Advanced Space Propulsion Systems

Lecture 317.014

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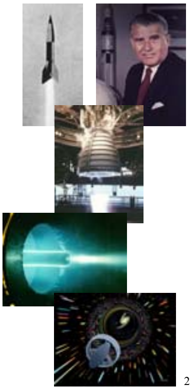
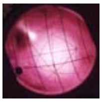
Content

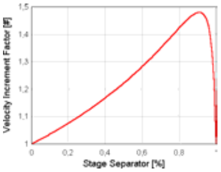
- Propulsion Fundamentals
- Chemical Propulsion Systems
- Launch Assist Technologies
- Nuclear Propulsion Systems
- Electric Propulsion Systems
- Micropropulsion
- Propellentless Propulsion
- Breakthrough Propulsion



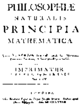


History & Propulsion Fundamentals

$$\Delta v = v_p \cdot \ln \frac{m_0}{m}$$



Propulsion Fundamentals – 1.1 History



Isaac Newton's
Principia Mathematia (1687)

Reaction Principle

- Feng Jishen invested Fire Arrow in 970 AD
- Used against Japanese Invasion in 1275
- Mongolian and arab troups brought it to Europe
- 1865 Jules Verne published *Voyage from Earth to the Moon*

Constantin Tsiolkovski (1857-1935)

- Self-educated mathematics teacher
- The Investigation of Space by Means of Reactive Drives (1903)
- Liquid-Fuel Rockets, multi-staging, artificial satellites

Robert Goddard (1882-1945)

- Launched first liquid-fueled rocket 1926
- Gyroscope guidance patens, etc.

Hermann Oberth (1894-1989)

- Die Rakete zu den Planetenräumen (1923)
- Most influencial on Wernher von Braun

1.1 History

Fritz von Opel – RAK 2 (1925)

Treaty of Versailles from World War I prohibits Germany from Long-Range Artillery

Walter Dornberger recruits Wernher von Braun from the Verein für Raumschifffahrt to develop missile in Penemünde (1932)

Fritz Lang – *Die Frau im Mond*

- Hermann Oberth contracted to built rocket for premiere showing
- Rocket was not finished, but key advancements accomplished and movie was big success

- A4 (V2) first ballistic missile
- A9/A10 on the drawing board (intercontinental missile)

1.1 History

A-4 / V-2

Wernher von Braun
(1912-1977)

Sergei Korolev
(1907-1966)

Valentin Glushko
(1908-1989)

Saturn V

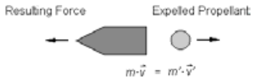
Space Shuttle

N-1

Energia / Buran

1.2 Propulsion Fundamentals

Conservation of Momentum



Force $\vec{F} = \frac{d\vec{I}}{dt} = \frac{d}{dt} m_p \cdot \vec{v}_p = \dot{m}_p \cdot \vec{v}_p$ Specific Impulse $I_{sp} = \frac{v_p}{g_0}$

$$m_0 \cdot \frac{dv}{dt} = \frac{dm_p}{dt} \cdot v_p \quad \xrightarrow{dm_p=dm_0} \quad dv = v_p \cdot \frac{dm_0}{m_0}$$

$$\int dv = v_p \cdot \int_{m_0}^{m} \frac{dm_0}{m_0}$$

Tsiolkovski Equation $\Delta v = v_p \cdot \ln \frac{m_0}{m}$ $m_p = m_0 \cdot \left[1 - \exp\left(-\frac{\Delta v}{v_p}\right)\right]$

1.2.2 Delta-V Budget

➡ *Most important to select propulsion system !*

$$\Delta v = \Delta v_g + \Delta v_{drag} + \Delta v_{orbit} - \Delta v_{initial}$$

	Gravitational Potential	Drag	Orbit	Initial	
LEO	1.4	0.1	7.8	- 0.4	= 8.9 km/s
GEO	10.3	0.1	3	- 0.4	= 13 km/s

Mission	Description	Typical Δv [km/s]
LEO, GEO, Planetary Targets	Satellites, Robotic missions	10-15
Human Planetary Exploration	Fast, direct trajectory	30 – 200
100 – 1,000 AU (Distance Sun-Earth)	Interstellar precursor mission	100
10,000 AU	Mission to Oorth cloud	1,000
Slow Interstellar	4.5 light-years in 40 years	30,000
Fast Interstellar	4.5 light-years in 10 years	120,000

1.2.2.1 Propulsion Requirements

Propulsion System		Specific Impulse [s]	Maximum Δv [km/s] *	Maximum Thrust [N]
Chemical	Solid	250 – 310	5.7 – 7.1	10^7
	Liquid	300 – 500	6.9 – 11.5	10^7
MHD		< 200	4.6	10^5
Nuclear	Fission	500 – 800	11.5 – 20.7	10^6
	Fusion	10,000 – 100,000	230 – 2,300	10^5
	Antimatter	60,000	1,381	10^2
Electric	Electrothermal	150 – 1,200	3.5 – 27.6	10^1
	Electrostatic	1,200 – 10,000	27.6 - 230	3×10^{-1}
	Electromagnetic	700 – 5,000	16.1 – 115	10^2
Propellantless	Photon Rocket	3×10^7	unlimited	10^{-4}
Breakthrough		?	?	?

* Assuming $(m/m_0)=0.1$ ⇒ Spacecraft consists of 90% Propellant

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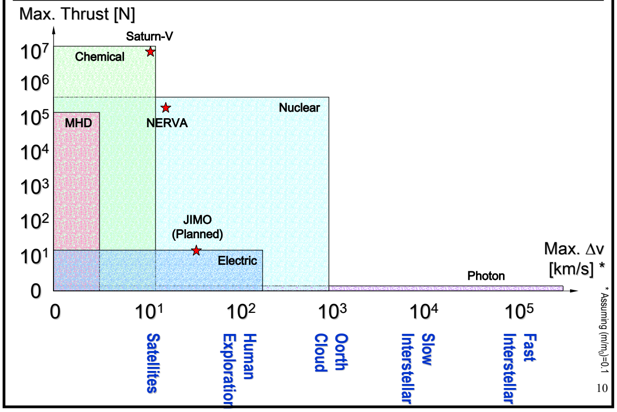
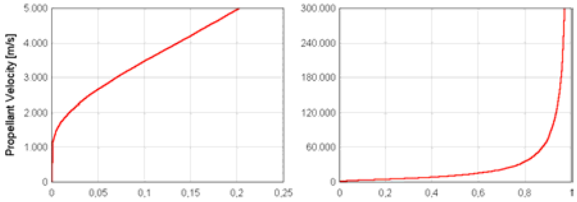
1.2.2.1 Propulsion Comparison



1.2.2 Single Staging – Multi Staging

- Payload mass is directly linked to propellant velocity (e.g. Chemical 3,000-4,000, Electric up to 100,000)
- Mass is directly linked to costs (e.g. 20 k$ / kg on Space Shuttle, 5 k$ on cheap Russian launcher)



Structural Factor: Ratio of Empty Rocket (Structure + Payload) to Full Rocket (Structure + Payload + Propellant)

Calculated for Orbital Speed (<u>Δv = 8,000 m/s</u>, Atmospheric Drag + Gravity 1,500 – 2,000 m/s)

➡ **Single Stage Chemical Propulsion System (3,500 m/s) needs 90% propellant !**

1.2.2 Single Staging – Multi Staging

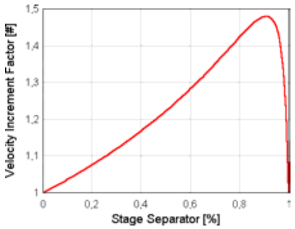
➡ **Multi-Staging with separate structures, engines and tanks**

$$\left(\frac{m_0}{m}\right)_1 = \frac{m_{structure} + m_{propellant} + m_{payload}}{m_{structure} + (1-\alpha)\cdot m_{propellant} + m_{payload}}$$

$$\left(\frac{m_0}{m}\right)_2 = \frac{(1-\alpha)\cdot\left[m_{structure} + m_{propellant}\right] + m_{payload}}{(1-\alpha)\cdot m_{structure} + m_{payload}}$$

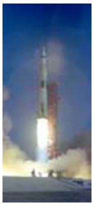
$$\frac{\Delta v_{1+2}}{\Delta v} = v_p \cdot \frac{\ln\left(\frac{m_0}{m}\right)_1 + \ln\left(\frac{m_0}{m}\right)_2}{\ln\frac{m_0}{m}}$$

- Example for 100 kg rocket of $m_{propellant} : m_{structure} : m_{payload}$ = 90 : 9 : 1 kg
- Two stage rocket has maximum velocity gain of 1.43 at stage separator percentage of 91%
- More stages increase velocity gain but also increases complexity
- Multi-Staging discovered by Tsiolkovski in 1924 article *Cosmic Rocket Trains*



1.2.2 Single Staging – Multi Staging (Saturn V)

	Stage 1	Stage 2	Stage 3
Launch mass	2,286,217 kg	490,778 kg	119,900 kg
Dry mass	135,218 kg	39,048 kg	13,300 kg
Propellant	LO_2/Kerosene	LO_2/LH_2	LO_2/LH_2
Propellant velocity v_p	2,650 m/s	4,210 m/s	4,210 m/s
Mass ratio	3.49	2.63	1.81
Velocity increment Δv	3,312 m/s	4,071 m/s	2,498 m/s



1.3 Trajectory and Orbits

Tycho Brahe
(1546-1601)

Johannes Kepler
(1571-1630)

Kepler laws are first correct description of the planet's motion around the Sun

$$m \cdot \left(\ddot{r} - r\dot{\Theta}^2\right) = -\frac{G \cdot M}{r^2}$$

Balance of gravitational and centrifugal forces

$$\frac{d}{dt}\left(mr^2\dot{\Theta}\right) = 0$$

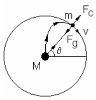
Conservation of angular momentum

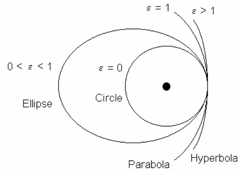
$$\frac{1}{r} = \frac{GM}{r^2 v^2} \cdot \left(1 + \varepsilon \cdot \cos\Theta\right) \qquad \varepsilon = \left(\frac{rv^2}{GM} - 1\right)$$

- Parabola trajectory leaves Earth

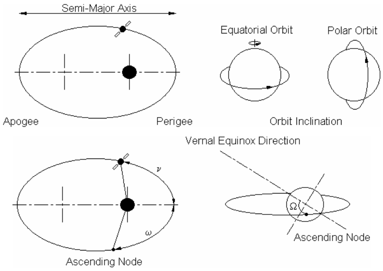
$$v = \sqrt{\frac{2GM}{r}}$$

- Just √2 greater than circle (minimum orbit) – Mach 24
- Hyperbola trajectory used for interplanetary flights





1.3.1 Keplerian Orbital Elements



- Semi-Major Axis *a* : size of elliptical orbit
- Eccentricity ε : shape of orbit
- Inclination *I* : angle of orbit with the equatorial plane
- Longitude of ascending node Ω : inclination around semi-major axis *a*
- Argument of perigee ω : Angle between ascending node and perigee
- True anomaly ν : Angle between perigee and the spacecraft's location

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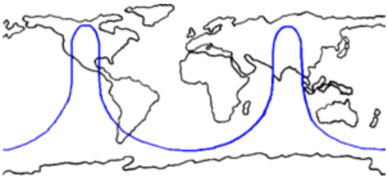
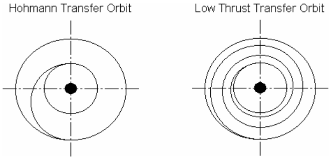
1.3.2 Orbit Types

	Altitude	Orbital Parameters	Application
Low Earth Orbit (LEO)	< 1000 km	-	Space Shuttle, Space Station, Small Sats
Geostationary Orbit (GEO)	42,120 km	$i = 0°$	Communications
Molniya Orbit	26,600 km	$e = 0.75$ $i = 28.5° / 57°$	Communication, Intelligence
Sun Synchronous Orbit	6,500 – 7,300 km	$i = 95°$	Remote Sensing



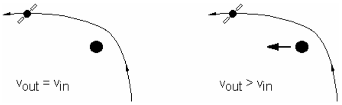
Molniya Orbit

1.3.3 Orbit Transfers



- Hohmann Transfer Orbit: Most common and fuel efficient (example GTO-GEO)
- Low Thrust Transfer Orbit: E.g. electric propulsion or solar sails

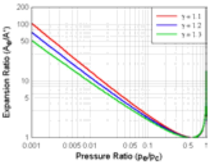
- Gravity Assist Trajectory
- Aerobrake Trajectory

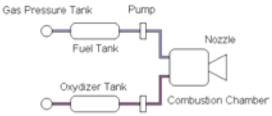


1.4 Classification of Propulsion Systems

	Internal Energy	External Energy	External / Internal Energy
Internal Propellant	Chemical	Electric	Nuclear (Induction Heating)
External Propellant	Air Breathing MHD	Propellantless (Laser, Solar Sail)	
Ext. / Int. Propellant			Air Breathing
No Propellant	Propellantless (Photon, Nuclear)	Propellantless (Solar Sail) Catapults	Breakthrough Propulsion

