# 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

Δv based on trajectory analysis (e.g. spiraling, continuous transfers, …)

*Mission:*
**Δv**
(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 *Δv* – based on orbit mechanics.
- But: Consideration of *propulsion capabilty* as *Δv* (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 $\Delta v$

$$\Delta v = \int_{\Delta t_b} a_c \, dt$$

Kinematics:
Relating $a_c$ and burn time

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

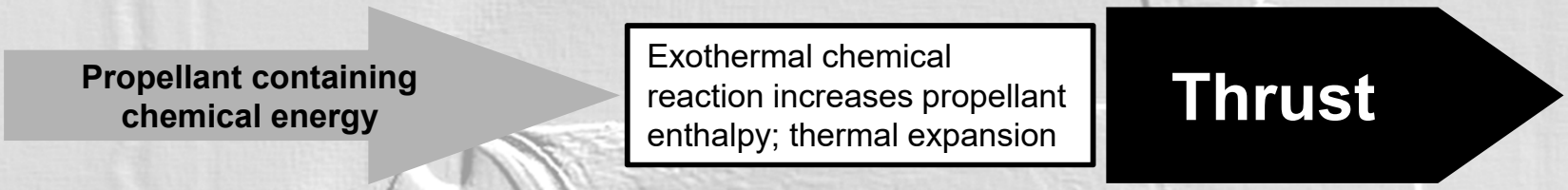
Tsiolkovsky's equation:
Relating $c_e$ and dry mass

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

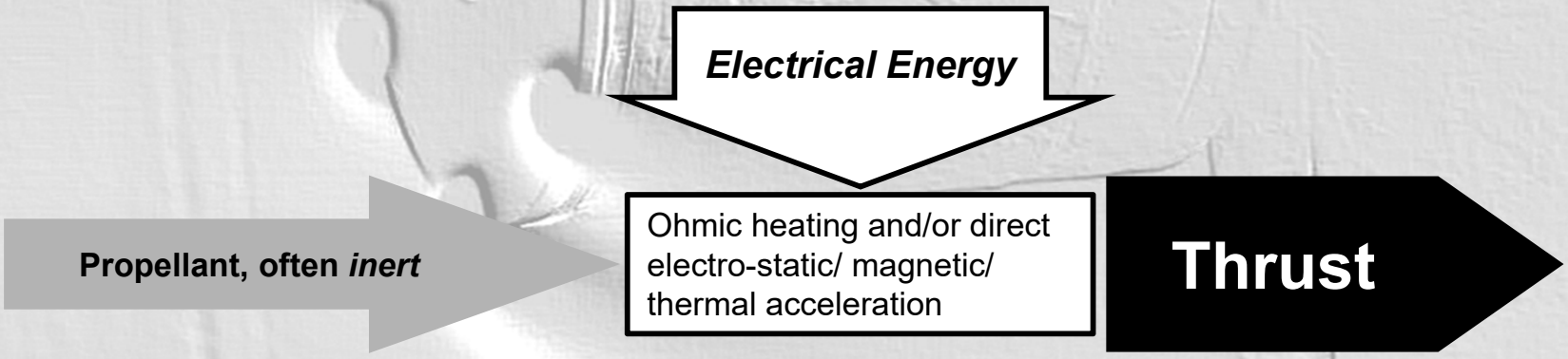
$$\frac{1}{2} a_c c_e \leq \alpha_{lim}$$

*Mass specific thrust power often limited (concerning power supply). Often desire of enhancement.*
*→ advanced propulsion with increased $\alpha_{lim}$, enhancement of EP thruster power*

# Power Increase for Electric Propulsion




*Schematic of typical chemical thruster*



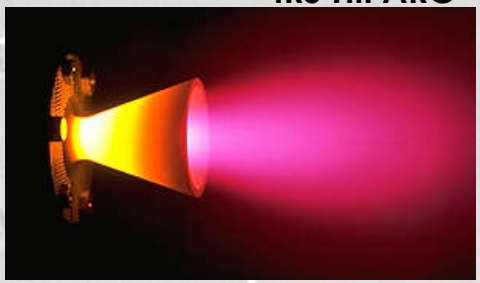

*Schematic of electric thruster*

# 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, $H_2$; alternative $NH_3$)
- Thrust efficiency depends on propellant 20-50%

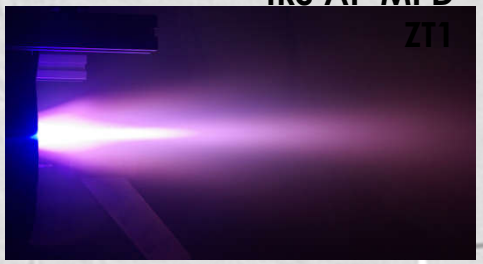
IRS HiPARC



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 ($H_2$, He, Ar, Kr, Xe, Li)
- Comparable high thrust efficiency 20-60%

IRS AF-MPD




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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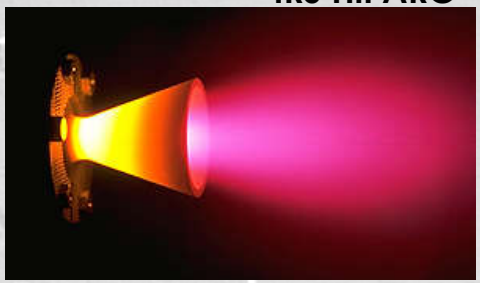

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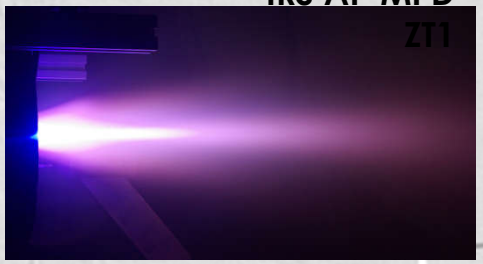


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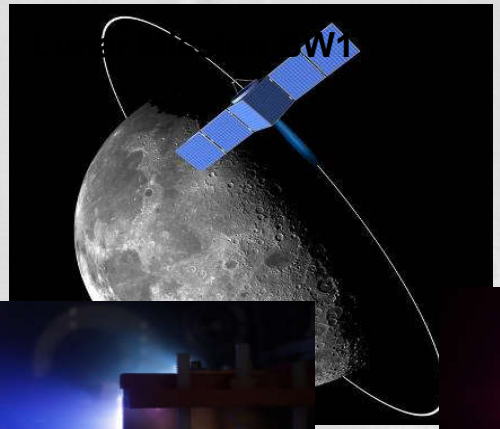
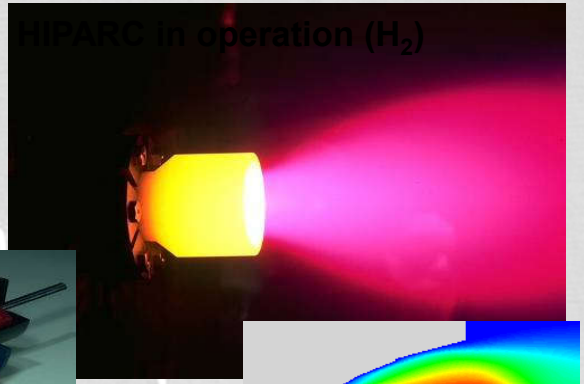
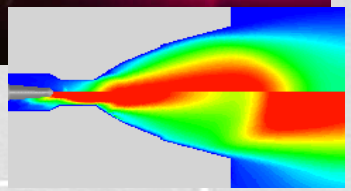
# Electric Propulsion at IRS:

**Development of**
- **Thrusters and**
- **propulsion systems**



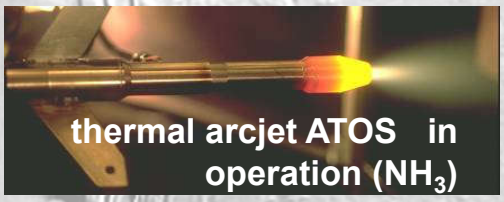


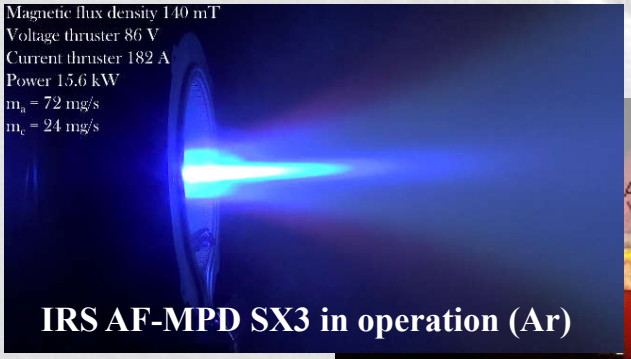



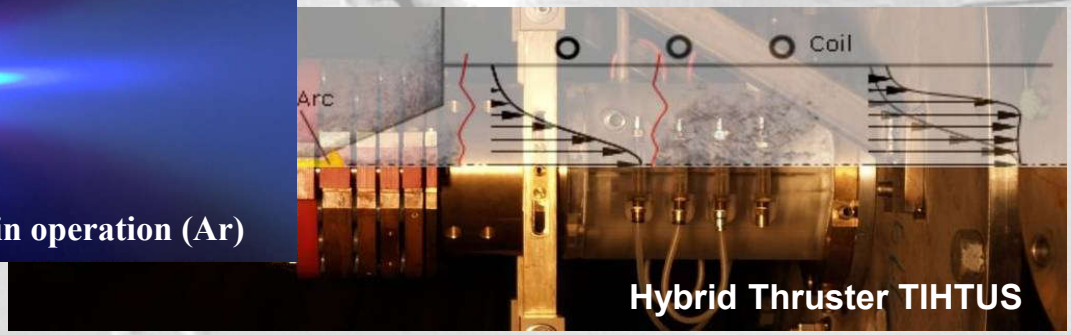



## Low power EP (50W up to some 10kW) (Satellites and Exploration)

- Thermal arcjet thrusters
- PPT (iMPD)
- Applied-field MPD thrusters

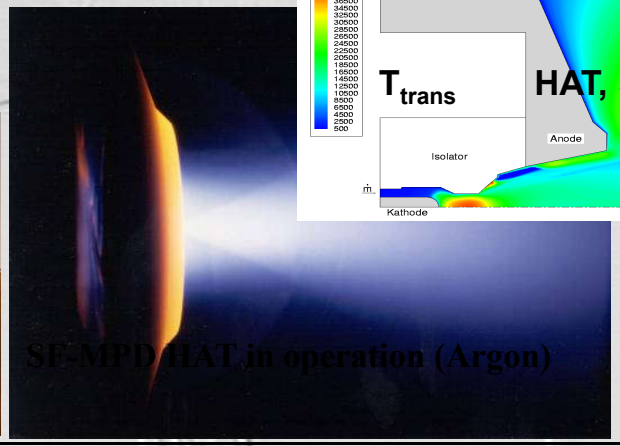


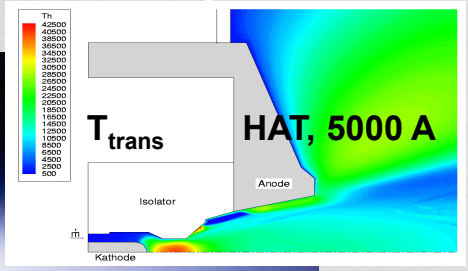




## High power EP (50 kW up to MW) (Transport of large payloads)

- thermal arcjet thrusters
- Self-field MPD thrusters
- Hybrid thruster TIHTUS

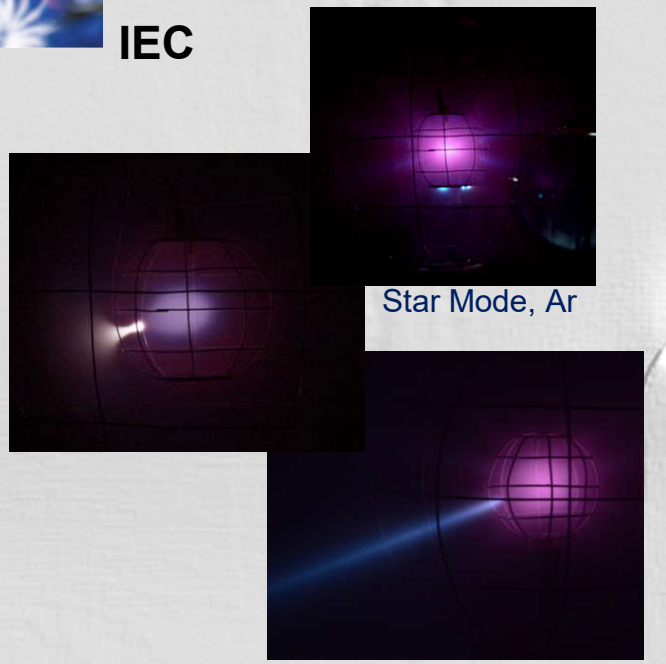


# Electric Propulsion at IRS:

**Development of**
- **Thrusters and**
- **propulsion systems**

## IEC



Star Mode, Ar

"Tight" Jet Mode, He

## Secondary electric propulsion

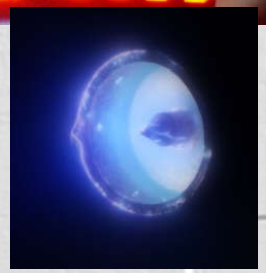
- Electrolyzer
- 1 N catalytic thruster
- Green propellant

