Magnetoplasmadynamic Thrusters

Part 1: Self-field MPD Thrusters

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Content of Part 1

- Introduction/ Motivation
  - Some definitions and thoughts
  - Propulsion problem
  - Electric Propulsion

- Self-field MPD Thrusters:
  - PPT (iMPD)
  - Discharge physics
  - Self-field Magnetoplasmadynamic Thrusters

- Summary

- (add slides: Verification + validation Tools (plasma diagnostics + modelling tools))

- Part 2:
  - Applied-field Magnetoplasmadynamic Devices
Propulsion Problem

- $\Delta v$ based on trajectory analysis (e.g. spiraling, continuous transfers, ...)

- **Mission:**
  - $\Delta v$ (velocity increment)
  - $\Delta v = \int_{\Delta t_b} a_c \, dt$
  - $\Delta v = c_e \log \left( \frac{m_0}{m_1} \right)$

  - Space flight missions defined via *propulsion requirement* typically via assignment of velocity increment $\Delta v$ – based on orbit mechanics.

  - But: Consideration of *propulsion capability* as $\Delta v$ (as well). Determined by propulsion system. Available acceleration $a_c$ impacts (continuous) „burn time“, effective exhaust velocity $c_e$ impacts required propellant mass.

  - Propulsion problem: Potentially long lasting transfers.
(Further) Consideration of the propulsion problem

How can we overcome this arduousness in propulsion?

A transfer is characterized by a velocity increment $\Delta v$

$$
\Delta v = \int_{\Delta t_b}^{\Delta t} \alpha_c \, dt
$$

Kinematics:
Relating $\alpha_c$ and burn time

$\Delta v = c_e \log \left( \frac{m_0}{m_1} \right)$

Tsiolkovsky’s equation:
Relating $c_e$ and dry mass

The link of $\alpha_c$ and $c_e$ is the mass specific thrust power.

$$
\frac{1}{2} \alpha_c c_e \leq \alpha_{lim}
$$

Mass specific thrust power often limited (concerning power supply). Often desire of enhancement.

$\Rightarrow$ advanced propulsion with increased $\alpha_{lim}$, enhancement of EP thruster power
Power Increase for Electric Propulsion

Propellant containing chemical energy

Exothermal chemical reaction increases propellant enthalpy; thermal expansion

Thrust

Schematic of typical chemical thruster

Propellant, often inert

Ohmic heating and/or direct electro-static/ magnetic/ thermal acceleration

Thrust

Schematic of electric thruster

Motivation/Introduction
Self-field MPD Thrusters
Summary
Types of Electric Propulsion (EP)

Electrothermal Thrusters (Arcjets)
- Devices up to 100 kW were tested (TRL 6)
- High thrust levels with exhaust velocities up to 20 km/s
- Light atomic gases as propellant (He, H₂; alternative NH₃)
- Thrust efficiency depends on propellant 20-50%

Steady state Electromagnetic Thrusters (SF-/AF-MPDT)
- Scalable up to MW power range; lab devices up to 1 MW (TRL 4)
- Average thrust levels with ce between 10 and 70 km/s
- Various propellants can be used (H₂, He, Ar, Kr, Xe, Li)
- Comparable high thrust efficiency 20-60%

Electrostatic Thrusters (HET, GIT)
- Tested in space environment (TRL 9)
- Heavy atomic gases as propellant (Xe)
- GIT: Relative low thrust levels with exhaust velocities of 70-90 km/s and thrust efficiency 60-80%
- HET: average thrust levels with exhaust velocities of 20-50 km/s and thrust efficiency of 40-70%

Advanced Thrusters:
- RF inductive and Helicon
- Hybrid thrusters (TiHTUS, VASIMR)
- IEC, FRC, etc.
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Advanced Thrusters:
- RF inductive and Helicon
- Hybrid thrusters (TiHTUS, VASIMR)
- IEC, FRC, etc.
High power EP (50 kW up to MW)  
(Transport of large payloads)  
- thermal arcjet thrusters  
- Self-field MPD thrusters  
- Hybrid thruster TIHTUS