Chemical Propulsion Systems





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2. Chemical Propulsion Systems

Thermodynamic Characterization

Combustion Chamber

Exit Plane

$$E_{gas} = c_p \cdot m_p \cdot (T_c - T_e)$$

Specific Heat at Constant Pressure

Equal Kinetic Energy

$$v_p = \sqrt{2 \cdot c_p \cdot (T_c - T_e)}$$

Classical Gas Theory

$$T \cdot p^{\gamma/(\gamma-1)} = \text{constant}$$

Specific Heat: 1.2 – 1.3

$$c_p = \frac{\gamma}{(\gamma - 1)} \cdot \frac{R}{m_{gas}}$$

- p_e/p_c influenced by nozzle and atmosphere
- T_c is function of chemical energy release
- m_{gas} small ⇒ high specific impulse but low thrust

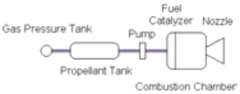
Propellant Velocity

$$v_p = \sqrt{\frac{2\gamma}{(\gamma-1)} \cdot \frac{R \cdot T_c}{m_{gas}} \cdot \left[1 - \left(\frac{p_e}{p_c}\right)^{(\gamma-1)/\gamma}\right]}$$

2.2 Liquid Propulsion Systems

- Liquid propellant stored in tanks – also mixture of liquid/solid called slush
- Fed into combustion chamber by pressurized gas or pump

Monopropellant Engines



Used for

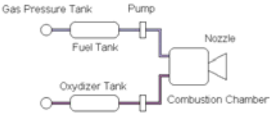
- Widely used for spacecraft attitude and orbit control

Propellant

- Hydrazin (N_2H_4)
- Hydrogen Peroxide (H_2O_2)

Due to catalyzer ⇒ low pressure required ⇒ low I_{sp} of 150 – 250 s

Bipropellant Engines



- Used for launchers and spacecraft primary propulsion systems
- Large variety available (LO_2 - LH_2, …)

Either separate plug is needed or propellants ignite at contact (hypergolic – like in Space Shuttle)

2.2 Liquid Propulsion Systems

Fuel	Oxydizer	Average Density [g/cm^3]	Specific Impulse [s]
Kerosine (RP-1)	Oxygen (O_2)	1.02	300 – 360
Hydrogen (H_2)	Oxygen (O_2)	0.35	415 – 470
Unsymmetrical Dimethyl Hydrazin (UDMH)	Nitrogen Tetroxide (N_2O_4)	1.20	300 – 340
Hydrogen (H_2)	Fluorine (F_2)	0.42	450 - 480

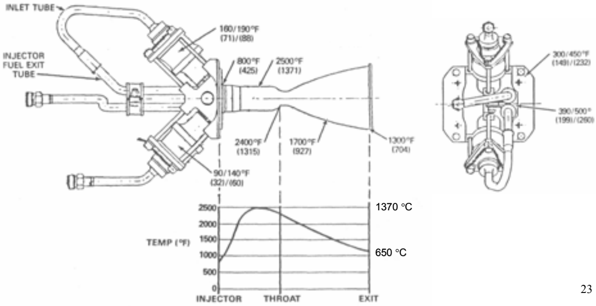
Propellant Combination Examples

Saturn V – F1

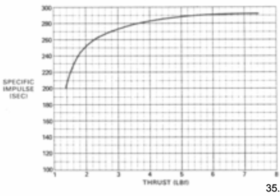
Largest ever produced engines are the F-1 (Saturn V) and the RD-170 (Energia)

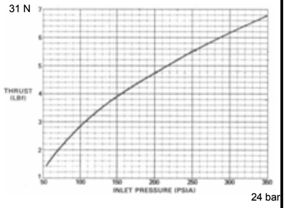
General Dynamics / R-6 Rocket Engine

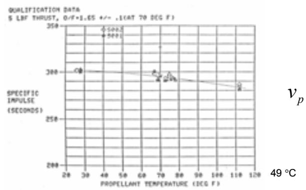
- Thrust: 22 N (6.2 – 32.9 N)
- I_{sp}=290 s at 22 N
- N_2O_4 (Nitrogen Tetraoxyde)– MMH (Monomethyl Hydrazine)
- O/F Ratio = 1.65



General Dynamics / R-6 Rocket Engine



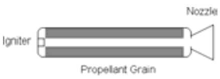




$$v_p = \sqrt{\frac{2\gamma}{(\gamma-1)} \cdot \frac{R \cdot T_c}{m_{gas}} \cdot \left[1 - \left(\frac{p_e}{p_c}\right)^{(\gamma-1)/\gamma}\right]}$$

2.2.2/3 Solid / Hybrid Propulsion Systems

Solid Propulsion Systems



Different shapes burn different surface areas over time (constant thrust profile)

- Fuel and oxidizer are stored as grains glued together forming a kind of rubber
- Typically hydrocarbon (fuel) and ammonium perchlorate (oxidizer)
- 16-18% of aluminium powder added to increase temperature and specific impulse

Cons

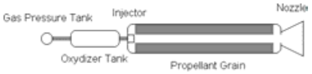
- Can not be stopped after ignition (special liquid can be injected to cease burn, difficult)
- Low specific impulse (260 – 310 s)

Pros

- Very simple, cheap
- High thrust (10^7 N)

Hybrid Propulsion Systems

- Oxidizer or fuel stored in liquid state
- Can be restarted / shut off
- Difficult technology



2.3 Nozzle Design

Most common nozzles:

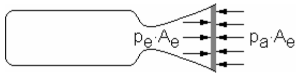
Cone Nozzle

Most simple

Bell Nozzle

Reduces Beam Divergence

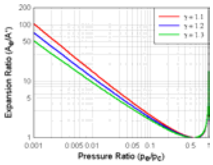
In atmosphere, the outside pressure is balanced everywhere but on the nozzle exit



Additional Force

$$F_{axial} = \dot{m}_p \cdot v_p + (p_e - p_a) \cdot A_e$$

- Nozzle length
- Expansion ratio A_e/A^*



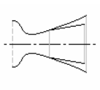
- Every nozzle is optimized for one specific pressure
- Also v_p is affected by pressure ratio
- Optimal nozzle: $p_e = p_a$
- Maximum thrust: $p_a = 0$ (nozzle ∞ long, A_e/A^* ∞ high ⇒ compromise)

Advanced Chemical Propulsion

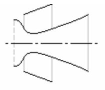
How can we <u>Improve</u> Chemical Propulsion Systems ?

- **Nozzle**
- **Propellant**
- **Alternative Designs**

2.3 Advanced Nozzle Designs



Droppable Insert

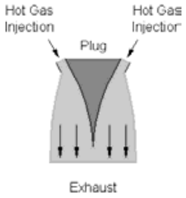


Extendible Nozzle

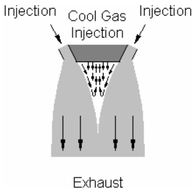
Linear Aerospike Engine

Aerodynamic Boundaries

Plug Nozzle



Aerospike Nozzle



2.4 Advanced Propellants

Example SSTO Launcher, Liquid Propulsion LO_2/LH_2

- 10% increase in propellant denity (e.g. slush) ⇒ 25 % increase in payload
- 10% increase in specific impulse ⇒ 70% increase in payload

Tripropellants

- Many chemical reactions produce more energy than LO_2/LH_2, but the reaction product in not gaseous
- Hydrogen can be used as a working fluid in addition to fuel and oxidizer
- Examples: Be/O_2 or Li/F_2 (I_{sp} = 700 s ⇒ 55% increase!)
- Problems: Toxic, contamination

High Energy Density Matter (HEDM)

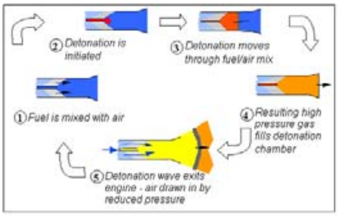
- Storage problems
- Very low temperature needed

- Atomic Hydrogen: H-H recombination releases 52.2 kcal/g compared to H_2-O_2 of 3.2 kcal/g (I_{sp}=2,112 s)
- Metastable Helium: 114 kcal / g (I_{sp}=3,150 s), can not be stored longer than 2.3 hours at 4 K !
- Metallic Hydrogen: 1.4 Mbar pressure (I_{sp}=1,700 s)

2.5 Alternative Designs

Pulse Detonation Rocket

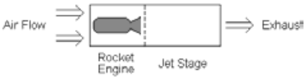
- Combustion occurs at constant volume instead of constant pressure (much higher inlet pressure)
- 10% higher thermodynamic efficiency
- Tube with open/close end
- Similar to V-1 rocket during WW-II



PDE Wave Cycle

2.5 Alternative Designs

Rocket Based Combined Cycle



- **Ejector mode:** Rocket works as compressor stage for jet engine
- **Ram jet mode:** Rocket engine turned off at Mach 2, air pressure is high enough
- **Scram jet mode:** Secondary fuel injection from jet stage is moved forward
- **Pure rocket mode**

Air Breathing saves a lot of propellant!

Rotary Rocket

Pumps replaced by centrifugal force !

2.6 Reusable Launch Vehicles

NASA Advanced Space Transportation Program (initiated 1994)

- Reduction of launch costs by one order of magnitude to a few hundred $/kg
- Increased safety: current launcher failures 1 – 10%, reduction to 0.1%
- Increased reliability: fully reusable parts, routine operations, much lower costs

Space Shuttle

- 1st generation RLV
- Replace solid with liquid boosters
- ⇒ X-Planes

X-15

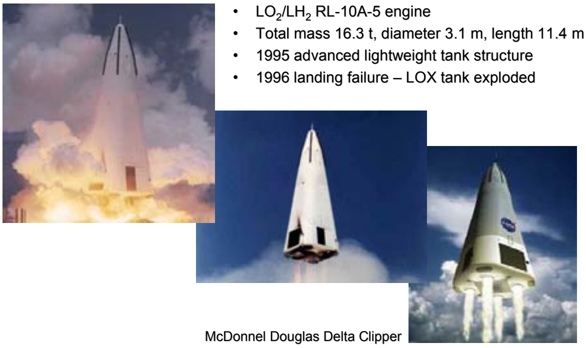
- North American X-15 flown 1959-1968
- Rocket plane – reusable launcher technology
- World record Mach 6.72, 108 km altitude

X-15A2 with external tanks

2.6 Reuseable Launch Vehicles

DC-XA Delta Clipper

- First vertical takeoff and vertical landing SSTO prototype (constructed 1991-1993)
- LO_2/LH_2 RL-10A-5 engine
- Total mass 16.3 t, diameter 3.1 m, length 11.4 m
- 1995 advanced lightweight tank structure
- 1996 landing failure – LOX tank exploded



McDonnel Douglas Delta Clipper

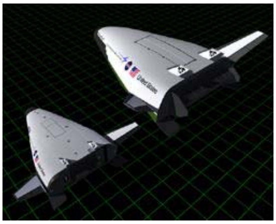
2.6 Reuseable Launch Vehicles

X-33 / Venture Star

- Development since 1996 (currently stopped)
- All lightweight structures (tank, outer skin, etc.)
- 2 day turnaround shall be demonstrated

Length	21 m
Width	23.5 m
Take-off Weight	142,500 kg
Fuel	LO_2/LH_2
Fuel Weight	105,000 kg
Main Propulsion	2 XRS-2200
Maximum Speed	Mach 13+

Lookheed Martin's X-33 and Venture Star



2.6 Reuseable Launch Vehicles

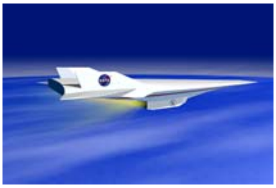
X-34

- TSTO testbed, Cancelled 2001
- LOX/Kerosene engine for Mach 8 and 76 km altitude
- Composite structure, advanced thermal protection system, etc.
- 500 k$ / flight cost demonstration

Orbital Sciences L-1011 Aircraft with Pegasus Booster

2.6 Reuseable Launch Vehicles

X-43 (HYPER-X)

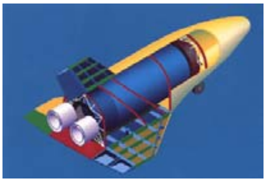


- Hyper-X will ride on Pegasus booster
- Scramjet technology demonstrator
- Mach 7 – 10 at 30 km altitude
- First test 2001 failed (Pegasus rocket exploded!) – 2nd test late 2003

2.6 Reuseable Launch Vehicles

European Future Launchers

- HERMES was cancelled mid 1990s
- German TSTO project Sänger cancelled end 1980s (ramjet + rocket)
- FESTIP 1994-2000, FLTP, FLPP
- European RLV prototype is scheduled for 2006-2007
- HOPPER programme – Precursor PHOENIX (led by EADS, first flights scheduled 2004 in Schweden)

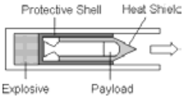


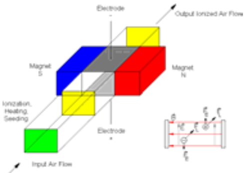
2.6 Reuseable Launch Vehicles

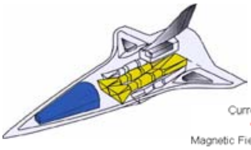
Japanese Future Launchers

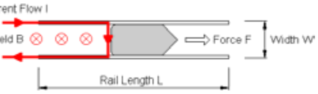
- HOPE – similar to HERMES
- On top of H-II launch vehicle
- Budget custs – HOPE-X demonstrator
- High speed flight demonstration started in 2003
- Cooperation with CNES underway

Launch Assist Technologies









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3. Launch Assist Technologies

Example SSTO Launcher, Liquid Propulsion LO_2/LH_2 (Isp = 450 s)
Δv_{LEO} = 8,000 m/s

- Payload mass fraction 16.3%
- Δv reduction only 300 m/s ⇒ payload mass fraction 17.5% (increase of 7% !)

$$\text{Payload fraction} = \exp\left(-\frac{\Delta v}{v_p}\right)$$

Exponential Law !