→ Small satellites


## Mini PPT

- PETRUS
- Thermal PPT
- Reliable, robust, cheap, …

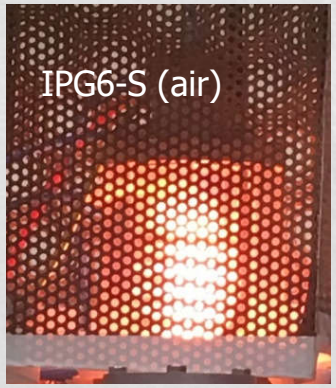
→ CubeSat application

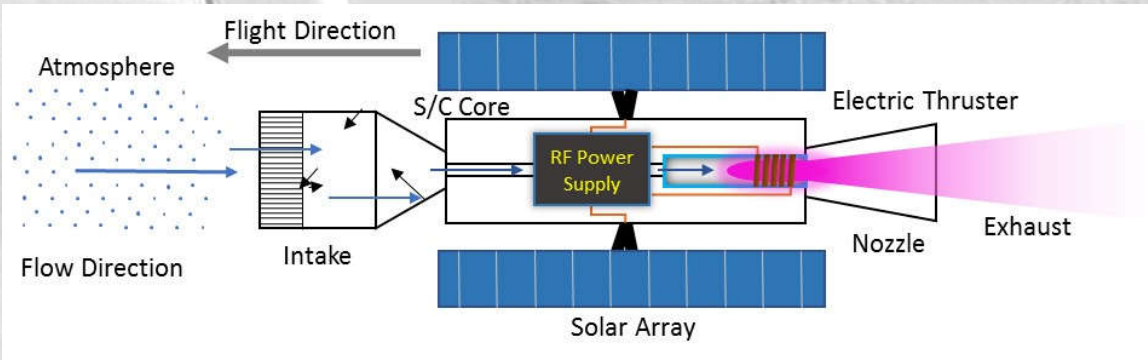


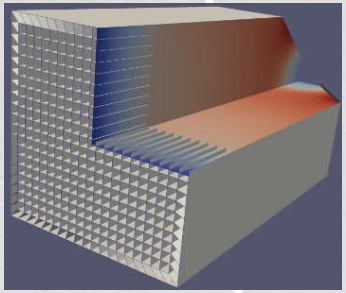
## ABEP

- Intake verification
- Intake design
- Inductive thruster

## IPG6-S

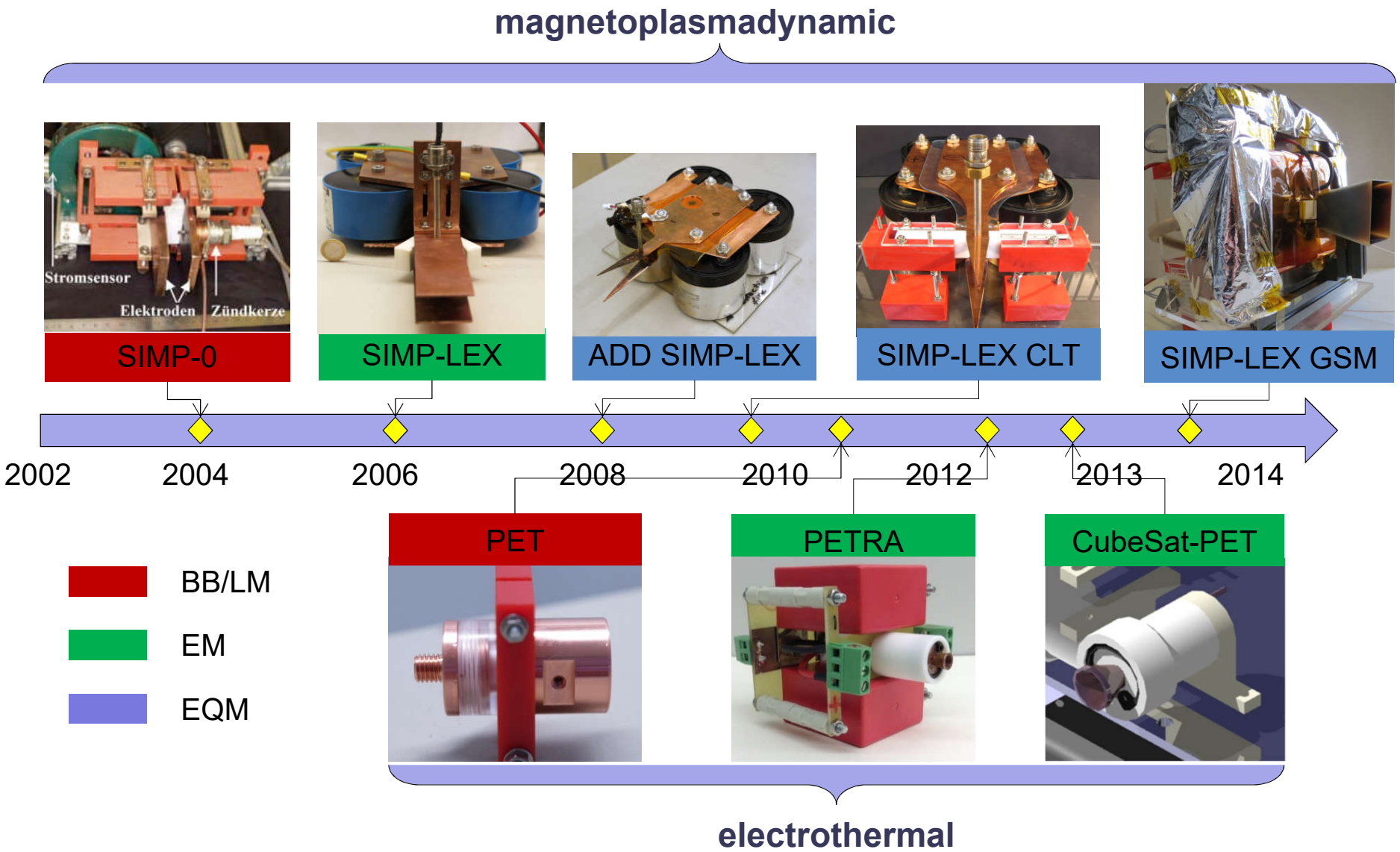


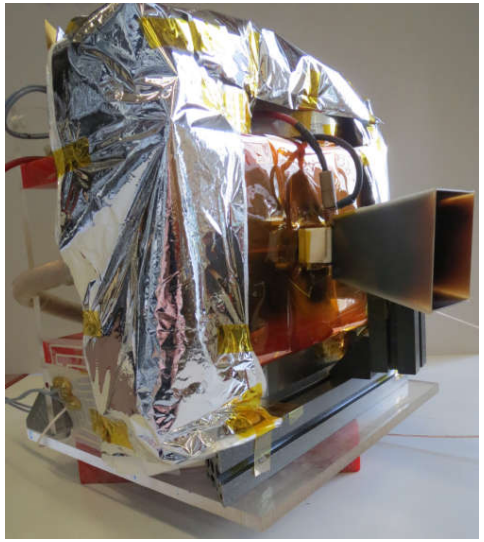



DSMC simulation of adapted intake geometry

# PPT Mile Stones at IRS (Flanking Projects for CAPE)

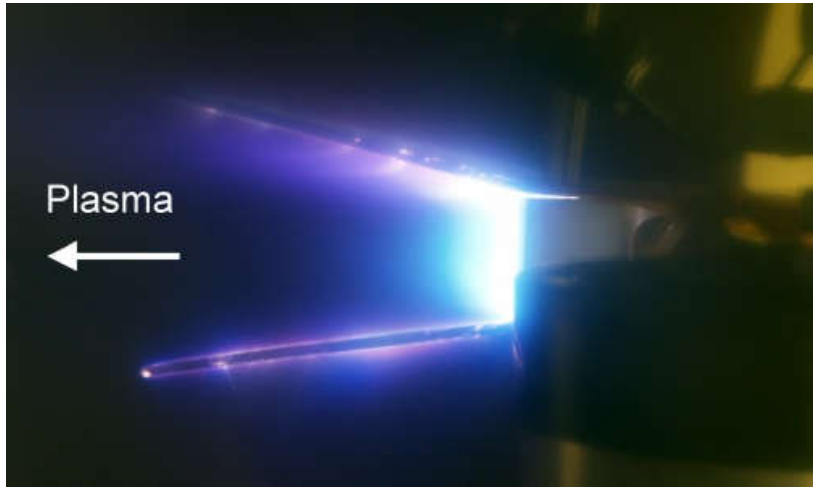


# Low Power EP: ADD SIMP-LEX



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

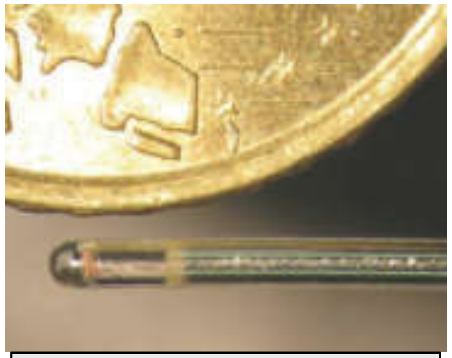
- **Thruster Characteristics:**
  - **Capacity:** 80 µF
  - **Bank Energy:** < 68 J
  - **Pulse Frequency:** < 2 Hz
  - **Impulse Bit:** >1.5 mNs/pulse
  - **Exhaust Velocity :** max. 30 km/s
  - **Thrust Efficiency:** max. 31 %



# 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)



Inductive Probe vs 10 cent


Tank 16:

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

Tank 19:

- **Miniaturization**
- Ø 0.3 m, L: 0.5 m
- p ~ $10^{-6}$ 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

# Motivation for (steady state) MPD-Thrusters

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

ISRU e.g. Mars Atmosphere !