Low power EP (50W up to some 10kW)  
(Satellites and Exploration)  
- Thermal arcjet thrusters  
- PPT (iMPD)  
- Applied-field MPD thrusters

**Electric Propulsion at IRS:**  
Development of  
- Thrusters and  
- propulsion systems

**Motivation/Introduction**  
**Self-field MPD Thrusters**  
**Summary**
Electric Propulsion at IRS:
Development of
• Thrusters and
• propulsion systems

Secondary electric propulsion
• Electrolyzer
• 1 N catalytic thruster
• Green propellant
→ Small satellites

Mini PPT
• PETRUS
• Thermal PPT
• Reliable, robust, cheap, ...
→ CubeSat application

ABEP
• Intake verification
• Intake design
• Inductive thruster

IPG6-S
IPG6-S (air)

Motivation/Introduction
Self-field MPD Thrusters
Summary
PPT Mile Stones at IRS (Flanking Projects for CAPE)

magnetoplasmadynamic


BB/LM EM EQM

SIMP-0 SIMP-LEX ADD SIMP-LEX SIMP-LEX CLT SIMP-LEX GSM

SIMP-LEX CLT

PETRA

CubeSat-PET

Motivation/Introduction  Self-field MPD Thrusters  Summary
Low Power EP: ADD SIMP-LEX

- Pulsed Plasma Thruster (PPT)
- Propellant: PTFE
- Improved Electrode Design
- High Overall Efficiency
- Increased Lifetime
- Flexible Power Consumption

Thruster Characteristics:

- Capacity: 80 μF
- Bank Energy: < 68 J
- Pulse Frequency: < 2 Hz
- Impulse Bit: >1.5 mNs/pulse
- Exhaust Velocity: max. 30 km/s
- Thrust Efficiency: max. 31 %
iMPD & PPT - Facilities at IRS

Test Heritage for PPTs at IRS:
- Development Testing (Miniaturization, Compatibility, Thrust Modulation, etc.), Thrust pendulum (> 1μNs)
- Functional Verification Testing (Thruster, System Hardware, Coupling etc.)
- Performance Characterization (Thruster and Subsystem Parameters, Magnetic field, (Fast) Cameras)
- Confidence Life Testing (Full Scale and Accelerated)

Tank 16:
- **Performance**
- Ø 0.5 m, L: 1.6 m
- p ~ 10^{-5} hPa

Tank 17:
- **Intrusive probes**
- Ø 0.3 m, L: 1.0 m
- p ~ 10^{-6} hPa

Tank 18:
- **Conf. Life Time**
- Ø 0.4 m, L: 0.6 m
- p ~ 10^{-6} hPa

Tank 19:
- **Miniaturization**
- Ø 0.3 m, L: 0.5 m
- p ~ 10^{-6} hPa
Motivation for (steady state) MPD-Thrusters

- High thrust density and thrust efficiency
- High specific impulse
- Throttability (e.g. aging of solar cells)
- Propellant flexibility

Scenarios for high thrust missions:
- Manned / heavy cargo missions > 1.5 AU
- Space Tugs
- Un-manned scientific missions (e.g. Kuiper-Belt Objects)
- Manned / heavy cargo missions to Mars (100 N and 3000 s)

Concept in general: as SEP < 1 AU and as NEP > 1 AU

- ISRU e.g. Mars Atmosphere!
- H₂, N₂, NH₃, He, Ne, Ar, Kr, Xe, Li, Na, K.
- Pulsed Quasi steady state
- Steady state
- 20 – 50 %
- 20 – 50 km/s
- kW – MW

Prometheus nuclear electric Deep Space Vehicle, JIMO Mission Module, NASA.
Self-field MPD Thruster: Thrust Generation

Through:
- Thermal expansion
- Magnetic forces

\[ F = C \dot{m} \sqrt{\frac{T_0}{M}} + \frac{\mu_0}{4\pi} \left( \frac{3}{4} + \ln \frac{r_a}{r_c} \right) I^2 \]

**For high magnetic thrust:**
- Propellant should be fully ionized
- Magnetic forces \( \sim I^2 \)
  - high current levels necessary
  - low voltage levels are desired