- Launching from an aircraft with initial velocity
- Providing initial boost with chemical/electromagnetic catapult
- Launching outside of the atmosphere on top of an ultra-high tower

All technologies have up-scaling problems !

3.1 Aircraft Assisted Launch

Advantages

- Additional velocity
- Reduced Air Drag

Problem Areas

- Separation is difficult for a big rocket
- Supersonic speeds and high altitudes are a costly technology

Present Technology

Pegasus on Boeing 747
(Speed 255 m/s, altitude 13 km)

3.1 Catapults

Problem Areas

- Very high velocities for orbit insertion (2,000 – 100,000 g!): humans require max. 3 g (very long tubes), special hardware protection against high accelerations (costs!)
- Heat shields: reduce payload capacity

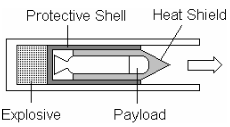
Catapult

$$a = \frac{v^2}{2 \cdot l}$$

- 300 m/s require 1.5 km tube at 3 g
- 100 m long gun for v=8,000 m/s requires 32,600 g!

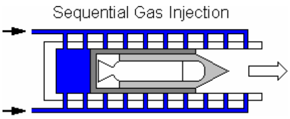
3.1 Gun Launch

Classical Gun



- Typical: 3,500 K and 3,500 bar
- Accelerations are withing 10,000 – 40,000 (not humans rated !)
- Long tubes used in WW I (Big Bertha 120 kg at 40 km) and during 1960's High Altitude Research Program (HARP)
- HARP record: 85 kg projectile to 180 km
- Maximum velocity: 3 km/s (limited by molecular weight of explosives)

Gas Gun



- Circumvents velocity limitation
- Reduced pressure of 1,000 bar due to continuous injection (problem for very long tubes
- Largest gun at Lawrence Livermoore National Laboratory with 5.8 kg to 2.77 km/s

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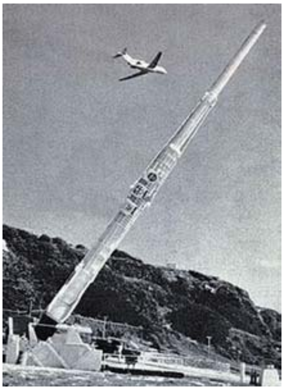
3.1 HARP Gun

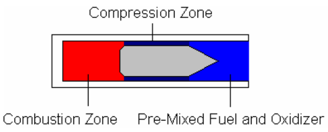


- Constructor: Gerald Bull
- Contracted by Iraq in 1980's to develop Project Babylon (put 2,000 kg projectile into 200 km orbit at 600$/kg)
- Assassinated by Israelis (consultancy for Scud missiles !)

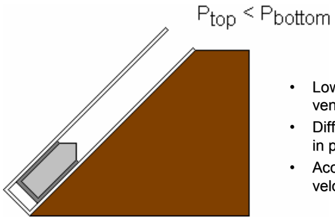
3.1 Gun Launch

Ram Accelerators

- Experiments were done with 4.29 kg to 1.48 km/s
- Different mixing rations lead to increase of speed and higher exit velocities



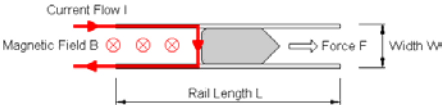
Pneumatic Catapult



- Lower end closed and upper end vented
- Difference in altitude of 2.1 km results in pressure difference of 0.25 bar
- Accelerations of 1.5 g and 300 m/s exit velocity

3.1 Rail Gun

- Simple EM accelerator
- Developed for the SDI program
- Efficiencies 40 – 70%
- 2 kg to 4 km/s with L=6 m and W=5 cm
- 6.5 million Ampere ⇒ single shot!
- Lower current with superconductors



Exit Velocity

Force on Projectile $F = B \cdot I \cdot W$

Kinetic Energy

$$\frac{mv^2}{2} = F \cdot L$$

Magnetic Energy gained along the Rail

$$v = \sqrt{\frac{2FL}{m}} = I \cdot \sqrt{\frac{2LW\mu_0}{m}}$$

Geometry & Mass

➡ Back induced Current Limitation ➡

Circuit Voltage

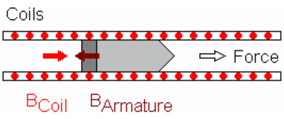
$$v_{\max} = \frac{V}{BL}$$

3.1 Mass Driver

Principle

Experiment 340 gram to 410 m/s

- Electromagnets stacked together
- Conductive projectile (+ permanent magnet can increase force)
- Sequence of coil energizing can be computer controlled



Pros

- Efficiencies 90% (superconducting coils)
- Acceleration levels can be controlled (humans possible)
- De-Acceleration is possible in case of problems
- Up-Scaling seems to be more easy

Seems to be ideal for use on Moon and other low gravity bodies!
(e.g. Fusion fuel delivery to Space Station, etc.)

3.1 Magnetic Levitation

- Combination of superconducting levitation and mass driver
- Spin – Off from train developments (e.g. Transrapid)

Maglifter

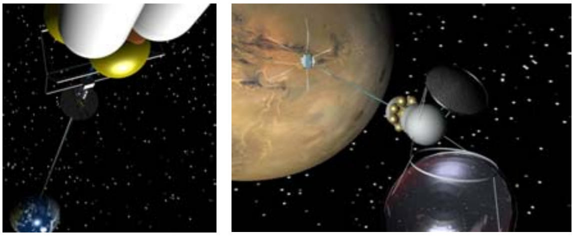
NASA Prototype aiming 300 m/s at 3g

3.1 Ultra High Towers

Ultra-High Towers (Space Elevator)

- Launching outside the atmosphere (> 50 km) can reduce Δv by 1-2 km/s
- Materials (?): Graphite-epoxy construction / Carbon Nanotubes
- Skyhook: Elevator from GEO to Earth
- Might be a very good idea for small moons

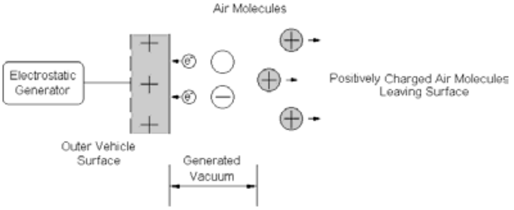
“Invented by Sir Arthur C. Clarke”



3.2 Advanced Drag Reduction

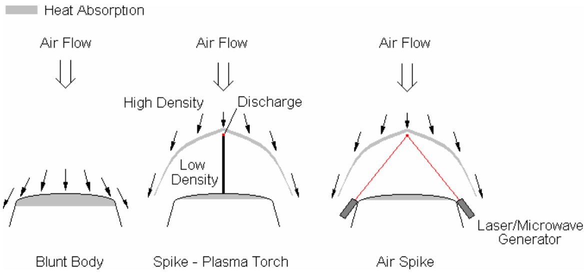
- Traditional methods try to shape surfaces to minimize turbulences
- Best concept obviously is to reduce air flow towards the vehicle

Surface-Charged Vehicles



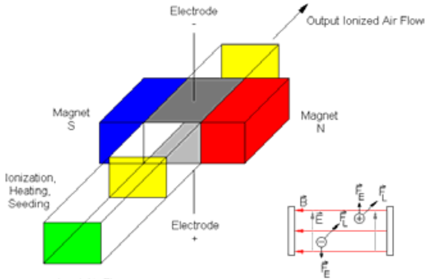
- Close to the surface air molecules are slightly positive, at higher altitudes negative (solar radiation)
- Patent by H. Dudley (1963): Charged model rockets could increase their maximum altitude by 500-600%

3.2 Energy Spike



- Reduction of Drag by Transfering Heat Exchange to Bow Shock initiated by Plasma Discharge or Laser/Microwave Excitation
- Enables Mach 50 Atmospheric Speeds - Significatly Reduces Re-Entry Thermal Loads
- Russian Skval torpedo class: rocket exhausts infront of vehicle

3.2 Magnetohydrodynamic (MHD) Propulsion



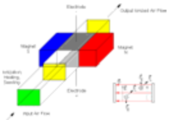
- Ionised Air Flow can be Accelerated / Slowed down by Electric Energy using MHD
- Energy Transfers with Ambient Environment are Possible

3.2 MHD Physics

Force Produced

$$\vec{F}_L = I \cdot \left(\vec{l} \times \vec{B}\right)$$

Ohm’s Law



Power Requriements

$$\vec{F}_L = \sqrt{\frac{P}{R}} \cdot \left(\vec{l} \times \vec{B}\right)$$

Resistance: Needs to be as low as possible for high thrusts

- Heat up of air ⇒ plasma
- Alkali metal seeding (e.g. Cesium, Gallium) to increase ionization fraction and lower required temperatures

Example

- Ariane 5 lift off thrust 6.7 MN
- 10% increase in I_{Sp}

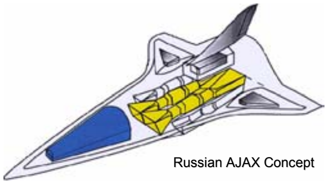
l=1 m,

B=20 T (Superconducting Magnets)

P=17 MW !

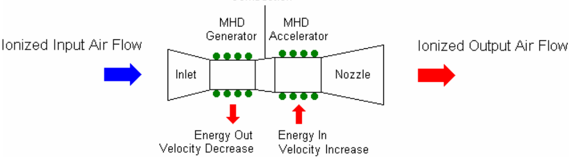
3.4 MHD Energy Bypass

- Air Ionisation by Laser/Microwave
- Advanced Drag Reduction
- Velocity Decrease to Enhance Combustion Efficiency
- Velocity Increase by Energy from Decrease

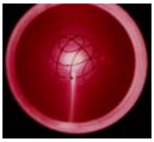


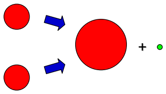
Russian AJAX Concept

Calculations show realistic 20% increase in I_{sp} at Mach 12



Nuclear Propulsion Systems





$${}_1^2D+{}_1^3T\longrightarrow{}_2^4He+n+17.7\text{ MeV}$$

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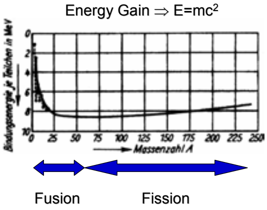
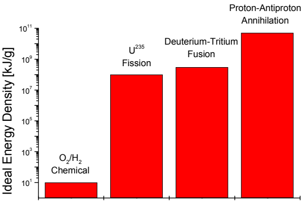
4. Nuclear Propulsion Systems

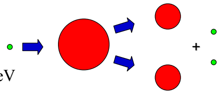
Energy Gain ⇒ $E=mc^2$





- > 9 order of magnitude higher energy density than chemical
- High energy density leads to very high specific impulse
- Involves very small quantities of mass ⇒ low thrust (needs working fluid)
- Enables manned solar system exploration *NOW!*

Fission Example



$$n+{}_{92}^{235}U\longrightarrow{}_{55}^{140}Cs^*+{}_{37}^{94}Rb^*+2n+200\text{ MeV}$$

4.2.1 NERVA Program

1961 US Atomic Energy Commission & NASA

Space Nuclear Propulsion Office (SNPO)

Nuclear Engine For Rocket Vehicle Application

Aerojet

Westinghouse

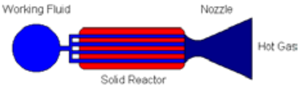
- Based on experience with KIWI and ROVER program from Los Alamos (1955)
- Directed towards manned exploration (Moon, Mars)
- Test firings at Nuclear Rocket Development Station in Nevada

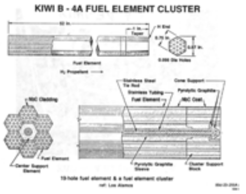
	NRX Series	Phoebus Series
Power	1,500 MW	4,500 MW
Mass Flow Rate	42 kg/s	129 kg/s
Thrust	333 kN	1,112 kN
Specific Impulse	825 s	820 s
Total Engine Mass	6,800 kg	18,150 kg

- NRX developed up to engineering level
- Test at September 1969 lastet 3 hours 48 minutes at full thrust level (333 kN!)