**20 – 50 %**
**20 – 50 km/s**
**kW – MW**

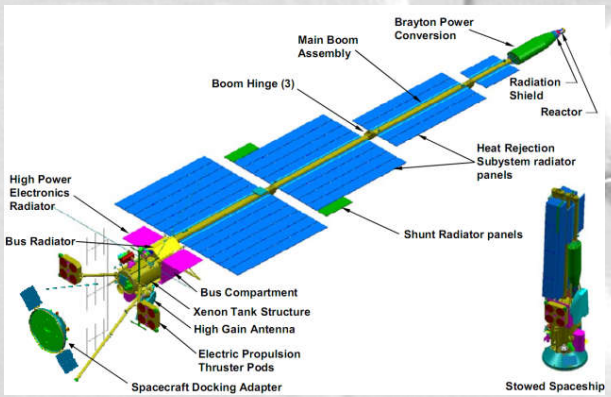
**Pulsed**
**Quasi steady state**
**Steady state**

**$H_2$, $N_2$, $NH_3$,**
**He, Ne, Ar, Kr, Xe,**
**Li, Na, K.**

Scenarios for high thrust missions:

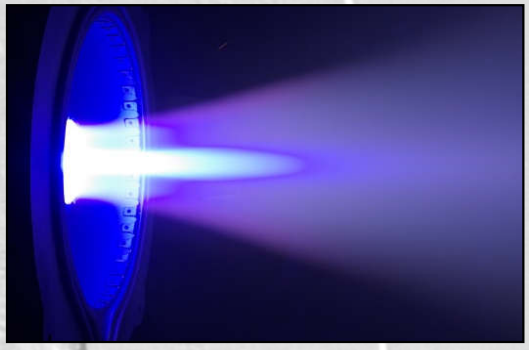
- ⇨ Manned / heavy cargo missions > 1,5 AU
- ⇨ Space Tugs
- ⇨ Un-manned scientific missions (e.g. Kuiper-Belt Objects)
- ⇨ Manned / heavy cargo missions to Mars (100 N and 3000 s)

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




Prometheus nuclear electric Deep Space Vehicle, JIMO Mission Module, NASA.

SF MPDT DT6 / IRS

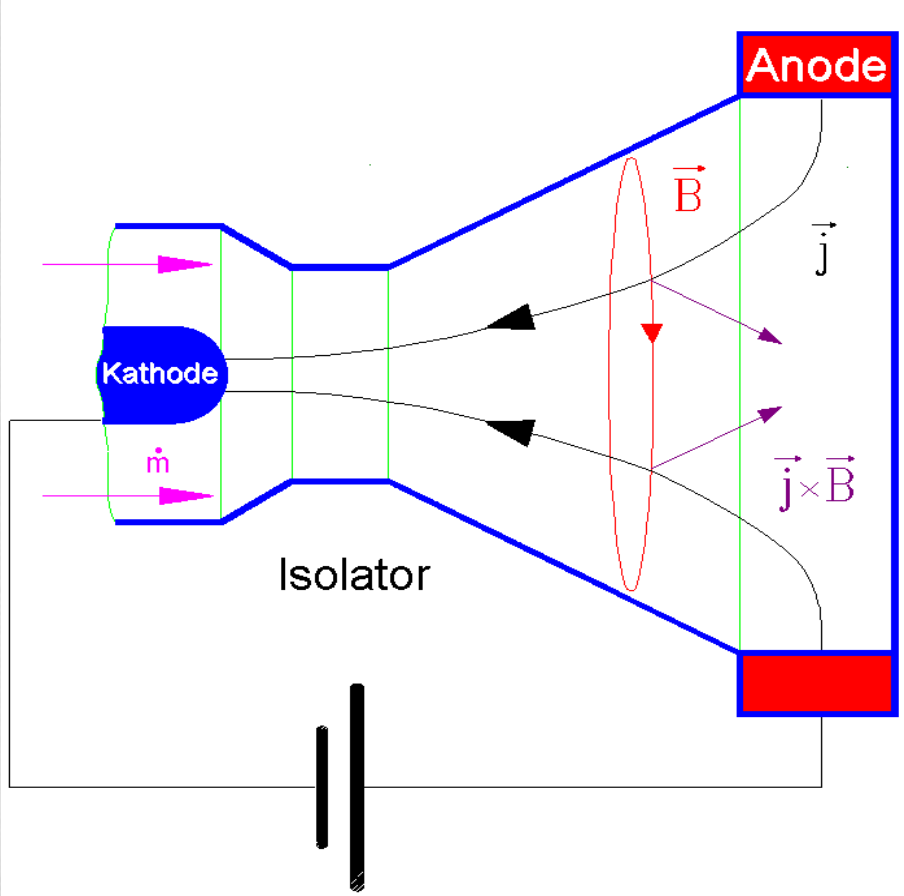


AF MPDT SX3 / IRS

# Self-field MPD Thruster: Thrust Generation

**through:**

- Thermal expansion
- Magnetic forces




$$F = C_1 \dot{m}\sqrt{\frac{T_0}{M}} + \frac{\mu_0}{4\pi}\left(\frac{3}{4} + \ln\frac{r_a}{r_c}\right) I^2$$

thermal magnetic

**For high magnetic thrust:**

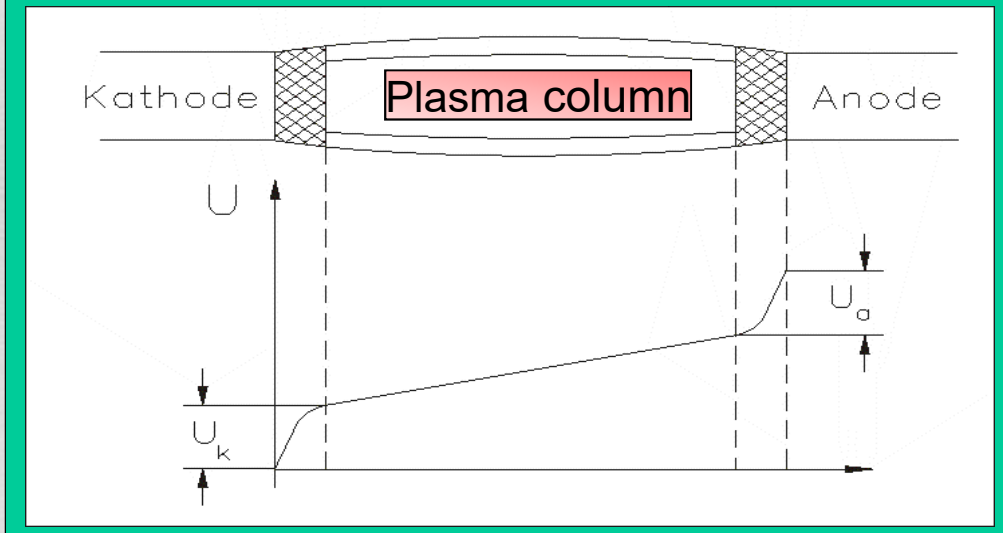
- Propellant should be fully ionized
- Magnetic forces ~ $I^2$
  - → high current levels necessary
  - → low voltage levels are desired

**For high thermal thrust:**

- Light weight propellant
- Nozzle geometry

# General Aspects: (Steady state) Arc Physics I

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




Plasma column

- Quasi-neutral → electron current ($I_e >> I_{ion}$)

Electrode fall regions

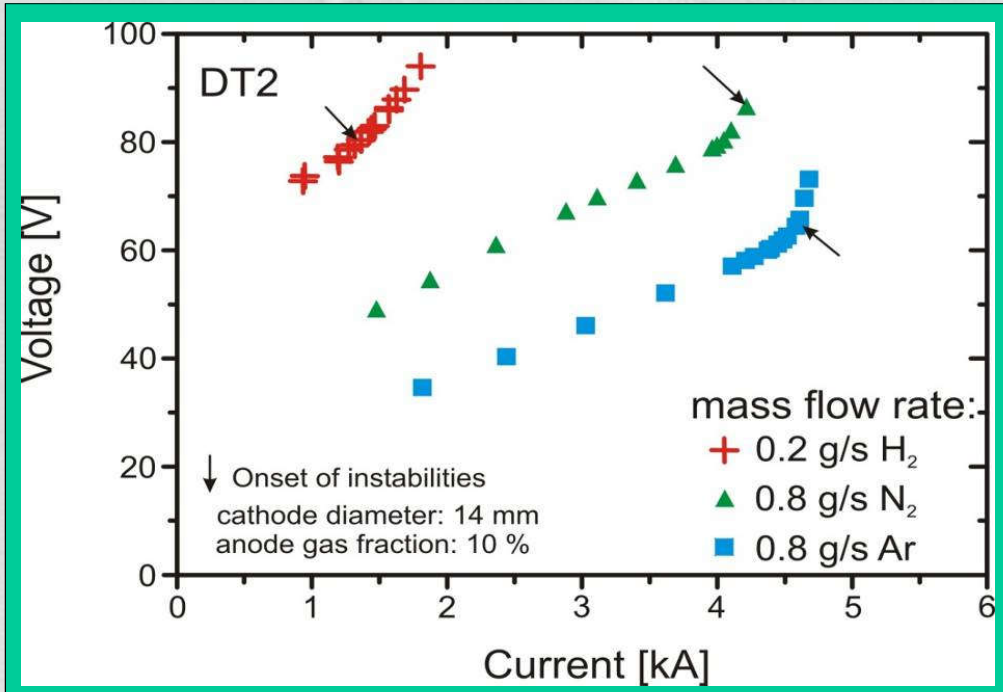
- Space charges
- Voltage non-linear, high field strengths
- Some free mean paths (thickness)
- Production of charged particles to maintain ion and electron currents

➢ Major cathode effects

- Field emission plays minor role
- Thermal emission of electrons. Can be assessed via Richardson-Dushman-Equation (strongly dependent on $T_{cathode}$ and material's work function $\Phi$)
  - motivation of high cathode temperatures (3000 K)
  - $\Phi$ → cathode material! (→ W+$ThO_2$ due to very low $\Phi$ while having high $T_{melt}$)

# General Aspects: (Steady state) Arc Physics II

Voltage-Current Characteristics of a steady state MPD Device:




Observations and Explanations

- Linear behavior → 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 → 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 → Instability

# General Aspects: (Steady state) Arc Physics III

Heating balance for cathode fall region and ion current assessment:

$$\dot{q}_I = j_I \left[ \left( U_K + \frac{3}{2} k T_I \right) a + E_I - \varphi \right]$$

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

Thought experiment:

- Assumption: $I_e$ and $I_{ion}$ result from movability → neglection of $I_{ion}$ → Heat flux from impacting ions << electron work function energy → cathode to cool down!
- Heat cathode → 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 $j_{ion} \approx O(10^3\ kA/m^2)$

# General Aspects: (Steady state) Arc Physics IV

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

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

charge = current x operation time

Cathode erosion:

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

➢ Findings

- Erosion dependent on $T_{cathode}$ as a lack of electrons produces spots to compensate this via "material"
- Cold cathode vs hot cathode → decrease of voltage