**For high thermal thrust:**
- Light weight propellant
- Nozzle geometry

<table>
<thead>
<tr>
<th>Motivation/Introduction</th>
<th>Self-field MPD Thrusters</th>
<th>Summary</th>
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</table>
General Aspects: (Steady state) Arc Physics I

General issues (believe it, I can prove it, but there is not enough time):

- Major cathode effects
  - Field emission plays minor role
  - Thermal emission of electrons. Can be assessed via Richardson-Dushman-Equation (strongly dependent on $T_{\text{cathode}}$ and material’s work function $\Phi$)
    - motivation of high cathode temperatures (3000 K)
    - $\Phi \rightarrow$ cathode material! ($\rightarrow W+\text{ThO}_2$ due to very low $\Phi$ while having high $T_{\text{melt}}$)

Plasma column
- Quasi-neutral $\rightarrow$ electron current ($I_e >> I_{\text{ion}}$)

Electrode fall regions
- Space charges
- Voltage non-linear, high field strengths
- Some free mean paths (thickness)
- Production of charged particles to maintain ion and electron currents
General Aspects: (Steady state) Arc Physics II

Voltage-Current Characteristics of a steady state MPD Device:

Observations and Explanations
- Linear behavior $\rightarrow$ almost fully ionized condition
- Strong acceleration of propellant
- Increase of current leads to extension of current field in downstream direction
- At certain current level: Change of linear behavior $\rightarrow$ Onset phenomenon
- Increasing voltage-current history

Findings
- Voltage-current history as a measure for adequacy of MPD operation!
- Onset (diagram!): Lack of charged particles in anode fall region $\rightarrow$ Instability
General Aspects: (Steady state) Arc Physics III

Heating balance for cathode fall region and ion current assessment:

\[ \dot{q}_I = j_I \left[ \left( U_K + \frac{3}{2} kT_1 \right) a + E_1 - \varphi \right] \]

\[ j = \frac{4}{9} \varepsilon_o \sqrt{\frac{2e}{m}} \frac{U_o^{3/2}}{d^2} \]

Thought experiment:
- Assumption: \( I_e \) and \( I_{ion} \) result from movability \( \rightarrow \) neglection of \( I_{ion} \) \( \rightarrow \) Heat flux from impacting ions \( \ll \) electron work function energy \( \rightarrow \) cathode to cool down!
- Heat cathode \( \rightarrow \) not the case in reality!
- \( I_{ion} \) is significantly larger in cathode fall region
- But: Space charge limitation for \( I_{ion} \)

Findings
- Cathode fall region is location of significant ion production. Energy: axial heat conduction, Ohm heating, energy from ions reflected at cathode surface
- Space charge limitation. Nitrogen (MPD) arc \( j_{ion} \approx O(10^3 \text{ kA/m}^2) \)
Erosion behavior (mass loss to be as low as possible due to lifetime):

### Findings

- Erosion dependent on $T_{\text{cathode}}$ as a lack of electrons produces spots to compensate this via “material”
- Cold cathode vs hot cathode $\rightarrow$ decrease of voltage

### Cathode erosion:

- Cold cathodes: Pulsed devices (PPT) and ignition of steady state devices
- Hot cathode: diffuse arc attachment
- Heat cathode $\rightarrow$ not the case in reality!
- Mind: convective cooling at high propellant mass flow rates, small traces of oxygen destroy cathode

**Erosion rate**

$$\text{Erosion rate} = \frac{\text{Mass loss}}{\text{Charge flux in same period}}$$

charge $= \text{current} \times \text{operation time}$
General Aspects: (Steady state) Arc Physics V

Erosion behavior (mass loss to be as low as possible due to lifetime):

- Findings
  - Steady state SF-MPD DT2: 3 orders of magnitude lower erosion rate
  - (thermal arcjet: 1-2 orders of magnitude)

<table>
<thead>
<tr>
<th>Propellant</th>
<th>IX12-IRS</th>
<th>TT30-IRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>6.77</td>
<td>0.026</td>
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<tr>
<td>N₂</td>
<td>5.38</td>
<td>0.072</td>
</tr>
<tr>
<td>H₂</td>
<td>15.3</td>
<td>0.032</td>
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<tr>
<td>N₂+2H₂</td>
<td>0.32</td>
<td>0.06</td>
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</table>