Program stopped in 1971 after 2.4 billion US$

4.2.2 Solid Core





- Fissionable material: Uraniun carbide
- Coated by Niobium to protect from corrision
- Hydrogen (or Ammonium) working fluid

4.2.2 Solid Core – NERVA Rocket Firing

4.2.2 Solid Core – NERVA Rocket Firing

4.2.2 PLUTO Nuclear Ramjet

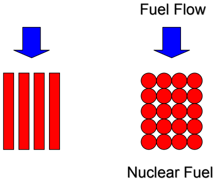
1957 Lawrence Livermoore National Laboratory

⬇

Develop Nuclear Ramjet to Counter Soviet Anti-Missile Threat

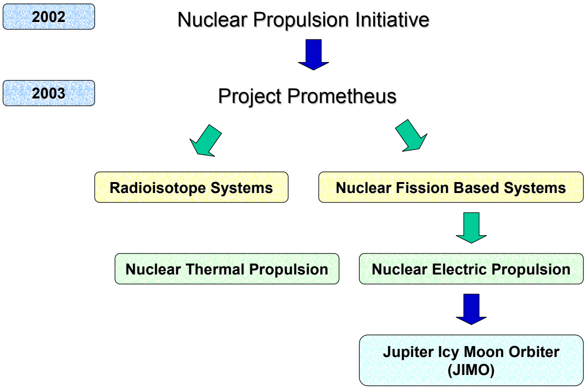
- Mounted on Railtrack
- 1961 Tory-IIA fired for a few seconds at fraction of full power
- 1964 Tory-IIC fired at full power (513 MW) at a thrust of 155 kN for five minutes !
- Project stopped shortly aftwards
- Revolution for RBCC Launcher!

4.2.2 Particle-Bed-Nuclear Reactor



- Developed in late 1980´s („Project Timberwind“)
- Higher Surface Area – Higher Power Density, Compact Design
- Specific Impulse ≈ 1000 s
- Thrust-to-Weight Ratio 30:1 (45:1)
- Thrust 180 kN

4.2.2 Project Prometheus



2002 Nuclear Propulsion Initiative

2003 Project Prometheus

Radioisotope Systems

Nuclear Fission Based Systems

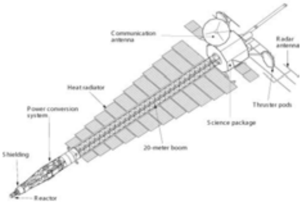
Nuclear Thermal Propulsion

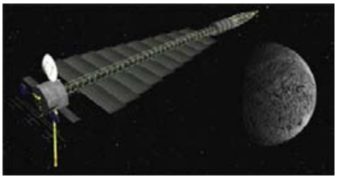
Nuclear Electric Propulsion

Jupiter Icy Moon Orbiter (JIMO)

4.2.2 JIMO Spacecraft

- Launch > 2012
- Provide in-orbit Δv=40 km/s !



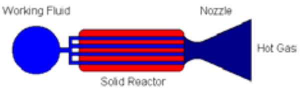


4.2.2 Russian Activities

- Nuclear Propulsion Program initiated 1954
- Late 1960's, Prototype Developed (Thrust 36 kN, Isp 920 s, Time of Operation 1 h)
- Testing continued on various test stands between 1978-1981
- More than 30 satellites equipped with nuclear reactor
- Topaz with 5 kW flown in 1987-1988
- Used together with electric propulsion !

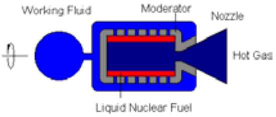
4.2.2/3 Solid / Liquid Core

Solid Core



- Material contraints: max. I_{sp}=900 s
- Fuel and thruster can be launched separately
- SSTO Launcher with solid core nuclear rocket (like NERVA): Payload capability 37%

Liquid Core



- Liquid nuclear fuel in rotating drum configuration
- Working fluid can be heated above nuclear fuel melting point
- Max. I_{sp} = 1,300 – 1,500 s
- Losses of nuclear fuel with working fluid

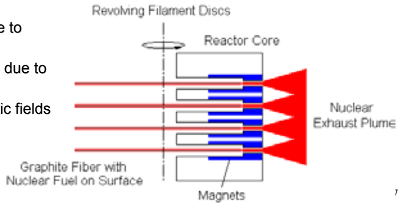
4.2.4/5 Gas Core, Fission Fragment

Gas Core

- Nuclear fuel contained in high-temperature plasma
- Radiant energy is transmitted to working fluid
- Liquid hydrogen is used also for cooling nozzle / plasma container
- Max. I_{sp}=3,000 – 7,000 s

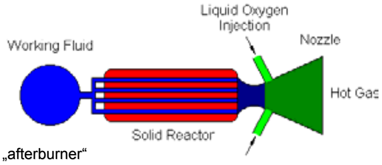
Fission Fragment

- No working fluid (I_{sp} close to speed of light)
- Nuclear products ionized due to radiation
- Directed through magnetic fields



4.2.6 Improvements

LOX-Augmented Nuclear Thermal Rocket (LANTR)

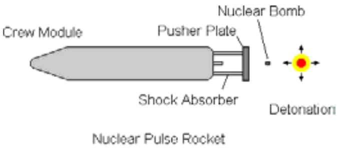


- Oxygen can be used as an „afterburner“
- Increases thrust and reduces I_{sp} (H_2O is heavier)
- Provides easy thrust modulation capability
- Oxygen can be collected during the mission e.g. from moon material or dissociation from CO_2 from the Marsian atmosphere

LANTR Mode
(oxidizer-fuel ratio 3)
67 kN at 940 s → 184 kN at 647 s

Induction Heating

4.2.6 Nuclear Pulse Rocket



Nuclear Pulse Rocket

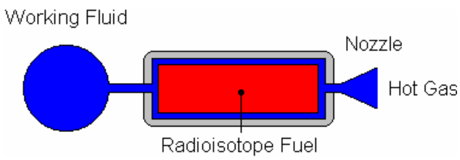
- Better energy yield utilization
- Spaceship becomes working fluid
- Shock absorbers needed to handle acceleration loads

Project ORION

- Studied by NASA in 1960's
- 10 m diameter, 21 m long
- 585 tons of weight
- 2000 atomic bombs required for 250 days round trip to Mars
- Subscale tests with chemical explosives proved concept
- Stopped due to political reasons

Project ORION

4.3 Radioisotope Nuclear Rocket

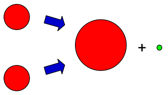


- Heat produced by nuclear decay (e.g. from Plutonium) – similar to RTG power generators
- Typical temperatures 1,500 – 2,000 °C (I_{sp}=700 – 800 s)
- 5 kW reactor, 13.6 kg, F=1.5 N
- Alternative fuel: Pollonium (half-life 138 days)
- TRW demonstrated Po-Thruster 65 hours test in 1965 !

4.4 Fusion Propulsion

- Fission requires neutrons to make the core unstable – fusion requires to overcome electrostatic repulsion of two nuclear cores and maintain it

Fusion Example

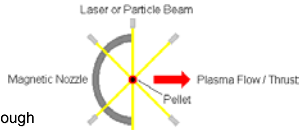


$$ {}^{2}_{1}D + {}^{3}_{1}T \longrightarrow {}^{4}_{2}He + n + 17.7\ \text{MeV} $$

- This reaction needs about 10 keV (≡ temperature of 75 million Kelvin)
- Can be achieved by: electromagnetic induction, laser / particle bombardment
- Technical difficulty is magnetic confinement: plasma must not touch chamber walls
- Uncontrolled fusion: hydrogen fusion bombs
- Controlled fusion: JET (Joint European Torous) achieved first major Deuterium-Tritium reaction (1991), later 60% of initial energy from fusion for 1 minute (1997)
- < 1 % energy gain is possible in many designs)

4.4.1/2 Inertial / Magnetic Confinement Fusion

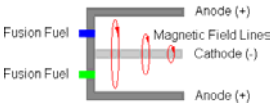
Inertial Confinement Fusion (ICF)



- Pellet with fusion fuel
- Outer shell with HEDM
- Pellet's inertia confines plasma long enough
- MICF: Additional metallic shell and magetic field to confine plasma longer (Magnetically Insulated ICF)

Magnetic Confinement Fusion (MCF)

- Magnetic bottle confines plasma (e.g. JET)
- Electromagnetic induction for heating

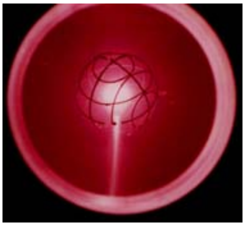


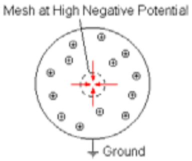
Dense Plasma Focus Thruster

Confine, compress and direct plasma in one process (magnetic pinch) similar to MPD thruster

4.4.3 Inertial Electrostatic Confinement Fusion

- Electrostatic fields used to confine plasma
- Fusion fuel: D^+, T^+, He_3^+
- Mesh at –100 kV, outer shell at ground
- Accelerated ions have enough energy to perform fusion reactions
- Plasma can escape from hole in mesh





Small scale IEC fusion devices are sold as portable neutron sources (energy gain <1%), upscaling is investigated!

4.5 Antimatter Propulsion

- Collision of matter-antimatter can produce radiation and/or matter and/or antimatter
- Highest energy density known up to now
- Produced as by-product in particle accelerators (e.g. CERN) from slowing down of particles at relativistic speeds (present costs 10 cents / anti-protons, 10^{12} / year !)
- Trapping and storing anti-matter requried very high vacuum conditions, and cooling to a few Kelvin

Not all anti-matter interesting for propulsion:

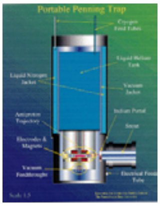
$$e^- + e^+ \longrightarrow 2\gamma + 511\,\text{MeV}$$

$$p^- + p^+ \longrightarrow 3.2\,\pi^+, \pi^- + 1.6\,\pi^0 \quad \checkmark$$

Propulsion devices require 10^{20} anti-protons

⬇

Due to very high costs and low production rate not feasible today!

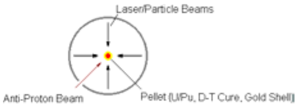


Penning Trap: Storage capability – 10^{10} anti-protons (10 femtograms)

4.5 Antimatter Propulsion

Anti-Proton Catalyzed Fission/Fusion

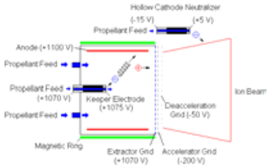
- Compatible with present production rate
- Anti-proton catalyzed fusion produces 6 times more neutrons
- Concept ICAN under study similar to Project ORION at Penn State University

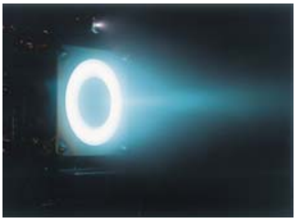


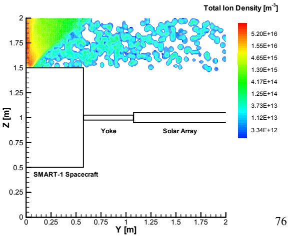
Direct Anti-Matter Propulsion

- Similar to Solid Core to heat up working fluid
- Anti-matter can also be injected into working fluid (I_{sp} – 2,500 s)
- Magnetic confinement heating (I_{sp} – 100,000 s)
- Only charged pion particles

Electric Propulsion Systems







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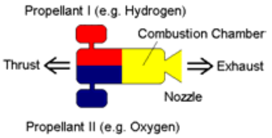
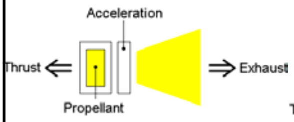
5. Electric Propulsion Systems

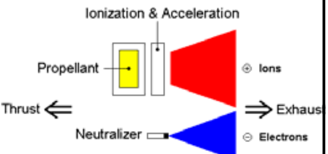


Energy stored in Propellant

➡ Exhaust Velocity limited by Chemical Reaction Energy Release

Electric Power from Spacecraft





➡ Exhaust Velocity limited by Power Available on Spacecraft

Electrothermal **Electromagnetic** **Electrostatic**

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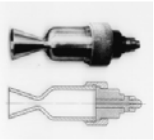
5. Electric Propulsion Systems



Already described by Tsiolkovski, Goddard, and Oberth

First thruster (Arcjet) built by Vladimir Glushko in 1929 at the Gas Dynamics Laboratory in Leningrad

Always believed that there is never enough power available on spacecraft, Ernst Stuhlinger's book Ion Propulsion for Spaceflight (1964) stimulated again research

⬇ Space Electric Rocket Test (SERT-1) in 1964 (US)

⬇ Zond 2 Interplanetary Mission to Mars in 1964 (Russia)

$$\eta = \frac{F^2}{2\dot{m}P} \qquad \eta = \frac{F^2}{2\dot{m}P + F^2_{\text{Initial Pressure}}}$$

Small thrusters with pressurized gas feeding

5. Electric Propulsion Systems

		Propellant	Power	Specific Impulse	Efficiency	Thrust
Electrothermal	Resistojet	Hydrazin, Ammonia	0.5 – 1.5 kW	300 s	80%	0.1 – 0.5 N
	Arcjet	Hydrazin, Hydrogen	0.3 – 100 kW	500 – 2,000 s	35%	0.2 – 2 N
Electrostatic	Ion	Xenon	0.5 – 2.5 kW	3,000 s	60 – 80%	10 – 200 mN
	Hall	Xenon	1.5 – 5 kW	1,500 – 2,000 s	50%	80 – 200 mN
	FEEP	Indium, Cesium	10 – 150 W	8,000 – 12,000 s	30 – 90%	0.001 – 1 mN
	Colloid	Glycerol	5 – 50 W	500 – 1,500 s		0.001 – 1 mN
	Laser Accelerated	Any kind	1 MW	10^7 s		0 – 100 mN
Electro-magnetic	PPT	Teflon	1 – 200 W	1,000 s	5%	1 – 100 mN
	MPD	Ammonia, Hydrogen, Lithium	1 – 4000 kW	2,000 – 5,000 s	25%	1 – 200 N
	VASIMR	Hydrogen	1 – 10 MW	3,000 – 30,000 s	< 60%	1 – 2 kN

Power Processing Unit (PPU) adds complexity, power losses and weight

---

5. Electric Propulsion Systems

Thrust = Massflow * Velocity

mN - MN High 1.000 - 3.000 m/s Chemical Propulsion

µN - N Low 20.000 - 100.000 m/s Electric Propulsion

➡ Same thrust level needs only up to 10% of propellant !