# General Aspects: (Steady state) Arc Physics V

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

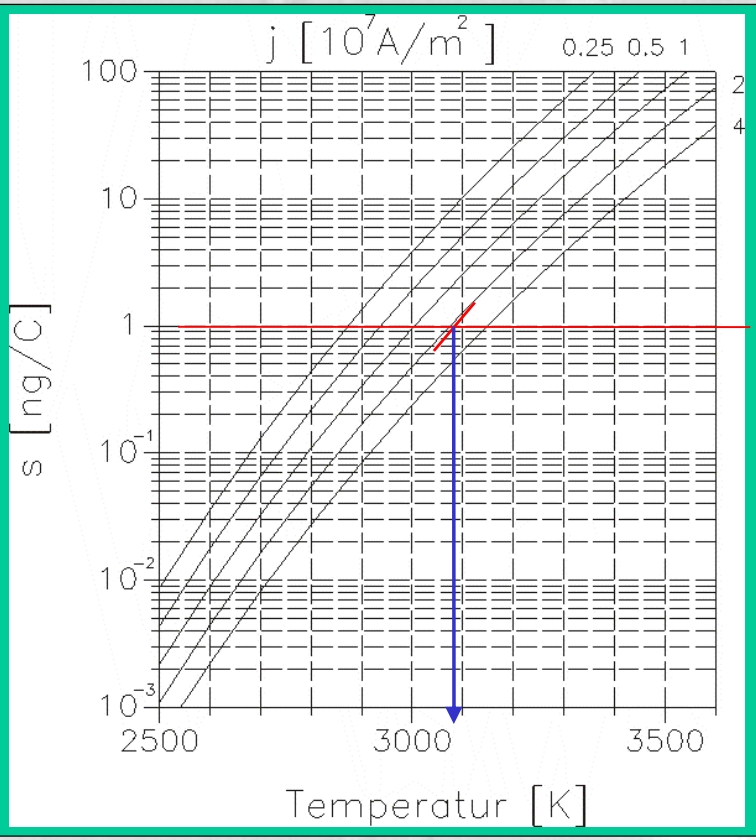
| Ignition Erosion Rate (cold cathode) | | |
|---|---|---|
| | *DT2-IRS* | |
| Propellant | [mg] | µg/C |
| Ar | 6,77 | 6,32 |
| $N_2$ | 5,38 | 5,90 |
| $H_2$ | 15,3 | 24,5 |
| | *TT30-IRS* | |
| | [mg] | ng/C |
| Ar | 0,026 | 21,5 |
| $N_2$ | 0,072 | 103,0 |
| $N_2+2H_2$ | 0,032 | 36,0 |

| Erosion Rate in steady state operation | |
|---|---|
| | *DT2-IRS* |
| Propellant | [ng/C] |
| Ar | 1,5 |
| $N_2$ | 0,5 |
| $H_2$ | 2,2 |
| | *TT30-IRS* |
| | [ng/C] |
| Ar | 1,7 |
| $N_2$ | 6,3 |
| $H_2$ | 0,6 |
| $N_2+2H_2$ | 1,3 |

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

# General Aspects: (Steady state) Arc Physics VI

Erosion behavior compared with sublimation rate:




Steady state self-field MPD Thrusters:

- $10^7$ A/m², $T_{cathode}$=3000K
- 1 ng/C

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

➢ <u>Findings:</u> IRS SF MPD have cathode erosion rates in order of sublimation rate

# General Aspects: (Steady state) Arc Physics VII

Anode fall region:

$$\dot{Q}_A = U_A I + \left(\frac{5}{2}\frac{k}{e}T_e + \Phi\right) I + \dot{Q}_{konv+Str}$$

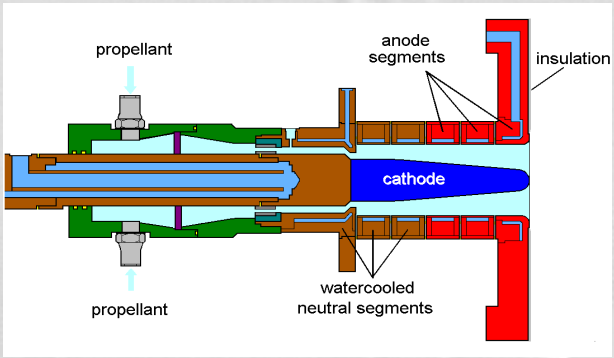
Production of ions via electron collission

- 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

➢ <u>Findings:</u>

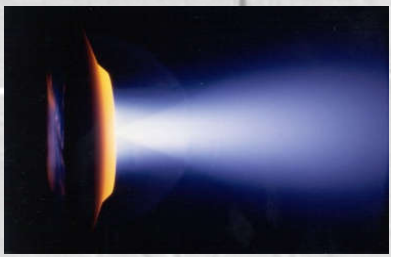
- Diffusive arc zone limits pressure regime of MPD devices

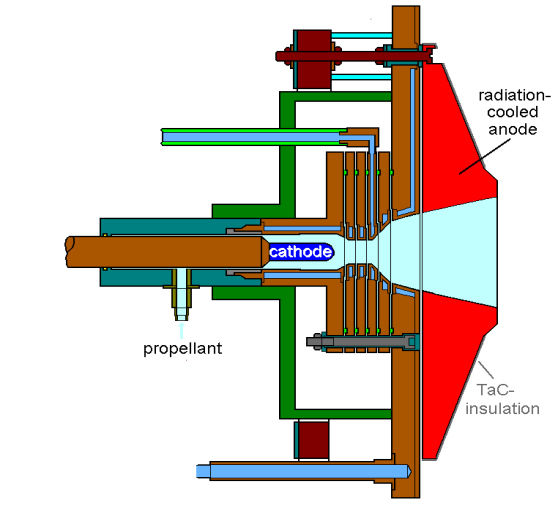
# Steady State self-field (SF) MPD thrusters



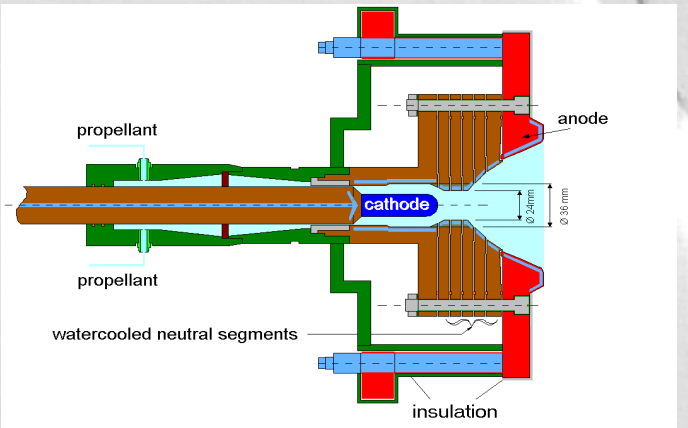

ZT

HAT



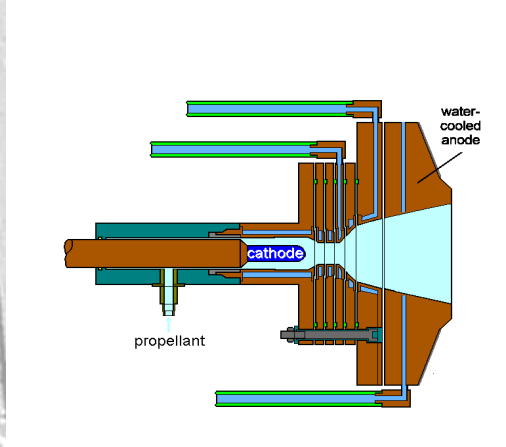



Investigation of **cylindrical thrusters** (ZT) and **nozzle type** thusters (with water-cooled (DT, CAT) and radiation-cooled (HAT) anode),
Power up to 550 kW, current up to 15 kA, thrust up to 27 N and efficiency up to 27% with argon as propellant.