<table>
<thead>
<tr>
<th>Propellant</th>
<th>DT12-IRS</th>
<th>TT30-IRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>1.5</td>
<td>1.7</td>
</tr>
<tr>
<td>N₂</td>
<td>0.5</td>
<td>6.3</td>
</tr>
<tr>
<td>H₂</td>
<td>2.2</td>
<td>0.6</td>
</tr>
<tr>
<td>N₂+2H₂</td>
<td></td>
<td>1.3</td>
</tr>
</tbody>
</table>
General Aspects: (Steady state) Arc Physics VI

Erosion behavior compared with sublimation rate:

Findings: IRS SF MPD have cathode erosion rates in order of sublimation rate

Steady state self-field MPD Thrusters:
- $10^7$ A/m², $T_{\text{cathode}} = 3000K$
- 1 ng/C

- Side story: Thermal Arcjets
  - Higher pressures
  - Higher current densities at arc attachment
  - Higher wall temperatures

Motivation/Introduction  Self-field MPD Thrusters  Summary
General Aspects: (Steady state) Arc Physics VII

Anode fall region:

Production of ions via electron collision:
- To maintain quasi-neutrality in plasma column → leads to increase of anode fall region voltage
- Other possibility: Production of ions via hot spots on anode
  - Leads to severe anode erosion and respective damage
  - Must be prevented via diffuse arc

Findings:
- Diffusive arc zone limits pressure regime of MPD devices
Investigation of **cylindrical thrusters** (ZT) and **nozzle type** thrusters (with water-cooled (DT, CAT) and radiation-cooled (HAT) anode),

Power up to 550 kW, current up to 15 kA, thrust up to 27 N and efficiency up to 27% with argon as propellant.
Steady State SF MPD thrusters

Motivation/Introduction
Self-field MPD Thrusters
Summary
Steady State self-field MPD thrusters

- Thrust values up to 15 N
- No instabilities up to 15 kA at 0.8 g/s (Argon)
- Electrical power up to 350 kW
SF-MPD Nozzle-Type Thrusters (DT) – at IRS

Laboratory devices:

- Anode and segments water-cooled and made from Copper
- Power level: several 100 kW up to 1 MW
- Designs differ in cathode and nozzle throat diameter
- Operated with Argon, Nitrogen and Hydrogen
Operated up to 25 N at 8000 A with Argon

Plasma instabilities limitation at ca. 15 km/s with Ar, H₂ and N₂
SF-MPD Nozzle-Type Thrusters (DT) – Performance Data

DT6: thrust efficiency vs. exhaust velocity

DT2: thrust efficiency vs. exhaust velocity
Summary Part 1

- **PPT**
  - Secondary propulsion
  - Primary cubesat propulsion
  - Optimization can lead to significant thrust efficiencies leading to an efficient low cost system that benefits from robustness and simplicity

- **Steady state self-field MPD Thrusters**
  - High power devices aiming at heavy cargo missions in general
  - Orbital space tugs: Thrust density saves time and mitigates regular transitions e.g. through the Van-Allen Belt
  - Adequate electrode design mandatory (also applies to AF-MPD Thrusters)
### Plasma Diagnostics