Typical Chemial Propellant Mass Fractions:

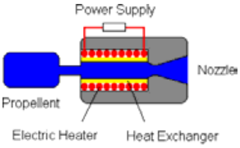
20% (LEO), 55% (GEO), 85% (Planetary)

- Drastically lower Spacecraft Mass & Costs
- Increase Transponders / Revenues
- Increase Lifetime
- Mission Enabling Technology using Ultraprecise Micro-Newton Thrusters (Drag Free, Scientific/Earth Observation, Small Satellites)

5.1 Electrothermal

Propellant velocity can be calculated similar to chemical propulsion systems !

Resistojet

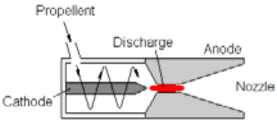


Propellant	Hydrazine, Ammonia
I_{Sp}	300 s
Thrust	0.1 - 0.5 N
Power	0.5 - 1.5 kW

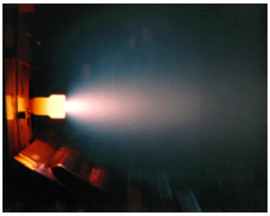
- Temperature limited by heat exchanger (Tungsten) – max. 3000 K
- Used for attitude control, competes against monopropellant (I_{sp}=150-250) and cold gas (I_{sp}=80 s) thrusters
- Also waste water can be used (space station)
- Efficiency: 80%

General Dynamics Resistojets (Iridium)

5.1.2 Arcjet



Propellant	Hydrazine, Hydrogen
I_{Sp}	500 – 2,000 s
Thrust	0.2 - 2 N
Power	0.3 - 100 kW



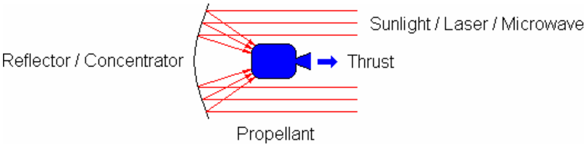
Commercial Arcjets used e.g. on Lookheed Martin Series 7000 Comsat

- Propellant swirled into chamber (increases time for heating)
- Either low voltage (100 V) and high current (hundreds of A) discharge or high-frequency high voltage discharge
- Very high local heating along center line (fully ionization)
- Strong temperature gradient towards walls
- Cathode erosion limits lifetime to typically 1,500 hours
- Also microwave and AC discharges

5.1.3 Solar / Laser / Microwave Thermal

Electric Propulsion ⟷ **Beamed Energy Propulsion**

- External energy source: Sunlight, laser or microwave
- Laser / microwave require Earth infrastructure and can only be used effectively in LEO
- Sun / Hydrogen produce I_{sp} between 800 – 1,200 s and several hundred mN
- Good concept for LEO to GEO transfers in about 20 days with little propellant (significant cost reduction)
- Low mass inflatable reflectors are presently under study



5.1.3 Solar Thermal Upperstage

5.2 Electrostatic Propulsion

$$v = \sqrt{\frac{2qU}{m}} \qquad \dot{m} = I \cdot \frac{m}{q} \qquad F = I \cdot \sqrt{\frac{2mU}{q}}$$

I_{sp} scales with $\sqrt{\frac{q}{m}}$

High I_{sp}: Multi-ionized, light ions

Thrust scales with $\sqrt{\frac{m}{q}}$

High thrust: Singly charged, heavy ions

More important

Ion Thruster Ionization through electron bombardment of high-frequency excitement

Propellant Cesium, Mercury (heavy, low 1st ionization potential, high 2nd ionization potential) → Contamination, Toxity → Xenon (heavy inert gas)

High I_{sp} (2,500 s) and thrusts (up to 200 mN at several kW)

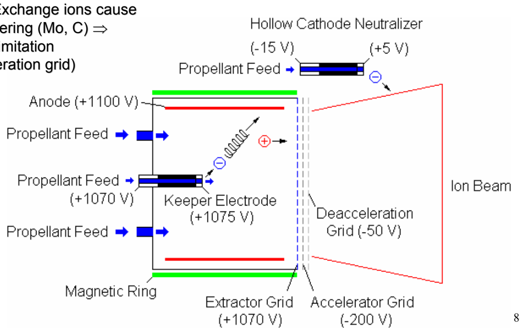
5.2.1 Electron Bombardment Thruster

- Invented by Prof. Kaufman
- Space charge limits grid size

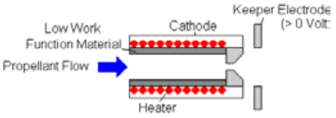
$$I = \frac{4}{9}\varepsilon_0 \sqrt{\frac{1q}{m}} \frac{U^{3/2}}{d^2} A$$

20 cm for 20 µN,
40 cm for 200 µ N

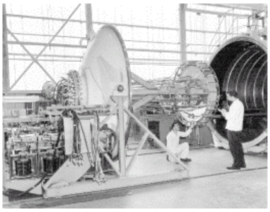
Charge-Exchange ions cause grid sputtering (Mo, C) ⇒ Lifetime limitation (deacceleration grid)



5.2.1 Electron Bombardment Thruster



- Thermionic electrons further ionize propellant (and create more electrons)
- Ions attracted by cathode (further heating)
- Outside CEX plasma is formed



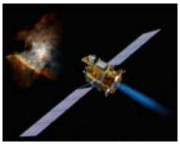
- Built at NASA Lewis in 1960's
- Flown on SERT-I (1964), SERT-II (1970, operated 11 years, 5,792 hours of thrusting) and ATS-6 (1974) using Mercury/Cesium
- NSTAR thruster on Deep Space 1 (Xenon, 1998)
- Also used by Hughes (HP 601 HP satellite bus, XIPS)

1.5 m diameter, 200 kW

5.2.1 Electron Bombardment Thruster

NSTAR Thruster

- First commerical satellite PAS-5 launched in 1997
- ESA ARTEMIS satellite is equipped with RIT-10 and UK-10 thruster
- Efficiencies towards 80%
- Presently shift towards Hall thrusters in Telecom-Satellites (lower power)



NASA Deep Space 1

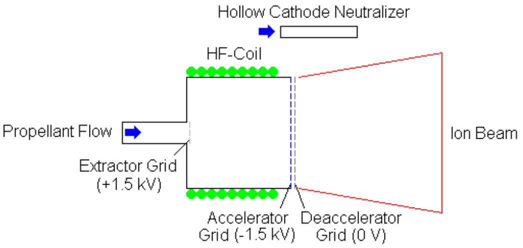
- First Interplanetary EP Mission (Launched 1998)
- Target: Comets
- Thruster Operated > 200 h

UK-10 Thruster

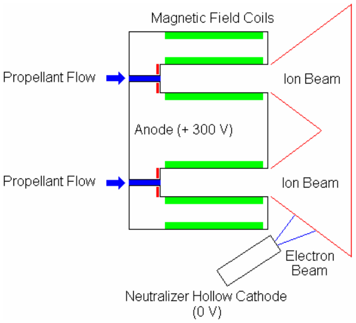
5.2.1 Radiofrequency Ion Thruster

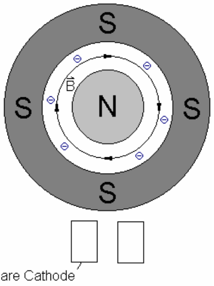
- Invented by Prof. Loeb
- No hollow cathode needed!
- Lower ionization efficiencies (overall efficiency 60%)
- RIT thrusters used on ARTEMIS

RIT-10 Thruster



5.2.2 Hall Thruster

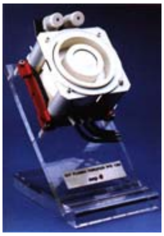


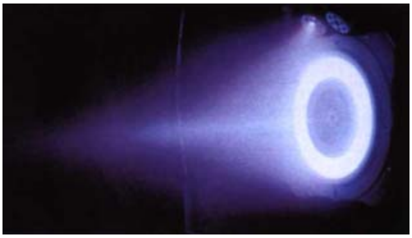


- Gridless, Efficiency 50%
- Lifetime limitation: Anode erosion

Propellant	Xenon
I_{Sp}	1,500 – 2,000 s
Thrust	80 - 200 µN
Power	1.5 - 5 kW

5.2.2 Hall Thruster

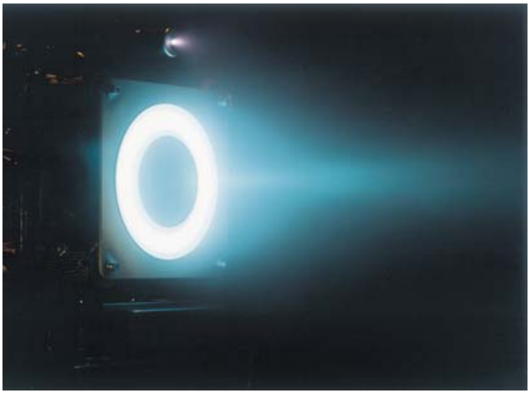




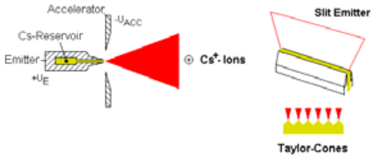
- Over 100 flights on Russian satellites for North-South Stationkeeping
- Low acceleration potential means less complex PPU
- Optimum specific impulse of 1,500 s for telecom satellites
- SMART-1 will use PPS-1350 Hall thruster for interplanetary flight

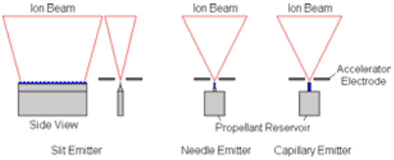
SMART-1

5.2.2 Hall Thruster



5.2.3 Field Emission Thruster





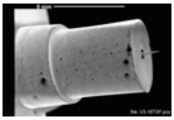
Propellant	Indium, Cesium
I_{Sp}	8,000 – 12,000 s
Thrust	0.001 - 1 mN
Power	10 - 150 W

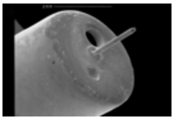
5.2.3 Field Emission Thruster

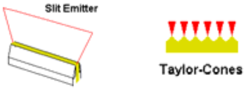
Propellant	Indium, Cesium
I_{Sp}	8,000 – 12,000 s
Thrust	0.001 - 1 mN
Power	10 - 150 W

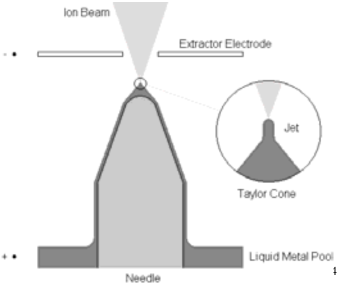
Unique:

Ionization and Acceleration in One Process



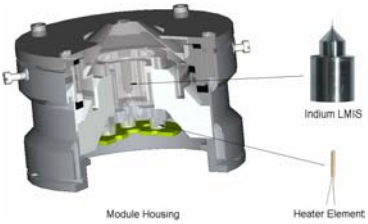






In-FEEP Thruster Details

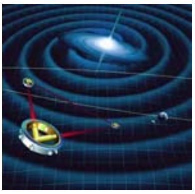
- Thermal Insulation
- Electrical Insulation
- Mechanical Interface
- Contains Heater and Indium LMIS



- Different Propellant Size Ranging from 0.22 – 15 grams, 30 grams in manufacturing (available Sept. 2002)
- 15 grams = 400 Ns total impulse

5.2.3 Field Emission Thruster

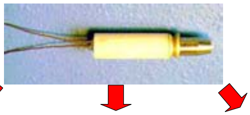
- Power-To-Thrust Ratio 60 – 75 W/mN (⇒ low thrust levels)
- Electrical Efficiency 99%
- Mass Efficiency ≈ 50%



Austrian In-FEEP Technology

Development of Indium Liquid-Metal-Ion-Source (LMIS)

20 years of development at ARCS ...