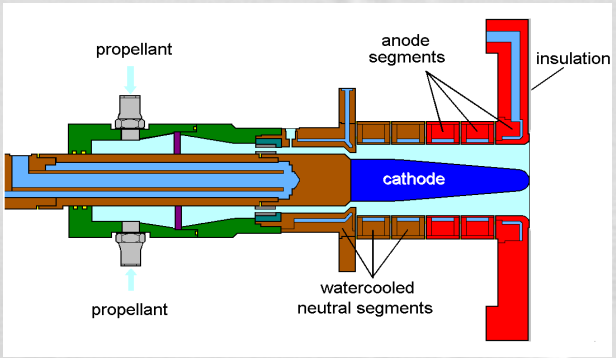



DT

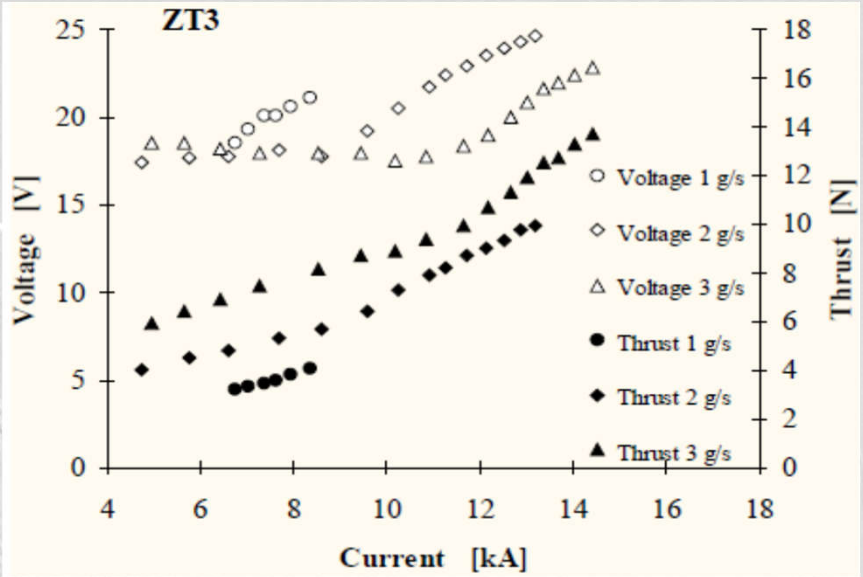
CAT

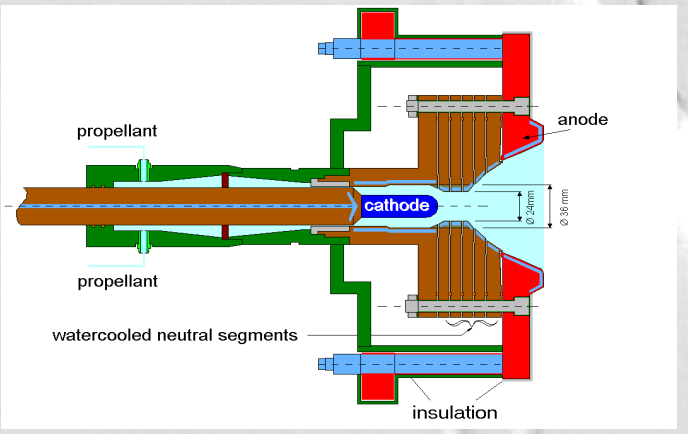


# Steady State SF MPD thrusters

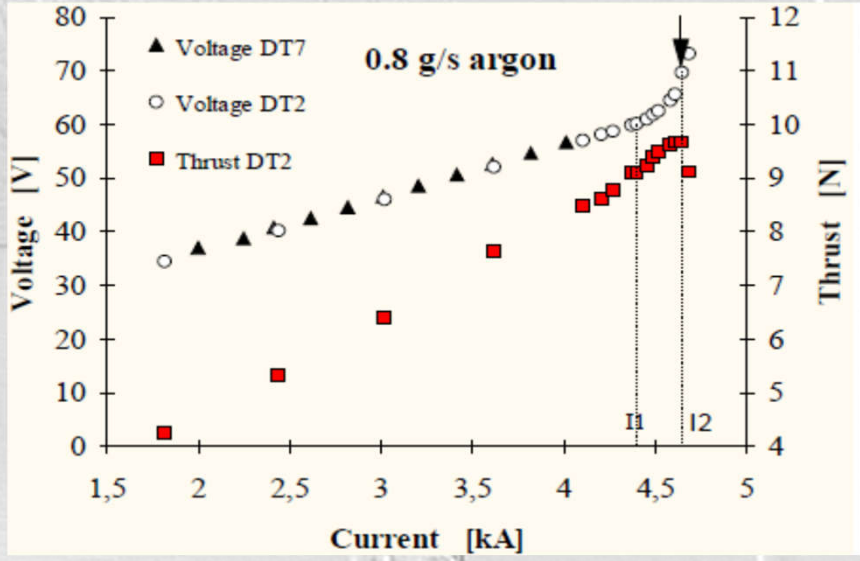



ZT

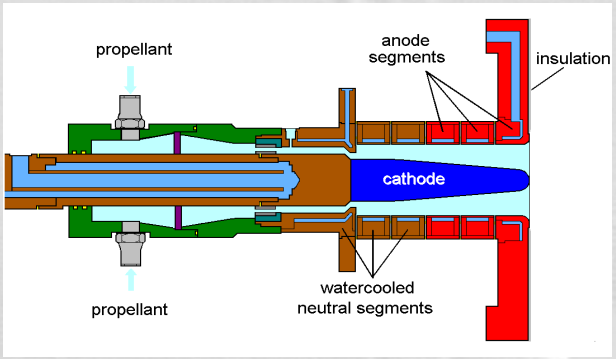


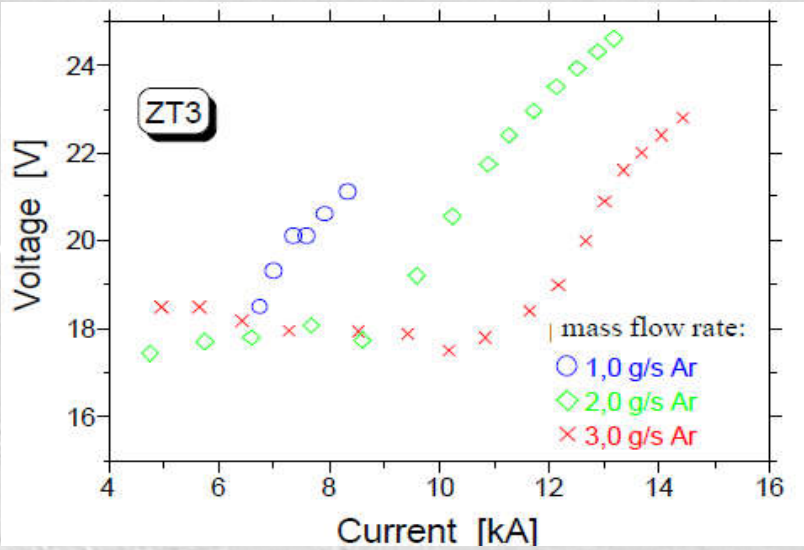

DT



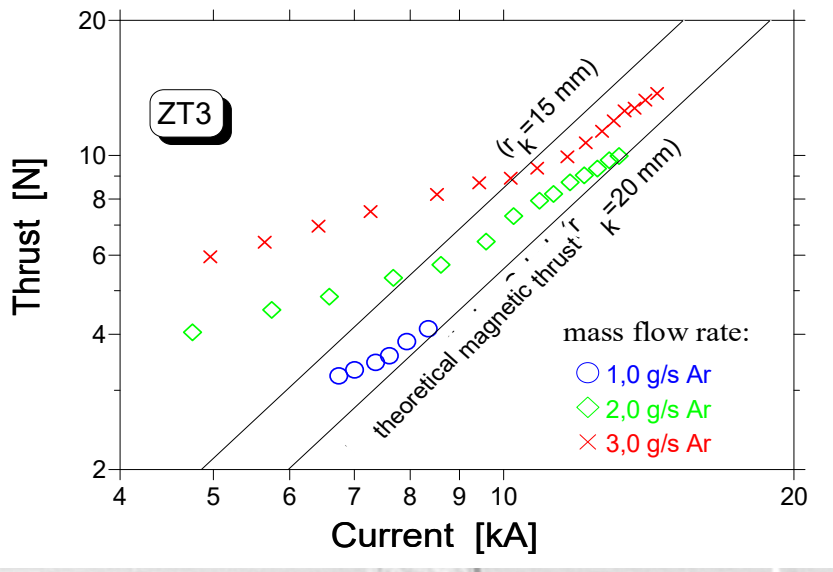
# Steady State self-field MPD thrusters




ZT



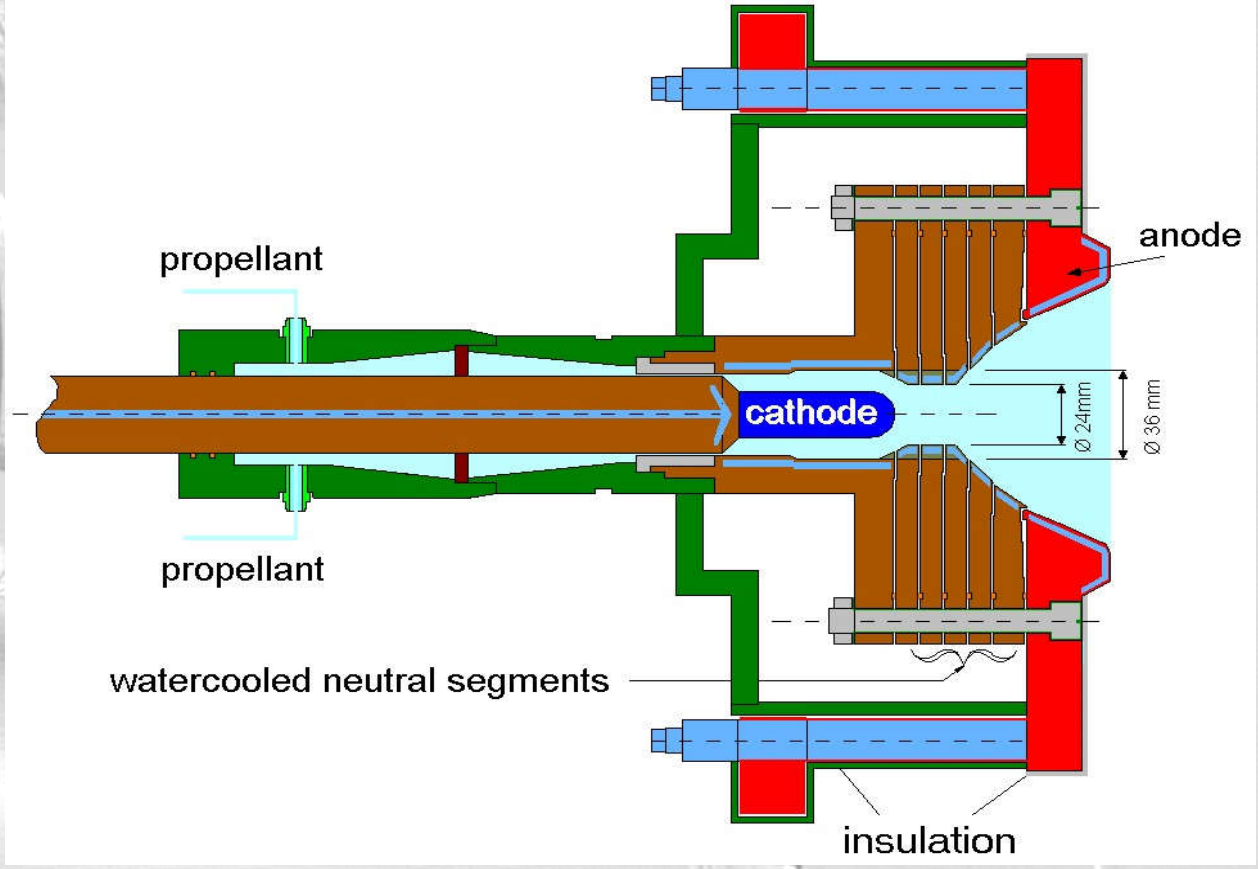

- Thrust values up to 15 N
- No instabilities up to 15 kA at 0.8 g/s (Argon)
- Electrical power up to 350 kW



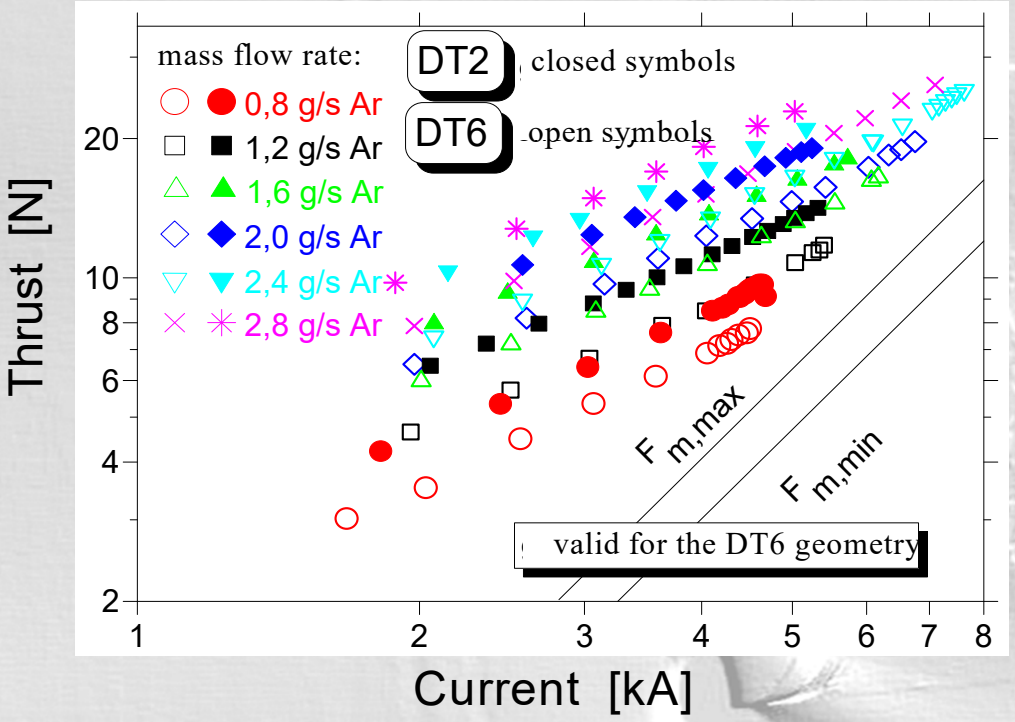
# SF-MPD Nozzle-Type Thrusters (DT) – at IRS

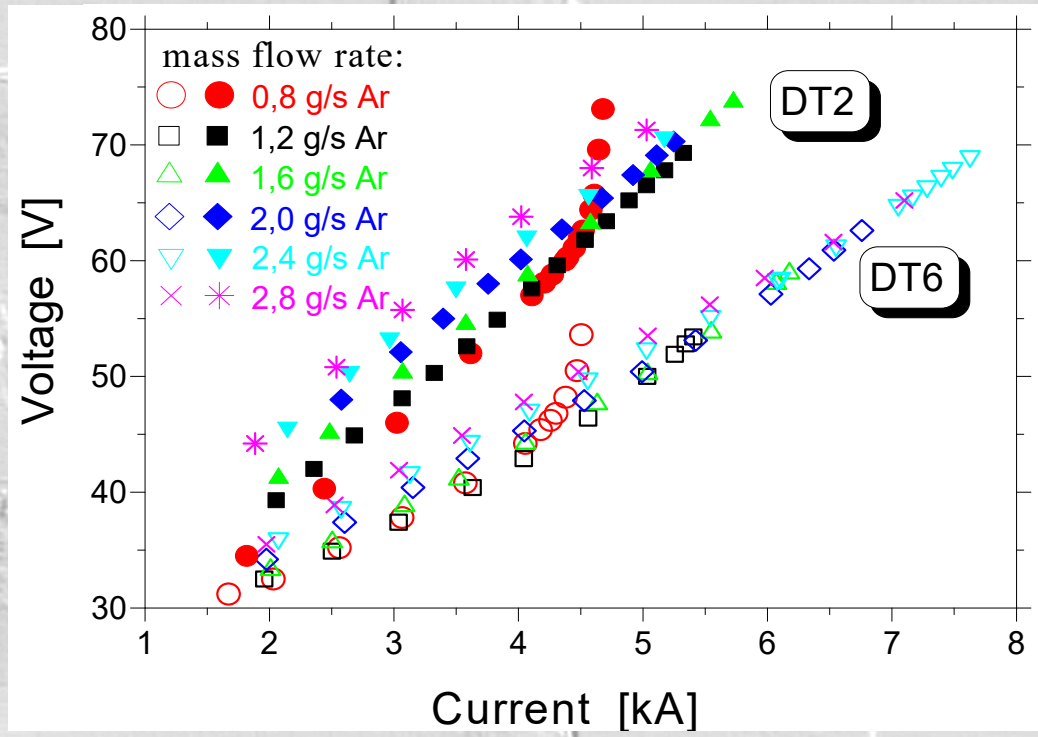
Laboratory devices:

- 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



# SF-MPD Nozzle-Type Thrusters (DT) – Performance Data

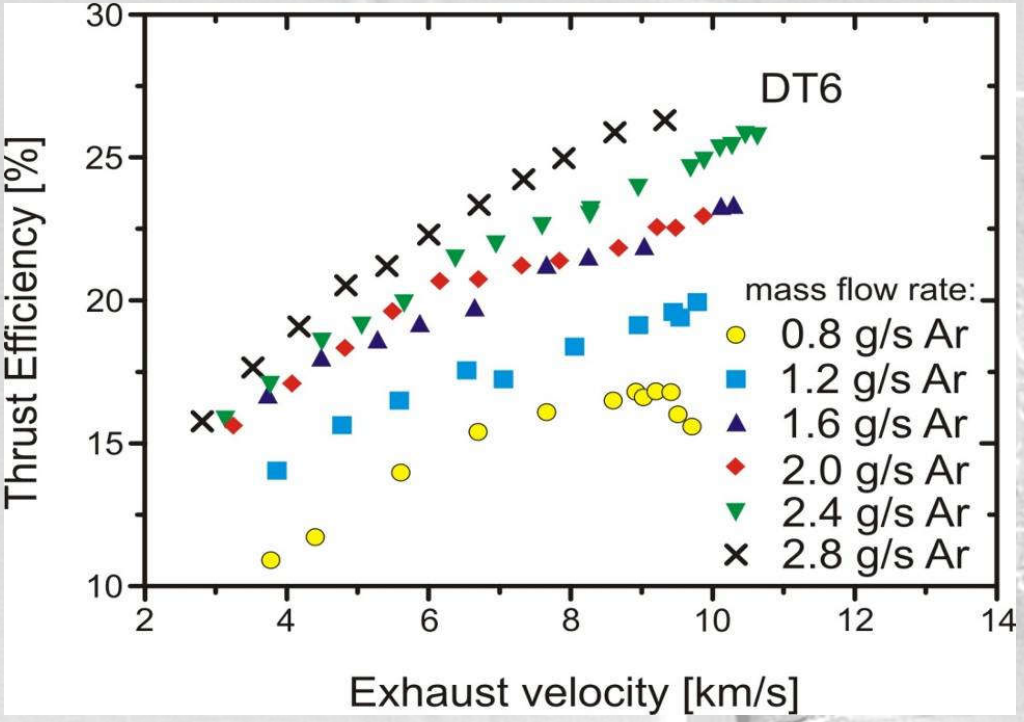


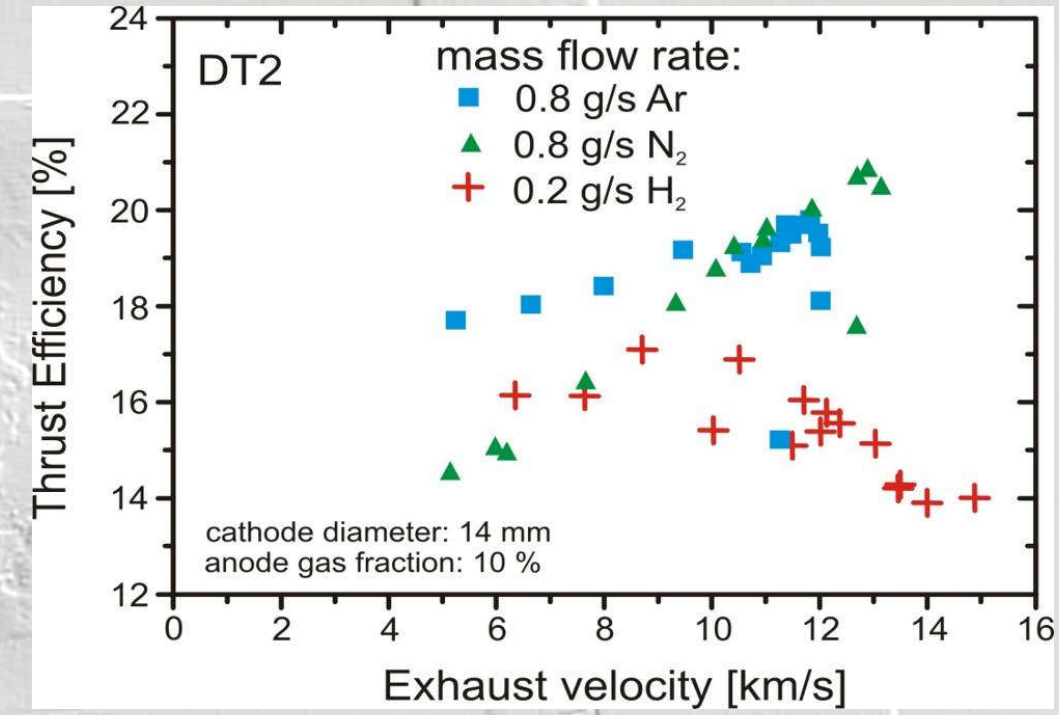

Operated up to 25 N at 8000 A with Argon

Plasma instabilities limitation at ca. 15 km/s with Ar, $H_2$ and $N_2$

# SF-MPD Nozzle-Type Thrusters (DT) – Performance Data




DT6: thrust efficiency vs. exhaust velocity



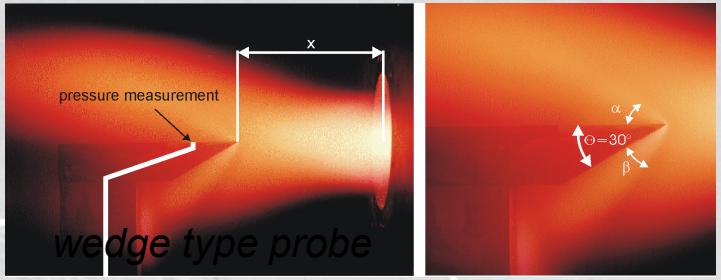

DT2: thrust efficiency vs. exhaust velocity

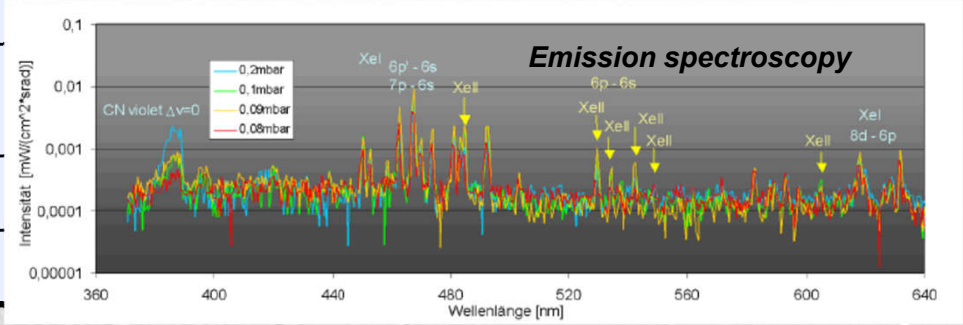
# Summary Part 1

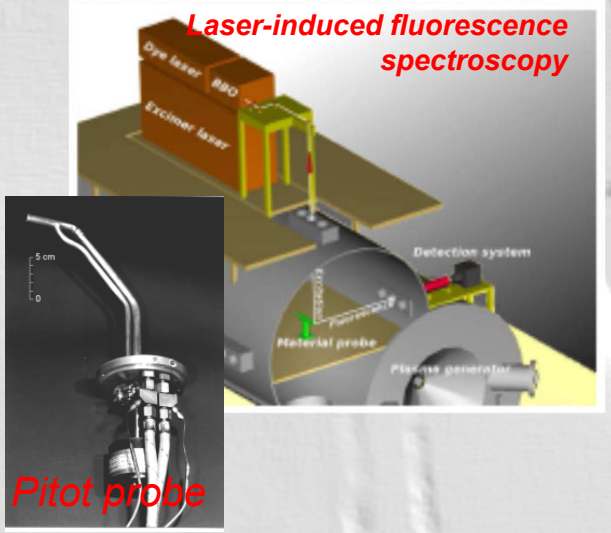
- PPT
  - Secondary propulsion
  - Primary cubesat propulsion
  - Optimization can lead to significant thrust efficiencies leading to an efficient low cost system that benefits from robustness and simplicity
- Steady state self-field MPD Thrusters
  - High power devices aiming at heavy cargo missions 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

| Probe-type | Value measured |
|---|---|
| Heat Flux Probe | heat flux |
| Pitot Probe | total pressure |
| Mass Spectrometer Probe | plasma composition |
| Wedge Type and Conical Probe | static pressure, Mach number |
| Enthalpy Probe | enthalpy |
| Electrostatic Probes | $T_e$, $T_i$, $v$, $n_e$, … |



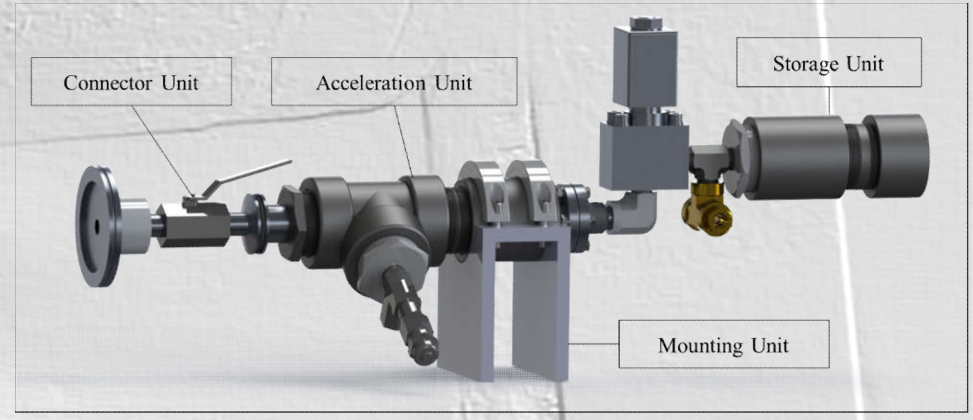

| Method | Measured quantity |
|---|---|
| Emission Spectroscopy (EMS) | $T_{ex}$ , $T_{rot}$ , $T_{vib}$ , $T_e$ , $n_e$ , ($n_{Plasma}$ ?) |
| Laser-Induced Fluorescence (LIF) | $T_{rot}$ , ($T_{vib}$ ), $T_e$ , $n_e$ , $n_{Plasma}$ , $v_{Plasma}$ |
| Thompson Scattering | $n_e$ , $T_e$ |
| Fabry-Perot Interferometry (FPI) | $T_{Trans}$ , $v_{Plasma}$ |
| Laser Absorption Spectroscopy (LAS) | $n_{Plasma}$ , $T_{Trans}$ , $v_{Plasma}$ |