<table>
<thead>
<tr>
<th>Probe-type</th>
<th>Value measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Flux Probe</td>
<td>heat flux</td>
</tr>
<tr>
<td>Pitot Probe</td>
<td>total pressure</td>
</tr>
<tr>
<td>Mass Spectrometer Probe</td>
<td>plasma composition</td>
</tr>
<tr>
<td>Wedge Type and Conical Probe</td>
<td>static pressure, Mach number</td>
</tr>
<tr>
<td>Enthalpy Probe</td>
<td>enthalpy</td>
</tr>
<tr>
<td>Electrostatic Probes</td>
<td>$T_e, T_i, v, n_e, \ldots$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Method</th>
<th>Measured quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission Spectroscopy (EMS)</td>
<td>$T_{ex}, T_{rot}, T_{vib}, T_e, n_e, (n_{Plasma} ?)$</td>
</tr>
<tr>
<td>Laser-Induced Fluorescence (LIF)</td>
<td>$T_{rot}, (T_{vib}), T_e, n_e, n_{Plasma}, v_{Plasma}$</td>
</tr>
<tr>
<td>Thompson Scattering</td>
<td>$n_e, T_e$</td>
</tr>
<tr>
<td>Fabry-Perot Interferometry (FPI)</td>
<td>$T_{Trans}, v_{Plasma}$</td>
</tr>
<tr>
<td>Laser Absorption Spectroscopy (LAS)</td>
<td>$n_{Plasma}, T_{Trans}, v_{Plasma}$</td>
</tr>
</tbody>
</table>
Under Development…New Diagnostics and Facilities

- **Measurement techniques:**
  - Refurbishment of electrostatic probe set-up (in use)
  - Multi-pressure port probe (set in operation)
  - Mechanical material sample holder with cooling (first preliminary tests)
  - Mach-Zender-Interferometer
  - Compact LAS-system (B/L assessment)

- **Facilities:**
  - Compact Light Gas Gun (<50 cm, readily developed, being manufactured); later in combination with ICP
Optical Diagnostics
Emission Spectroscopy, LIF, DLAS, FPI

Air Plasma

CO₂ Plasma

Laser-induced fluorescence

Optical Diagnostics at IRS means
Mobile non-intrusive diagnostic setups

→ species temperatures number densities velocities
## Overview of available codes at IRS

<table>
<thead>
<tr>
<th>URANUS</th>
<th>SAMSA</th>
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<th>PICLas</th>
<th>LasVegas</th>
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<tr>
<td>Navier-Stokes</td>
<td></td>
<td></td>
<td>Particle Method / Boltzmann Equation</td>
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<tr>
<td>continuum flow, thermal and chemical non-equilibrium</td>
<td></td>
<td>rarefied plasmas, strong non-equil.</td>
<td>Rarefied gases, strong non-equil.</td>
<td></td>
</tr>
<tr>
<td>re-entry</td>
<td>MPD</td>
<td>TLT, IPG, PWK</td>
<td>PPT, Ion thruster,…</td>
<td>Re-entry</td>
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<td>2D rotational symm. / 3D</td>
<td>2D rotational symmetric</td>
<td>3D (rotational symmetric)</td>
<td>3D</td>
<td>2D rotational symmetric</td>
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<tr>
<td>fully implicit</td>
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<td></td>
<td>explicit</td>
<td></td>
</tr>
<tr>
<td>fully coupled</td>
<td>unstructured, adaptive grids</td>
<td>structured multiblock grids</td>
<td>Unstructured grids</td>
<td>unstructured, adaptive grids</td>
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<tr>
<td>structured multiblock grids</td>
<td>Air, CO₂</td>
<td>Argon</td>
<td>Air, N₂, H₂, CO₂</td>
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<td>PARADE/HERTA gas-radiation coupling</td>
<td>Herbert</td>
<td>HERTA gas-radiation coupling</td>
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<tr>
<td>Gas kinetic gas-surface interaction model with catalytic reaction schemes. CVCV mult. temperature gas-phase model</td>
<td>changeable chemical modules</td>
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![Numerical simulation of gas flow](image1.png)

![Theoretical model of plasma interaction](image2.png)
CubeSat Atmospheric Probe for Education (CAPE)

1. Deployment
e.g. from ISS

2. De-orbit
- De-orbit down to separation altitude
- Atmospheric measurements
- PPT demonstration

3. Separation
of SDM and MIRKA2 at approx. 158 km altitude

4. Re-entry of MIRKA2
Measurement of the ambient conditions and the re-entry performance of the capsule

5. Transfer of re-entry data via satellite
Transmission of data through Iridium communication system

6. Demise of SDM, impact of MIRKA2
Potential for monitoring of break-up and demise
CAPE Vehicle Configuration

Service and Deorbit Module SDM (3 CubeSat units):
- Performs deorbit manoeuvre using PPT
- Demises upon re-entry
- Scientific payload: e.g. FIPEX, dust sensors
- Potential standard carrier for future CubeSat science missions