… 10 years involved in space programs

Mass Spectrometer | S/C Potential Control | FEEP Thruster

Experiment	Spacecraft	Operation Time
EFD-IE	GEOTAIL	600 h ('92 -)
PCD	EQUATOR-S	250 h ('98)
ASPOC	CLUSTER	Launch Failure '96
ASPOC-II	CLUSTER-II	1700 h ('00 -)

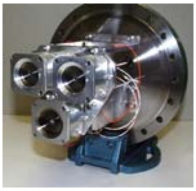


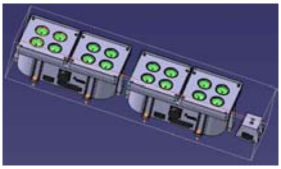

ASPOC Before ...

... and After Launch Failure

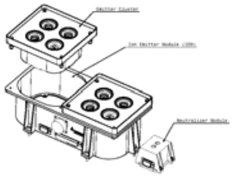
Clustering – Higher Thrust

Conventional Clustering

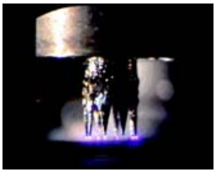




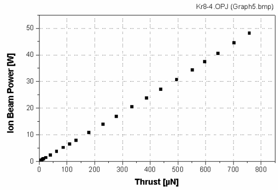
- Developed within GOCE Program (Maximum Thrust 650 μN)
- Tests Start September 2002
- Either Power Supply - Thruster or One Power Supply – Thruster & Individual Extractor Control

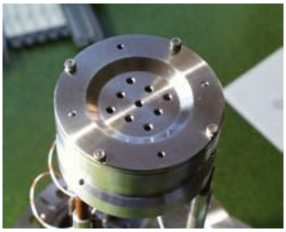


Multiemitter



8 Tip Crown Emitter





Multicapillary Emitter

More Emissions Zones per Thruster

→ **Full Prototype Tested, 1 mN Thrust Range Reached**

Extractor Heater

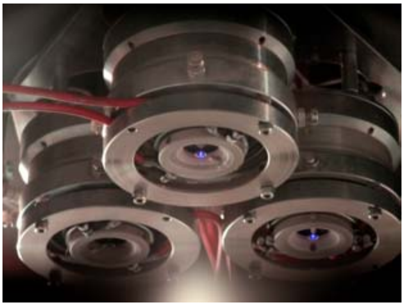
Extractor Heater to Evaporate any Contamination

→ **Not Necessary for Thrust < 2 μN !**

Heater Successfully Implemented in 2,000 Hours Lifetime Test

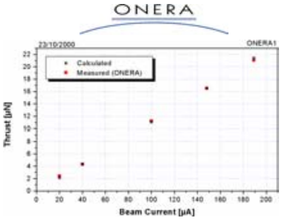
Lifetime Testing

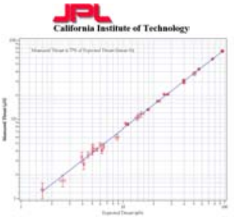
- > 2,700 hours in space
- 4000 h Endurance Test at 1.5 μN
- 820 hours at 15 μN
- 2,000 hours at 0-54 μN
- 5,000 h Test Starts in September

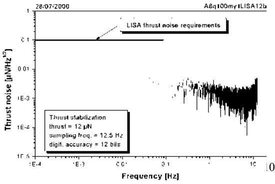


2,000 h Enduranace Test of 2 Thruster (out of 3)

Austrian In-FEEP Technology



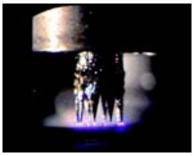




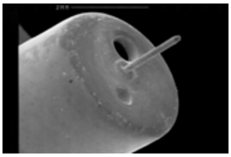
AUSTRIAN RESEARCH CENTERS SEIBERSDORF

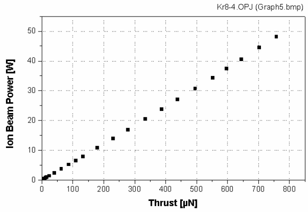
- World-first direct thrust measurement in μN range
- Already fulfills challanging LISA thrust noise requirement

Austrian In-FEEP Technology


8 Tip Crown Emitter

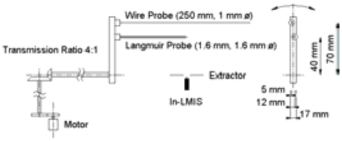

Porous Ring Emitter

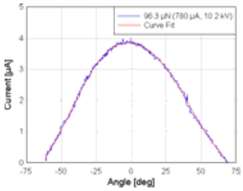

Capillary Tube Emitter



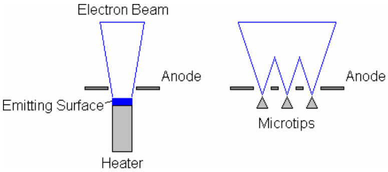

Blade Emitter

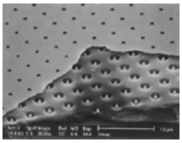
ARCS In-FEEP Diagnostics

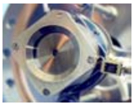




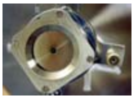
5.2.3 Field Emission Thruster / Neutralizers



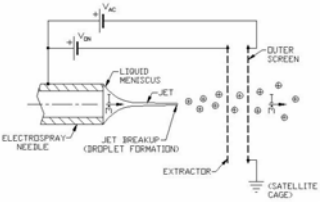




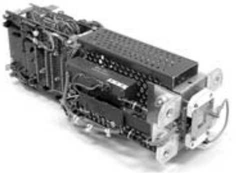
- Thermionic cathode: 1.5 – 2 W/mA
- Field emission cathodes: 10 mW/mA



5.2.4 Colloid Thruster



Propellant	Glycerol + additives
I_{Sp}	500 – 1,500 s
Thrust	0.001 - 1 mN
Power	5 - 50 kW



- Similar to FEEP with glycerol + additives as propellant
- Extensively studied in 1960's (TRW – Dan Goldin!, NASA, ESA, MAI)
- Too high acceleration potential for competing with ion engines

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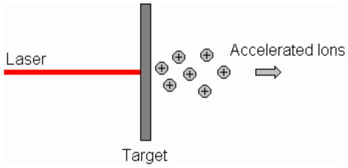
5.2.5 Laser Accelerated Plasma Propulsion



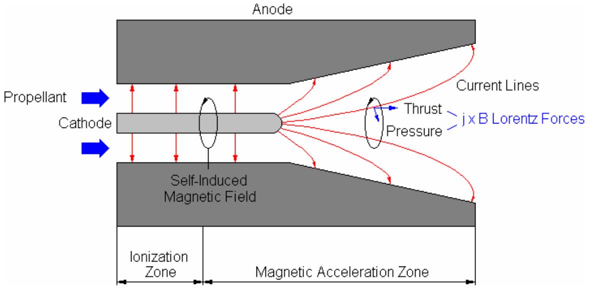
Propellant	Any kind
I_{Sp}	10^7 s
Thrust	0-100 mN
Power	1 MW

- Currently under study at University of Michigan
- Ultrashort laser (picoseconds and below) with very high intensities (hundreds of Terrawatt) focused on a small spot creates high temperature plasma on surface
- Electrons at relativistic speeds penetrate material generating very high electric fields (GV/m) which can accelerate ions out of target material
- State-of-the-art laser (500 J with 500 fs pulse length) performance would be 100 mN and 10^7 s I_{sp} !
- Incredible potential – problem is to get laser infrastructure into space
- Requires 1 MW nuclear reactor
- Future lasers will offer > N thrust capabilities

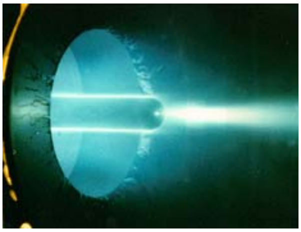
5.3 Electromagnetic Propulsion

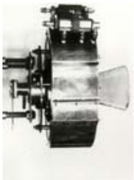
Magnetoplasmadynamic (MPD) Thruster

Propellant	Ammonia, Hydrogen, Lithium
I_{Sp}	2,000 – 5,000 s
Thrust	1 – 200 N
Power	1 – 4,000 kW

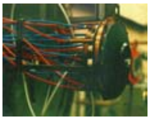


5.3.1 MPD Thruster



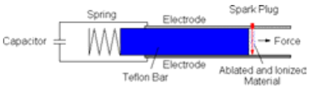


20 mN (1KW) quasi-steady state MPD flown by ISAS in 1997

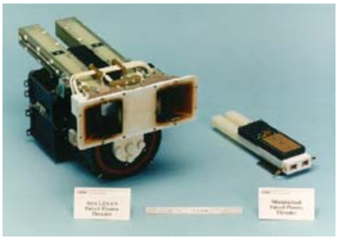


- Low voltage / high current discharge ionizes propellant
- Self-Field / Applied-Field (coils, permanent magnets)
- Lorentz-Force: Thrust scales with I^2 (velocity, mass flow)
- Also high tempearture (2,500 °C) contributes to thrust (one order of magnitude below)
- Very high thrusts, capability to transmit very high power loads, efficiencies 35-70%
- Interesting candidate for manned Mars mission

5.3.2 Pulsed Plasma Thruster

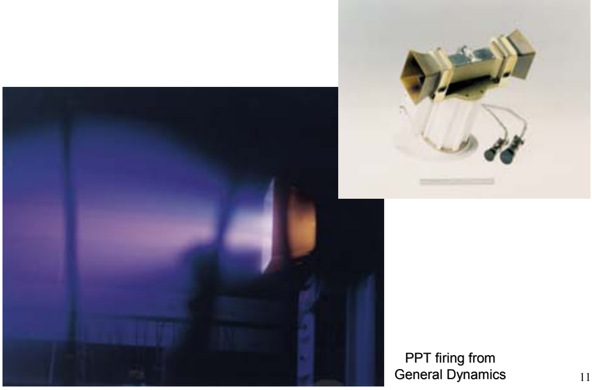


Propellant	Teflon
I_{Sp}	1,000 s
Thrust	1 – 100 mN
Power	1 – 200 W



- Heat transfer from discharge ablates and ionizes the propellant
- Typically 1 – 3 Hz frequency each producing hundreds of μN
- No warm up time, no standby power, no propellant tank and feedlines
- Very cheap and simple
- Disadvantage: efficiencies 5-15%
- Flown on Zond-2 in 1964 !

5.3.2 Pulsed Plasma Thruster

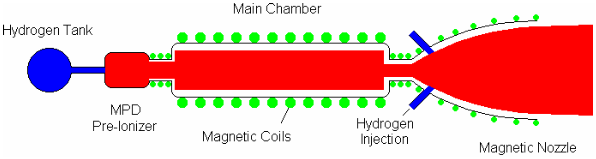


PPT firing from General Dynamics

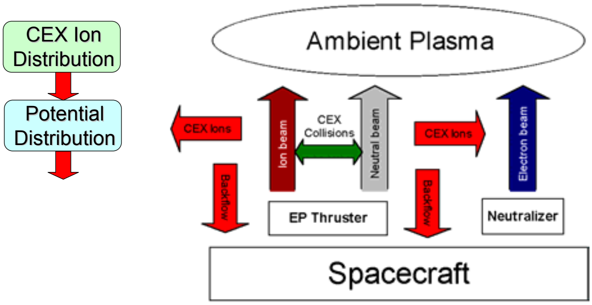
5.3.3 Variable I_{sp} Plasma Rocket (VASIMR)

- Magnetic field to confine plasma and EM energy to heat it (RF fields)
- Isp can be changed by RF power
- Efficiencies < 60% (TBC !)
- Under study at NASA JSC, prototype shall be tested on board ISS

Propellant	Hydrogen
I_{Sp}	3,000 – 30,000 s
Thrust	1 – 2 kN
Power	1 – 10 MW

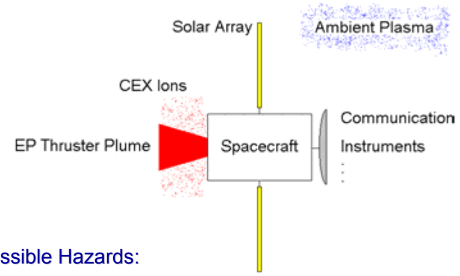


5.3.4 Induced Spacecraft Interactions



Charge-Exchange Collision: $Ion_{Fast} + Neutral_{Slow} \rightarrow Ion_{Slow} + Neutral_{Fast}$

5.3.4 Induced Spacecraft Interactions



Possible Hazards:

- Contamination, Sputtering and Erosion on Spacecraft Surfaces
- Degradation of Solar Array
- Influence on Measurements (Ambient Plasma, ...)
- Spacecraft Charging
- Influence on Communication
- Lifetime Reduction
- ...