# 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

TPS material probe

electrostatic probe, detector head

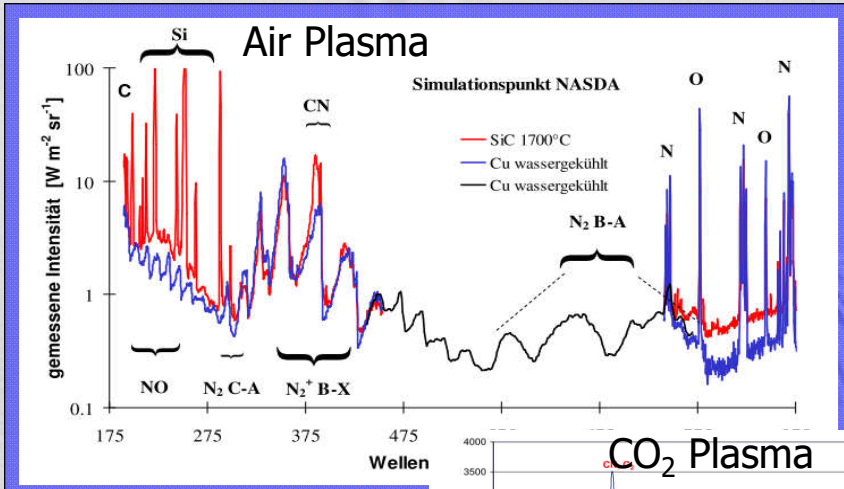


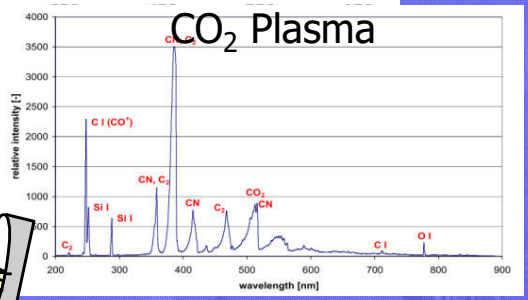
# Optical Diagnostics

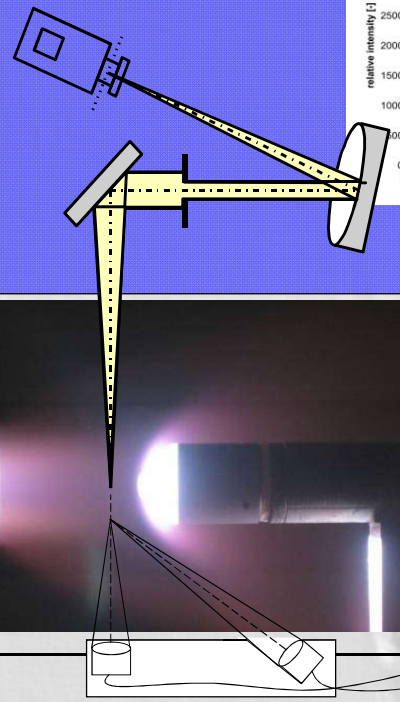
## Emission Spectroscopy, LIF, DLAS, FPI

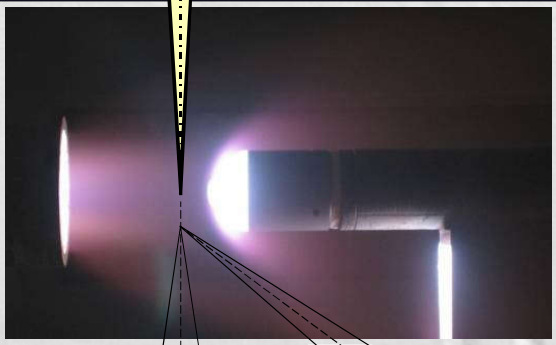
Verification

### Emission spectr.

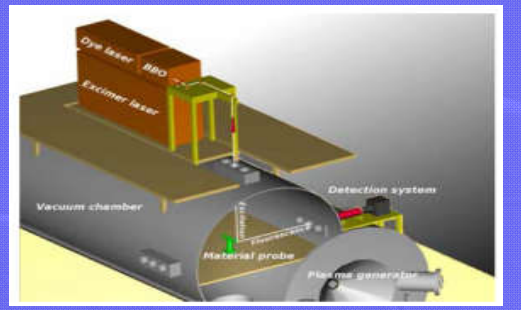


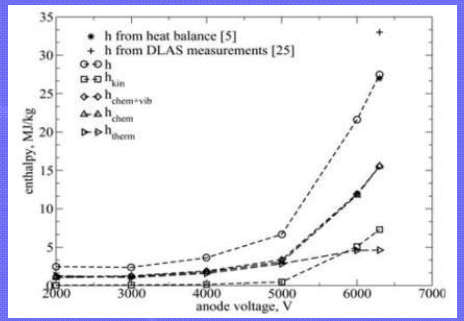



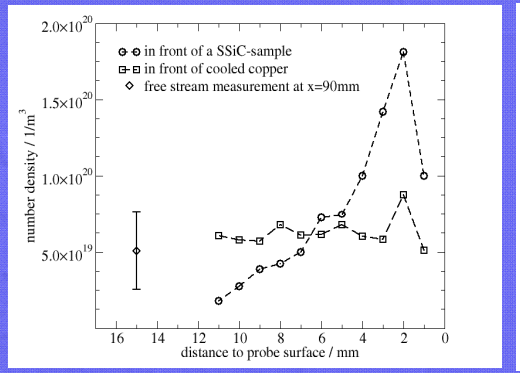



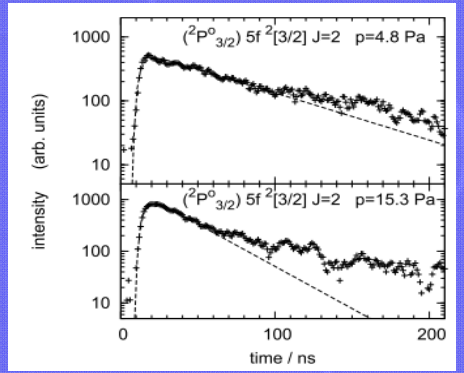


### Laser-induced fluorescence



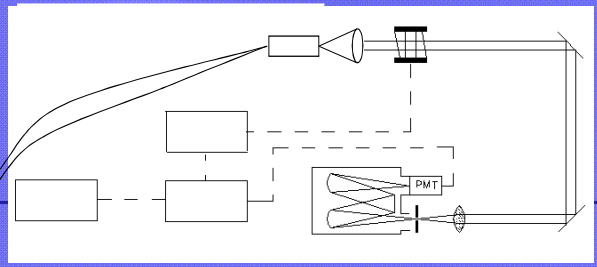



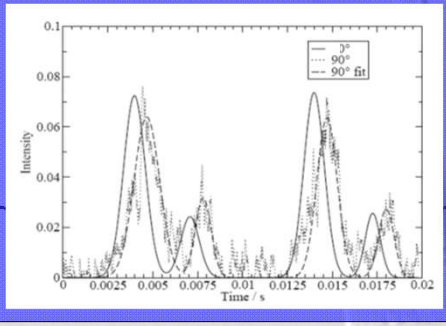

**Optical Diagnostics at IRS means**

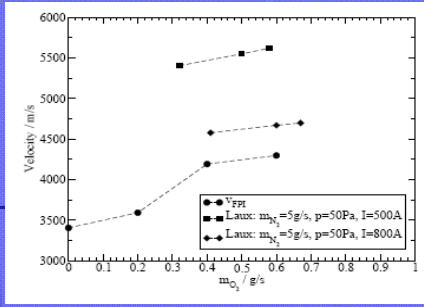
***Mobile non-intrusive diagnostic setups***

**→ species temperatures number densities velocities**

### Fabry-Perot-Interf.



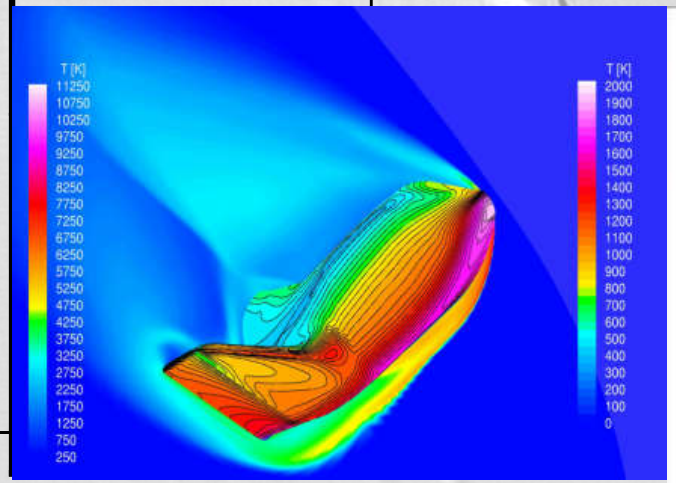



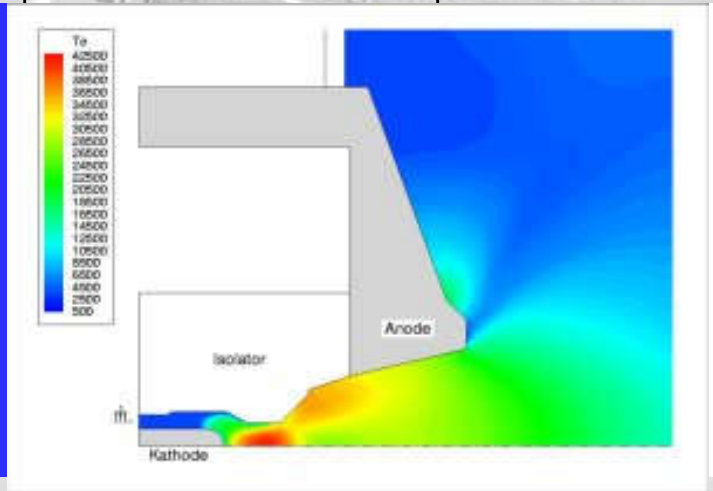
# Overview of available codes at IRS

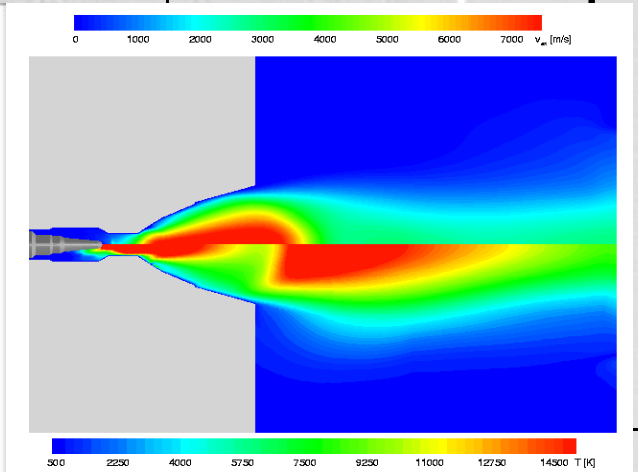
| URANUS | SAMSA | SINA / ARCHE | PICLas | LasVegas |
|---|---|---|---|---|
| Navier-Stokes | | | Particle Method / Boltzmann Equation | |
| continuum flow, thermal and chemical non-equilibrium | | | rarefied *plasmas*, strong non-equil. | Rarefied *gases*, strong non-equil. |
| re-entry | MPD (self and applied field) | TLT, IPG, PWK | PPT, Ion thruster,… | Re-entry |
| 2D rotational symm. / 3D | 2D rotational symmetric | 3D (rotational symmetric) | 3D | 2D rotational symmetric |
| fully implicit | explicit | | | |
| fully coupled | | loosely, iteratively coupled | | single |
| structured multiblock grids | unstructured, adaptive grids | structured multiblock grids | Unstructured grids | unstructured, adaptive grids |
| Air, $CO_2$ | Argon | Air, $N_2$, $H_2$, $CO_2$ | any | any |
| **PARADE/HERTA** gas-radiation coupling | | **HERTA** gas-radiation coupling | | |
| Gas kinetic gas-surface interaction model with catalytic reaction schemes. CVCV mult. temperature gas-phase model | | changeable chemical modules | | Gas kinetic gas-surface interaction model with catalytic reaction schemes. |

