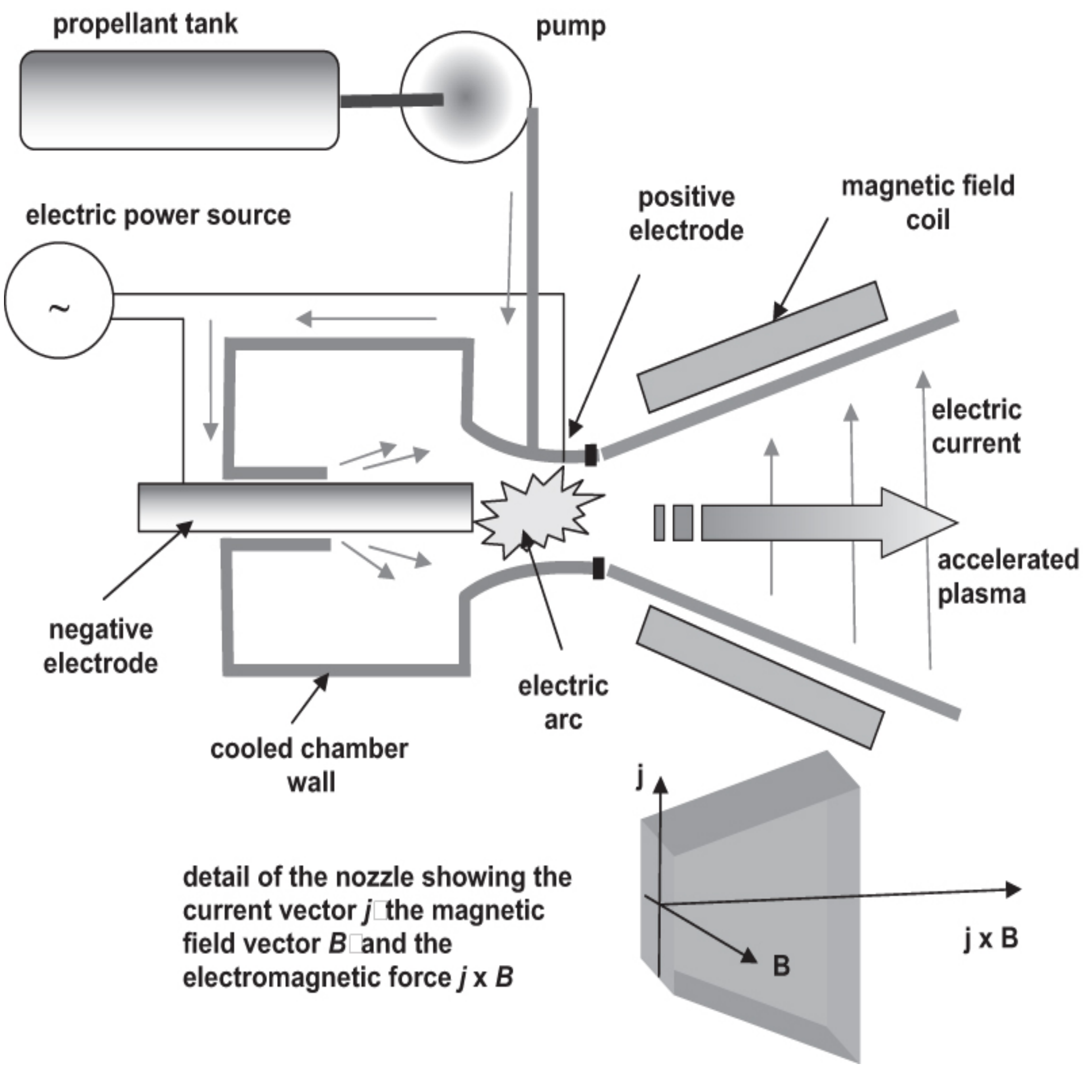
- Acceleration caused by a Coulomb force (i.e., a static electric field) in the direction of acceleration.

- Works on principle of attraction or repulsion of electrically charged particles to accelerate a stream of charged ions
  - ion engines first flew in the mid 1960's
  - very high exit velocities; 5-10x chemical
  - very efficient use of fuel (high I_{sp})
  - low thrust, long "burn" time

Electrostatic Ion Thruster



Electromagnetic Thruster



detail of the nozzle showing the current vector *j* the magnetic field vector *B* and the electromagnetic force *j* x *B*

- Acceleration caused by a Lorentz (j x B) Force perpendicular to magnetic field
- EM forces used to accelerate a hot *plasma* or a *conducting cold gas*
  - positive ions and negative electrons
  - net neutral beam is produced
  - higher thrust per unit area than electrostatic thruster
  - ~ 3000 to 5000 K
- Classifications:
  - magneto-plasma-dynamic
  - pulsed plasma
  - Hall effect thruster

ELECTROSTATIC/ELECTROMAGNETIC: PROPELLANTS

- Alkali Metals: H, Li, Na, K, Rb, Cs
  - Low ionization potential (easy to create ions), 1 electron in outer shell
- Inert Gases : He, Ne, Ar, Kr, Xe, outer shell full
- Hg: two electrons in outer shell