5.3.4 Induced Spacecraft Interactions

Ground-Testing

- Vacuum Chamber Background Pressure
- Chamber Walls
- Neutralisation from Secondary-Electrons, Sputtering, ...

Space-Measurements

- Only Single-Point Measurements
- Very Expensive
- Not Flexible

Comparison

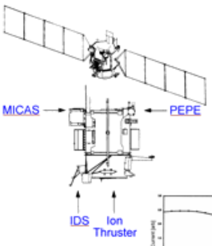
Modelling and Simulation

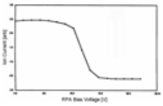
- Full Characterisation of EP Influence on Spacecraft
- Optimisation of Experiments, Missions
- Cheap and Flexible

5.3.4 Induced Spacecraft Interactions

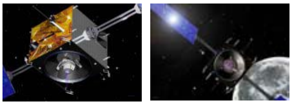
Test Satellites:
- ATS-6, SERT-1, 2, … (NASA) 1970´s
- NSSK - Spacecraft (Russia) 1970‘s, 1980‘s

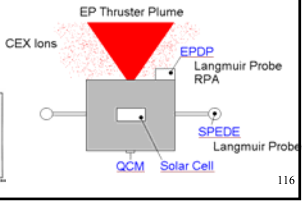
NASA Deep Space 1 (1998)





ESA SMART-1 (2002)





5.3.4 Induced Spacecraft Interactions

3D Particle-In-Cell (PIC-MCC) Code

- Average Plasma Parameters to Grid Structure
- Monte-Carlo Charge-Exchange Collisions (Calculate Probability)

Full Particle / Hybrid Model

- Ions/Neutrals as Computer Particles
- Electrons as Fluid or Particles

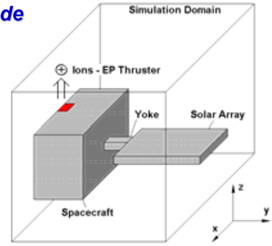
Environment

- Vacuum - Space

Simulation Parameters

- Grid Size: 100x100x100
- 1,500,000 Computer-Particles

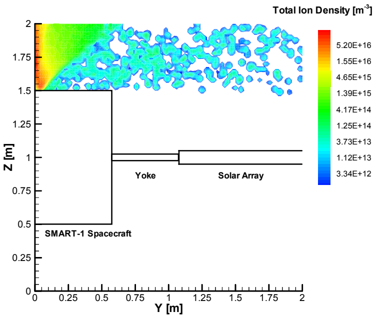
- Grid Size: 40x40x40
- 300,000 Computer-Particles

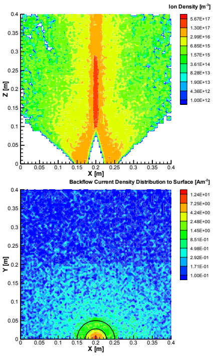


Electron Fluid vs SOR Potential Solver

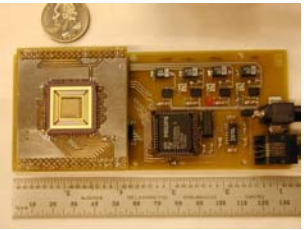
$$n_i \approx n_e = n_{e\infty} \cdot \exp\left(\frac{e\Phi}{kT_e}\right)$$

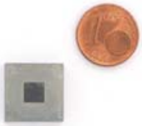
5.3.4 Induced Spacecraft Interactions





Micropropulsion





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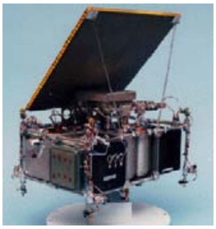
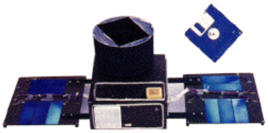
6. Micropropulsion

Relatively new area investigating drastic reduction of thruster size and mass

- Computer and microstructure is advancing ⇒ Microspacecraft ⇒ requires Micropropulsion
- Micropropulsion technology can reduce thrust to mass ratio



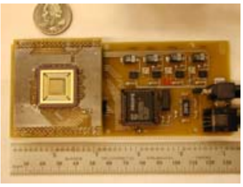
- Microsatellit (100 kg), Nanosatellite (10 kg), Picosatellite (1 kg)
- Requires MicroElectroMechanical Systems (MEMS) engineering capabilities



6.1 Chemical Micropropulsion

Solid Microthrusters

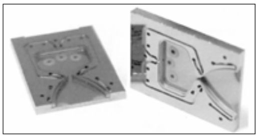
- Solid propellant heated and microvalve is opened
- Simple concept digital microthrusters: multitude of single-shot thrusters on silicon chip (e.g. from Honeywell: 10^6 thrusters on 10 cm wafer, each can provide 3 µNs, total mass 2.4 g)



Honeywell / Princton Megapixel Thruster

Micro Bi-Propellant Thruster

- Studied at MIT and Mechatronic (A)
- MIT aims at 15 N and 5 g/s

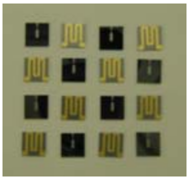


6.1 Chemical Micropropulsion

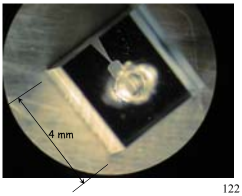
Cold Gas Thruster

- Nitrogen fed through valve and nozzle
- Valve leakage typicalle 10%
- MOOG built 4.5 mN thruster with 34.5 kPa and I_{sp} of 65 s (total weight 7.34 g)
- MEMS version under study in Sweden

Cold Gas Thruster



Microheater – Higher I_{sp}



6.2 Electric Micropropulsion

Micro Ion Thruster

- Kaufmann thruster with 1 – 3 cm range under development at University of Southern California and JPL
- A few µN targeted
- Requires field emission technology and high magnetic field strengths

Low Power Hall Thruster

- 4 mm diameter Hall thruster developed at MIT
- 1.8 mN, 865 s, 126 W and 6% efficiency
- 50 W Hall thrusters under development at Keldysh Research Center and Busek (100 W, 4 mN and 20%)

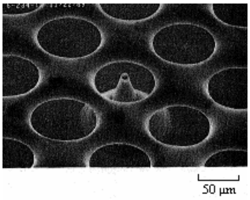
6.2 Electric Micropropulsion

Micro PPT Thruster

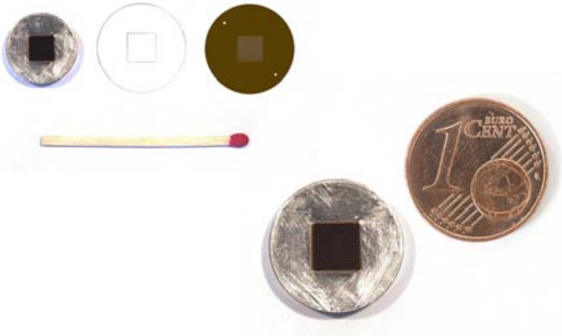
- Under development at Air Force Research Laboratories
- Size of standard TV coaxial cable
- Complete thruster including electronics weights 0.5 kg, 2-30 N and 1-20 W

MEMS Colloid/FEEP

- MEMS field emission cathode technology used for ion sources
- Microvolcano structure successfully built at SRI
- Variable I_{sp} with additional grid – adjustable power-to-thrust ratio

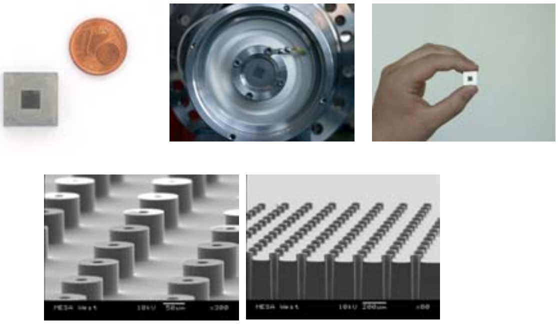


6.2 Electric Micropropulsion - µFEEP



400 single emitters on 5x5 mm !

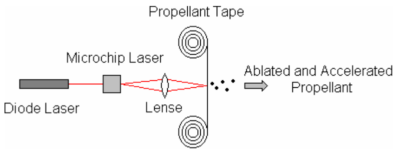
6.2 Electric Micropropulsion - µFEEP



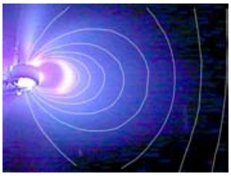
6.2 Electric Micropropulsion

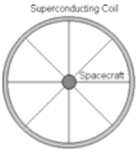
Microchip Laser Thruster

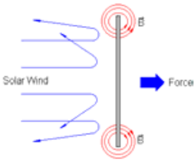
- Standard 1 W diode laser used to pump microchip laser to transform into high intensity pulsed laser light
- Propellant tape e.g. Teflon coated with Aluminium
- Material is heated, ablated and ejected at high thermal velocities
- Complete thruster weight 400 g including PCU, 0.3 nN – 3 μN at 6.5 W
- Specific Impulse 1,000 s
- Efficiency around 1%

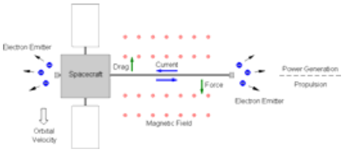


Propellantless Propulsion







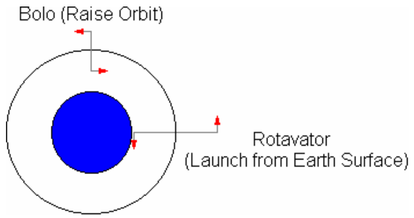


7. Propellantless Propulsion

Tethers are long cables connected to a spacecraft

Momentum Exchange Tether

- Atmospheric drag will slow down and heat up tether significantly
- Difficult for Earth environment, possible for Moon or Mars



7.1.2 Electrodynamic Tether

Propulsion

$$F = \frac{B^2 l^2 v}{\underset{\uparrow}{R}}$$

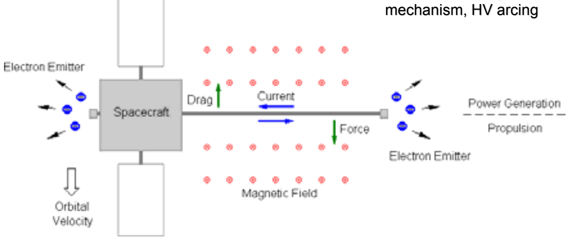
Resistance

Example: B=20 μT (LEO)
v=6,800 m/s
L=5 km
R=185 Ω (5 km Aluminium)
F=0.36 N

Power

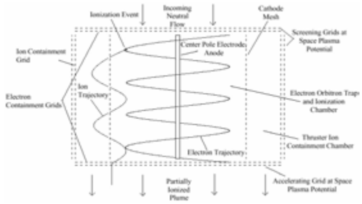
$$P = F \cdot v = \frac{(B \cdot l \cdot v)^2}{R}$$ P=2.4 kW

- Can be used to re-boost ISS, de-orbit satellites, etc.
- Problems: Deployment mechanism, HV arcing



7.2 Propellantless Electric / Nuclear Propulsion

- Ionise and Accelerate Ambient Neutral Gas Atmosphere (LEO Orbit, low altitude Mars Orbit, ...)
- In LEO, Power-to-Thrust ratios of 80 W/mN achievable



Interstellar Ramjet

- Collect interstellar hydrogen
- Use it as fuel in fusion reactor and create thrust by expelling it
- 10,000 km^2 collection area are needed for 10 ms^{-2}

7.3/4 Photon Rocket, Beamed Energy

Photon Rocket

Directly converts electric energy into kinetic energy via the use of a laser

Energy emitted by Laser

$$W = h \cdot f$$

Propulsion Characteristics

$$F = \frac{W}{c} = \frac{h \cdot f \cdot R}{c} \qquad I_{sp} = \frac{c}{g}$$

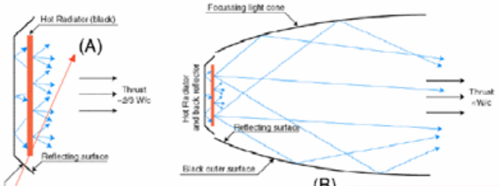
Example: 1 MW laser will produce 3.3 mA at 3x10^7 s !

Beamed Energy Earth-to-Orbit Propulsion

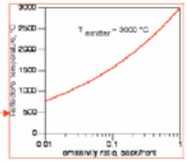
- Laser can heat air and create thrust
- Estimated at 1 MW / kg
- US Air Force is experimenting with small prototype (Lightcraft)

7.3 Rubbia´s Photon Propulsion Concept

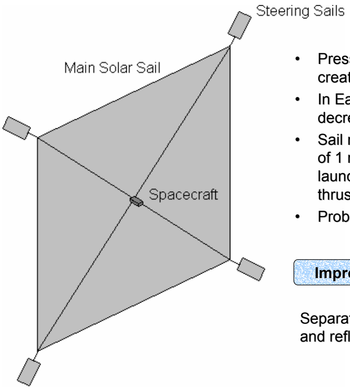
Conceptual layout



In (A) the unwanted radiation is reflected back onto the plate by a reflector. In (B) a concentrating cone is added in order increase the directionality of the emitted light. In order to keep the temperature of the reflectors in (A) and (B) to a reasonable value, while the surface facing the hot plate is made highly reflective or diffusive, the outer surface is blackened to enhance heat dissipation.