MIRKA2 re-entry capsule (1 CubeSat unit):
- Uses ZURAM-based ablative TPS
- Scientific payloads: e.g. Thermocouples, radiometer, pressure transducers, etc.
- Potential standard for flight qualification of heat shield materials
Trajectory Analysis

- Mission analysis performed with IRS in-house code REENT
- Starting orbit: ISS
  - 400 km altitude
  - 51.56° inclination
- Downward spiralling manoeuvre
- Propulsion system: Pulsed Plasma Thruster (PPT):
  - 93 µN at 5.8 W (continuous)
  - 48 µN at 3.0 W (continuous operation with extra contingency for payloads)
- De-orbit:
  - Min.: 56 days
  - Max.: 176 days
Technology Demonstration: Micro Return Capsule

- CubeSat-compatible size
- Small size allows for ground-based testing of entire vehicle, e.g. in plasma wind tunnel
- Basic measurements of:
  - flight behaviour
  - re-entry environment
  - thermal protection system (TPS) performance
- Transmission of data via Iridium network after black-out phase

- Separation via LOTUS (Low Orbit Technical Unit Separator) spring-powered ejection mechanism
- High-performance ablutor materials ZURAM considered as candidates for TPS
  → Flight qualification
Scientific Application: Atmospheric Characterisation

Two optional on-board scientific experiments are under investigation. The gradual downward spiralling manoeuvre provides ideal conditions for a spatial characterisation of the lower thermosphere.

**FIPEX**
- In-situ measurement of atomic oxygen concentrations in lower thermosphere
- Successfully flown on ISS

**Piezo Dust Detectors**
- In-situ measurement of impact velocity and incidence angle of µm- to mm-sized dust particles
- Relies on piezoelectric effect

(DLR)
Potential Applications of CAPE

Technological / economical
- Cost-effective potential standard for
  - Flight qualification of thermal protection system materials
  - Nanosatellite servicing
- Conceivably controlled capture and deorbit of space debris and meteoroids using SDM

Scientific
- Standardised platform for spatially and temporally resolved atmospheric measurements in general.
- Quantitative data of contamination of atmospheric gas sensor measurements through electric thruster exhaust.
- Micro return capsule data provides valuable reference scenario with direct application to ground testing facilities.
- Potential for tracking of atmospheric break-up and demise of SDM
Space Travel – a Definition

- Generally all anthropogenic activities in space:
  - Launch (to access space) ✓
  - Operation of diverse objects in vicinity to Earth ✓
  - Missions near Earth, but outside its gravitation regime ✓/✗
  - Travel within our solar system ✓/✗
  - Interstellar flight ✗
Space Travel – a Resumé

- **Balance:**
  - Space travel mostly in regime near Earth.
  - Most missions are un-manned.

- **Examples:**
  - Ballistic launchers, satellites, probes
  - Manned launchers, space stations, moon landers

- **Propulsion characteristics:**
  - Launch with chemical high thrust systems, energy limited \(\rightarrow\) limited effective exhaust velocities \(c_e\).
  - Either impulsive orbit manoeuvres applying low \(c_e\) or un-/pulsed low thrust spiralling applying high \(c_e\) systems.
Function of iMPD and PET

iMPD

- Discharge ablates PTFE
- MHD-based acceleration
  ⇒ **Thrust:** µN - mN

PET

- Discharge ablates PTFE
- Gas dynamic acceleration
  ⇒ **Thrust:** nN - µN
Thruster System Design Strategy

Motivation/Introduction

Self-field MPD Thrusters

Summary
ADD SIMP-LEX for Satellite Missions

- Main Propulsion System for Lunar Mission BW1
- Secondary: Attitude and Orbit Control
- Cluster of Thrusters for required $\Delta v$ of 5km/s
- Award-Winning Propellant Feed Concept

- Investigation of ADD SIMP-LEX at IRS and UoT:
  - Thrust Balance + Mass Balance
  - Electrostatic Probes
  - Inductive Magnetic Field Probes
  - High-Speed Camera
  - Voltage and Current Monitors