7.5 Solar Sail



- Pressure of solar photons used to create thrust
- In Earth's orbit around 9 N/km^2, decreasing with 1 / r^2 from the sun
- Sail material under study has thickness of 1 m (limited by stresses during launch – space manufacturing ?), gives thrust-to-weight ratio of 10^{-5} N/kg
- Problem: Deployment mechanism

Improvement

Separating function of collecting photons and reflecting them to create thrust

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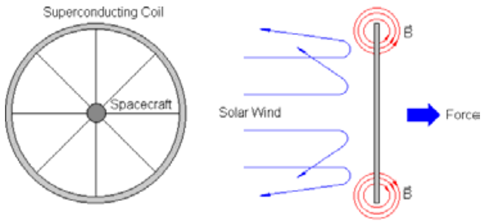
7.6 Magnetic Sail



- Superconducting Current Loop forms Dipole which deflects Solar Wind
- Solar Wind travels at 300 - 800 km/s (Voyager spacecraft 17 km/s)
- Mission Applications: Interplanetary Cargo - Interstellar Precursor

Major Technical Difficulties

- Superconducting Technology - Cooling, forms Radiation Belt, Structures - Weight

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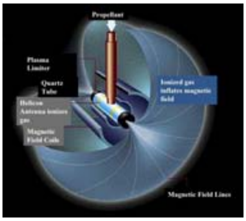
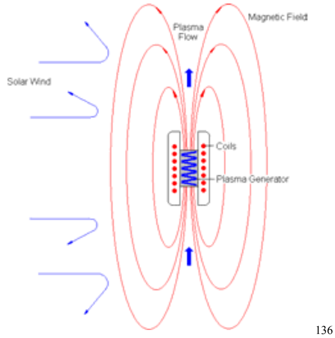
7.6 Magnetic Sail / M2P2

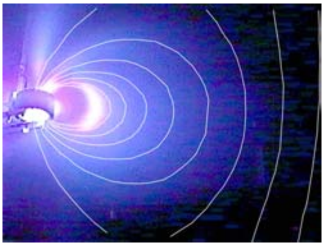


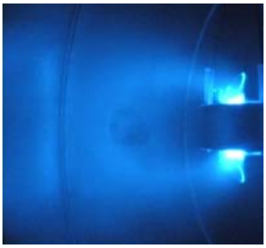
Mini-Magnetosphere Propulsion (M2P2)



- Injects plasma (e.g. Argon) to enlarge magnetic field from electromagnet
- Couples to solar wind like Magnetosphere
- 20 km magnetic bubble seems possible

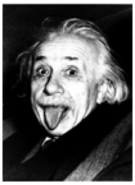
7.6 Magnetic Sail / M2P2

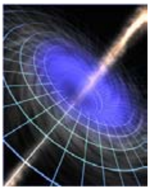


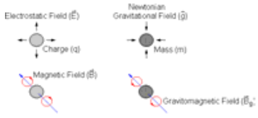


M2P2 Ground Experiments

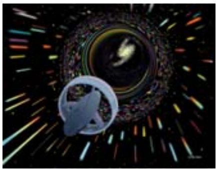
Breakthrough Propulsion

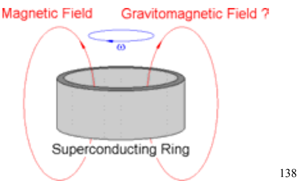






$$\kappa = -\frac{m}{e}\frac{\mu_g}{\mu_0} = -\frac{m}{e}\frac{\varepsilon_0}{\varepsilon_g} = -7.41x10^{-21} \cdot \frac{m}{e}$$





8. Breakthrough Propulsion

- Classical technology limits already reached are known (e.g. LO_2/LH_2 Space Shuttle engine has 95% efficiency – not much room for improvement)
- Nuclear propulsion like NERVA is ready to use – will enable manned interplanetary missions

How can we explore OTHER solar systems within a crew's lifetime ?

Proxima Centauri: Closest three star system

- Alpha Centauri is 4.3 lightyears away
- Δv required to reach it in 10 years is 100.000 km/s, compared to today's robotic missions of 10 km/s
- Even with nuclear rockets we are 2 orders of magnitude away from this goal

We need a breakthrough in physics !

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8. Breakthrough Propulsion

Today's Limits

- Thermodynamics: Energy can only be transformed but not created out of nowhere (no Perpetuum Mobile)
- Relativity Theory: The fastest possible speed is the speed of light, mass is a function of spacetime curvature (we need something like a black hole to modify space, time and mass)

It was scientifically proved that machines heavier than air can not fly, that we can not go to the Moon, and that we can not go to other stars ...

In 1996, NASA estabilshed the Breakthrough Propulsion Physics Program, US Department of Energy, and ESA followed

How can we use present theories to overcome those limits ... ?

8.2 Quantum Theory

- Heisenberg's uncertainty principle requires that atoms still move at zero Kelvin
- Average energy is called Zero-Point-Energy

$$\langle E\rangle_{ZPE}=\frac{hf}{2}$$

Casimir Effect (1948) ⇒

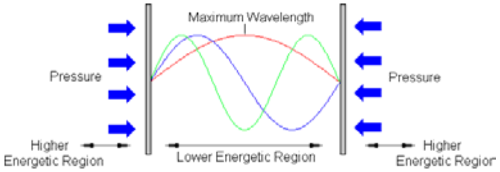
$$\frac{F}{A}=\frac{\pi hc}{480L^4}$$

<u>Example:</u> 1 m² at 1 µm distance gives 1 mN

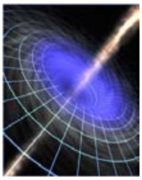
Scharnhorst Effect (1990) ⇒

$$\frac{c_\perp}{c_{\mathrm{II}}}=1+\frac{1.59\times10^{-56}}{L^4}$$

Can also be used to explain inertial mass and how it can be modified!

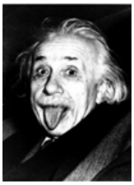


8.2 Coupling of Gravitation and EM



General Relativity Theory

1916



Einstein

Linearization

Maxwell

Extension to Time-Dependent Systems

- **Gravitational Poynting Vector (Heaviside)**
- **Conservation of Energy & Momentum (Jefimenko)**

Newton

8.2 Coupling of Gravitation and EM

General Relativity Theory

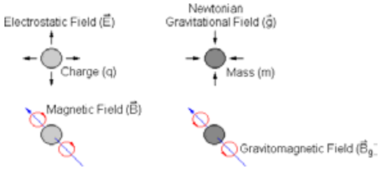
Gravitoelectric Part

- Newtonian Gravity

Induction ⇔

Gravitomagnetic Part

- Lense-Thirring Effect
- Frame Dragging
- Gravity Probe B



8.2 Coupling of Gravitation and EM

$$rot\,\vec{E}=-\frac{1}{\kappa}\frac{\partial\vec{B}_g}{\partial t}$$

$$rot\,\vec{B}=\frac{e}{m}\mu_0\rho_m\vec{v}+\frac{1}{\kappa}\frac{1}{c^2}\frac{\partial\vec{g}}{\partial t}$$

Gravitation ⇒ Electromagnetism

$$rot\,\vec{g}=-\kappa\frac{\partial\vec{B}}{\partial t}$$

$$rot\,\vec{B}_g=-\frac{m}{e}\mu_g\rho\vec{v}-\kappa\frac{1}{c^2}\frac{\partial\vec{E}}{\partial t}$$

Electromagnetism ⇒ Gravitation

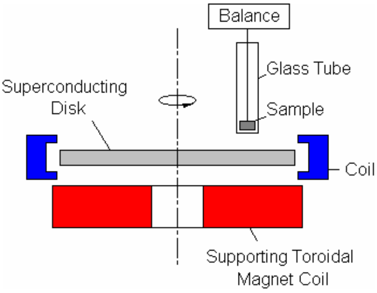
$$\kappa=-\frac{m}{e}\frac{\mu_g}{\mu_0}=-\frac{m}{e}\frac{\varepsilon_0}{\varepsilon_g}=-7.41x10^{-21}\cdot\frac{m}{e}$$

Coupling Coefficient

8.3 Experiments leading to Breakthroughs

Superconductor Gravitational Shielding

- Discovered by Podkletnov in 1992
- Maximum weight shiedling 2%

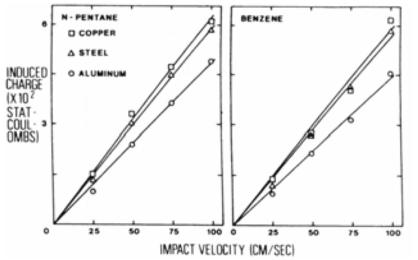


8.3 Experiments leading to Breakthroughs

Coupling of Charge, Mass and Acceleration

James Woodward - Rotating Masses Charge up during Rotation, Projectiles Induce Charge on Target

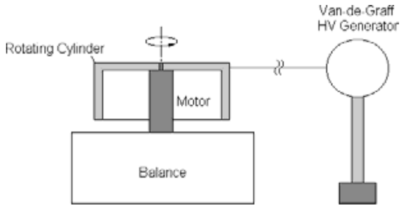
$$q' \cong \text{Constant} \cdot m \cdot a$$



8.3 Experiments leading to Breakthroughs

Yamashita/Toyama - Weight Change of Rotating Charged Cylinder

- Positively Charged + 4 grams (out of 1300 grams total)
- Negatively Charged - 11 grams
- Weight changed according to speed of rotation (no electrostatic)
- No change of weight difference if orientation of ratation changed (no magnetic)



8.3 Experiments leading to Breakthroughs

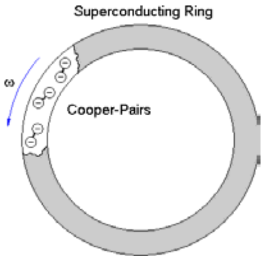
Inside Quantum Materials

$$\oint \vec{p}_s \cdot d\vec{l} = \oint \left(m\vec{v}_s + e\vec{A}\right) \cdot d\vec{l} = \frac{nh}{2}$$

Mechanical Momentum

Magnetic Vector Potential

Both vector fields are linked to each other



London Moment

$$\vec{B} = -\frac{2m}{e} \cdot \vec{\omega}$$

Magnetic Field is generated without the influence of the permeability !

8.3 Experiments leading to Breakthroughs

How well do experimental values fit quantum theory ?

London Moment

$$1 - \frac{\vec{B}_{\text{theory}}}{\vec{B}_{\text{experiment}}}$$

- **Normal SC 3-15 % (Hildebrandt, PRL 1964)**
- **High-T_c SC, heavy fermion SC 5-10 % (Sanzari, APL 1996)**
- **etc.**

Measured discrepancy between experiment and quantum theory!

Ginzburg-Landau

$$\frac{m_{\text{Cooper-Pair}}}{2m_e} = 0.999992$$

Including Quantum and Relativistic Corrections

$$\frac{m_{\text{Cooper-Pair}}}{2m_e} = 1.000084(21)$$

Most accurate measurement from Tate et al (PRL, 1989)

8.3 Experiments leading to Breakthroughs

Expand Canonical Momentum to Include Gravitational Effects.

Already done by DeWitt in 1970s (Princeton)

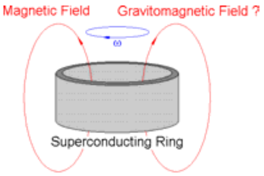
Inside Quantum Materials

$$\oint \vec{p}_s \cdot d\vec{l} = \oint \left(m\vec{v}_s + e\vec{A} + m\vec{A}_g\right) \cdot d\vec{l} = \frac{nh}{2}$$

Mechanical Momentum

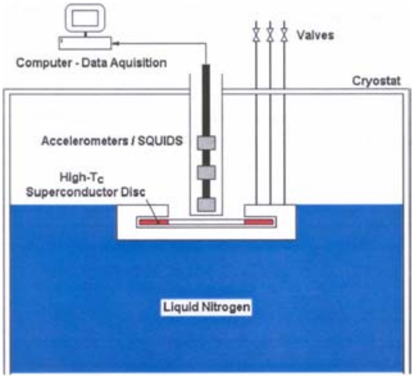
Gravito-Magnetic Vector Potential

Magnetic Vector Potential



All three vector fields are linked to each other

8.3 Experiments leading to Breakthroughs



8.4 When will we Revolutionize Space Travel

When will we revolutionize Space Travel

?

- Rocket propulsion is 1,000 years old
- Lastet until 1940 to suddenly develop the V-2
- Technology stayed the same until JFK decided to go to the Moon
- Space Shuttle technology from 1970's – shall be used up to 2020
- Slow implementation of new technologies (air breathing, etc.)

Breakthrough When ?

As history taught us, it can happen very quick and very soon ...

8.4 When will we Revolutionize Space Travel