- Further Research Topics (Cooperation with UoT):
  - Further Lifetime Investigation
  - Plasma Diagnostics
  - Successful System Approach (with ASP GmbH)
SF-MPD Nozzle-Type Thrusters (DT) – Plasma Instabilities

Scaling of Nozzle Equipped steady state SF MPD (Schmidt)

- Hydrogen data are significantly lower in power ($I_{\text{max}} = 1.35 \text{kA}$)
- Argon data as shown here
## ADD SIMP-LEX GSM (TRL = 7)

**Test of total system in DLR STG Facility (incl. PPU)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Capacitor Dry Mass</td>
<td>kg</td>
<td>&lt; 6</td>
</tr>
<tr>
<td>Max. Pulse Energy</td>
<td>J</td>
<td>67.6</td>
</tr>
<tr>
<td>Electrode gap (HxW)</td>
<td>mm</td>
<td>21 x 20</td>
</tr>
<tr>
<td>Propellant</td>
<td>-</td>
<td>Solid PTFE</td>
</tr>
<tr>
<td>Mechanical Feeding Type</td>
<td>-</td>
<td>Side-fed</td>
</tr>
<tr>
<td>Total Capacitance</td>
<td>µF</td>
<td>80 (4 x 20)</td>
</tr>
<tr>
<td>Capacitor Type</td>
<td>-</td>
<td>Wound Mica Foil</td>
</tr>
<tr>
<td>Capacitor Voltage</td>
<td>V</td>
<td>1300</td>
</tr>
<tr>
<td>Igniter Insulation Material</td>
<td>-</td>
<td>Al$_2$O$_3$</td>
</tr>
<tr>
<td>Igniter Voltage Capability</td>
<td>kV</td>
<td>Up to 20</td>
</tr>
<tr>
<td>iMPD Power Consumption</td>
<td>W</td>
<td>&lt; 85</td>
</tr>
<tr>
<td>Impulse per Pulse</td>
<td>µNs</td>
<td>1.5</td>
</tr>
<tr>
<td>Specific Impulse</td>
<td>s</td>
<td>&lt; 2650</td>
</tr>
<tr>
<td>Mass per Pulse</td>
<td>µg</td>
<td>60</td>
</tr>
<tr>
<td>Thrust Efficiency</td>
<td>%</td>
<td>~ 30</td>
</tr>
<tr>
<td>Demonstrated Pulse Life</td>
<td>-</td>
<td>2 Mio.</td>
</tr>
<tr>
<td>Demonstrated Total Impulse</td>
<td>Ns</td>
<td>3000</td>
</tr>
</tbody>
</table>

### Motivation/Introduction

**Self-field MPD Thrusters**

<table>
<thead>
<tr>
<th>Summary</th>
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</thead>
</table>
Electric Propulsion for interplanetary missions and orbit transfers

![Diagram showing electric propulsion for different missions.](image)

**Antriebsvermögen Δv [km/s]**

**Hüllkurve chemisch Raketen**

**1te Stufe chemisch**

**2te Stufe chemisch**

**3te Stufe chemisch**

**3te Stufe elektrisch**

**Struktur Nutzlast**

**Antrieb Wandler Energieversorg. Treibstoff**

\[ m_0 = m_{LS} + m_W + m_T \]

\[ 1 = \mu_{LS} + \mu_W + \mu_T \]

Raketengleichung für Einstufer:

\[ \Delta v = c_e \ln \left(1 - \mu_T\right) \]

Annahme: \( \mu_{LS} >> \mu_W \) \( \mu_{LS} + \mu_W \)

**Startmasse**

**Hüllkurve**

**Antriebsverhältnis µLS**

**P/L ratio depending on Dv using chemical and electrical upper stage**

Motivation/Introduction

Self-field MPD Thrusters

Summary
Operational Satellites with Electric Propulsion

Motivation/Introduction

Self-field MPD Thrusters

Summary

Cumulative Number of Satellites Employing EP = 226
Number of Satellites Employing Aerojet EP = 156