# Numerical / theoretical modeling: Available codes at IRS

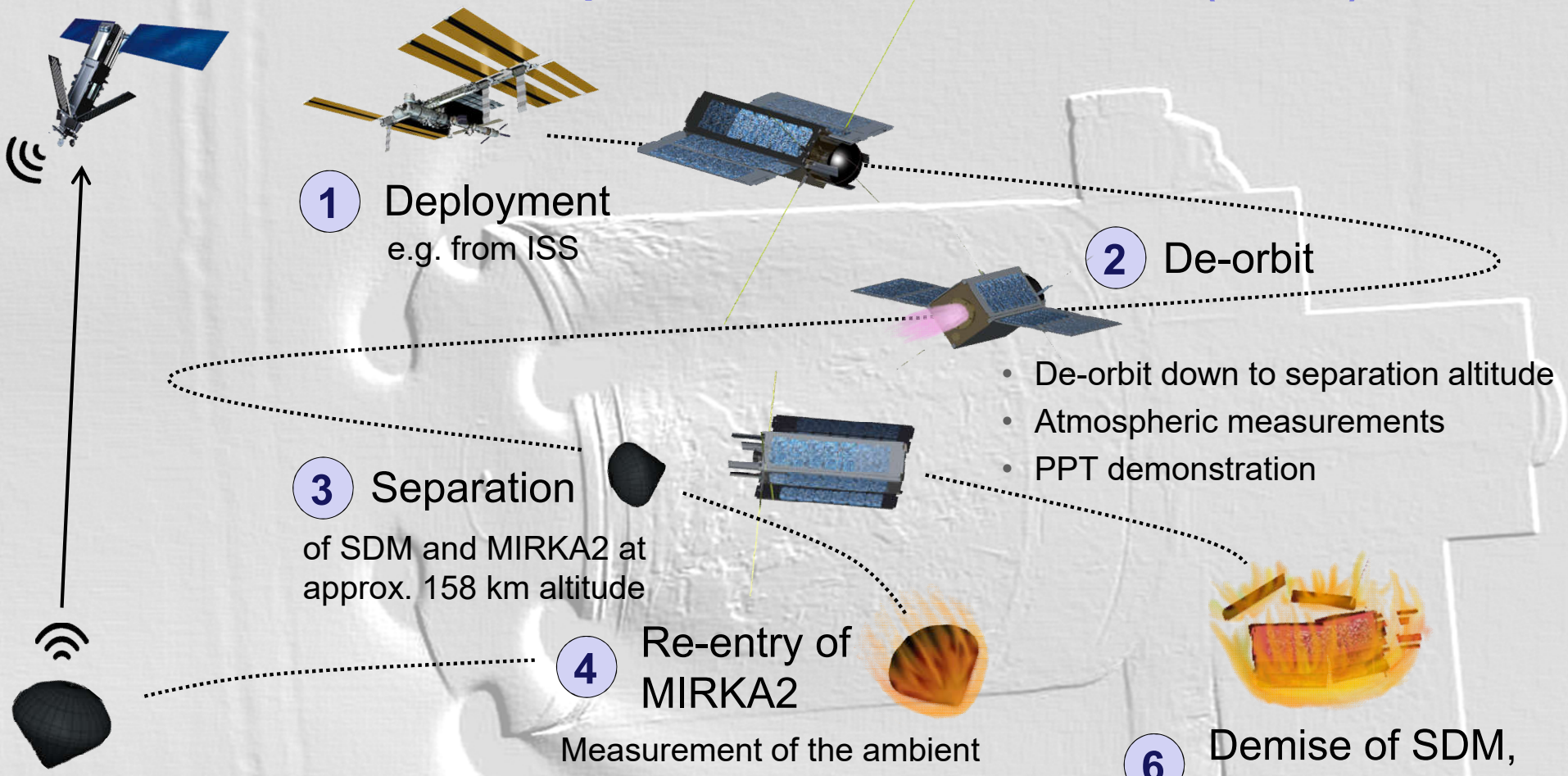
| URANUS | SAMSA | SINA / ARCHE | PICLas | LasVegas |
|---|---|---|---|---|
| Navier-Stokes | | | Particle Method / Boltzmann Equation | |
| continuum flow, thermal and chemical non-equilibrium | | | rarefied *plasmas*, strong non-equil. | Rarefied *gases*, strong non-equil. |
| re-entry | MPD (self and applied field) | TLT, IPG, PWK | PPT, Ion thruster,… | Re-entry |
| 2D rotational symm. / 3D | 2D rotational symmetric | 3D (rotational symmetric) | 3D | 2D rotational symmetric |
| fully implicit | explicit | | | |
| fully coupled | | loosely, iteratively coupled | | single |
| structured multiblock grids | unstructured, adaptive grids | structured multiblock grids | Unstructured grids | unstructured, adaptive grids |
| Air | Argon | Air, $N_2$, $H_2$ | any | any |



# 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

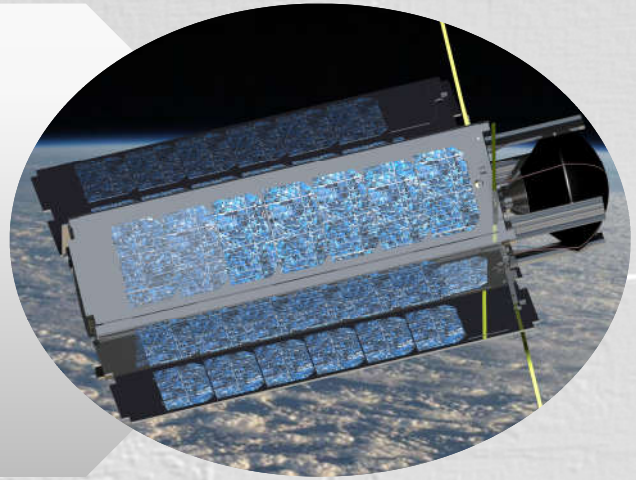
**5 Transfer of re-entry data via satellite**
Transmission of data through Iridium communication system

**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):*

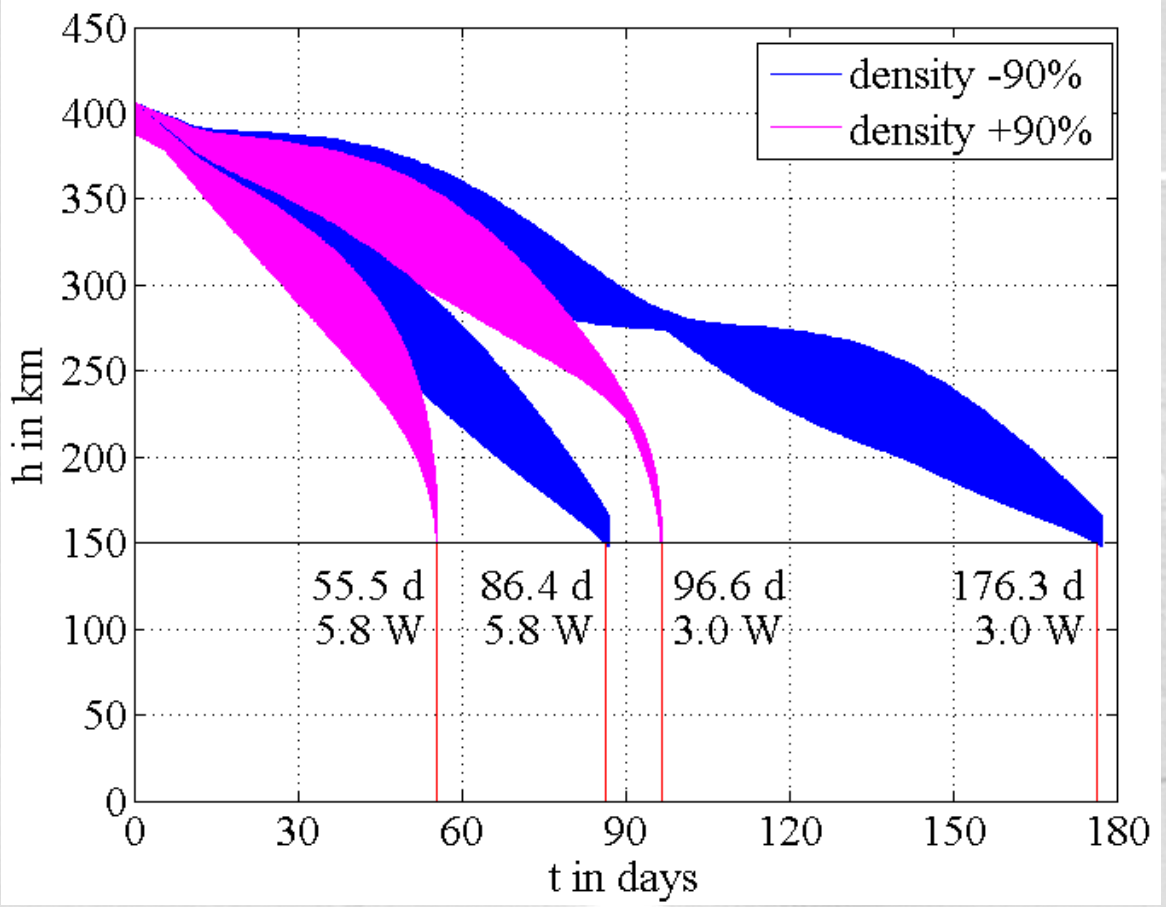
- Performs deorbit manoeuvre using PPT
- Demises upon re-entry
- Scientific payload: e.g. FIPEX, dust sensors
- Potential standard carrier for future CubeSat science missions



## 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

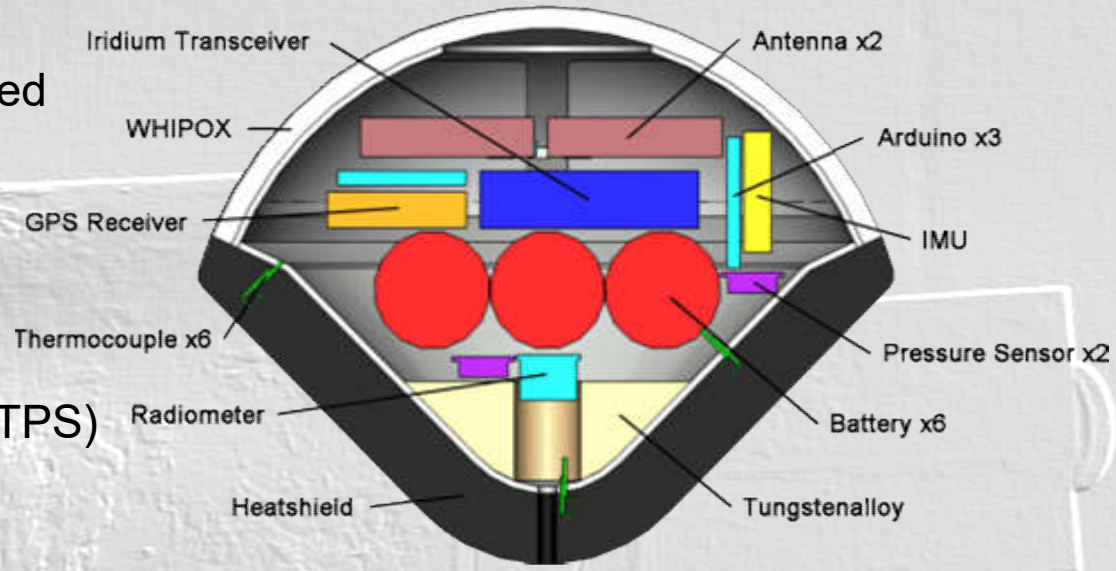
# Trajectory Analysis



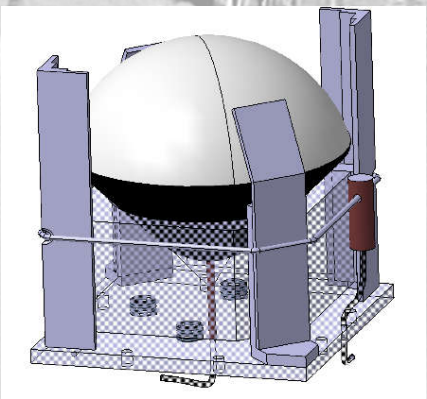

- Mission analysis performed with IRS in-house code REENT
- Starting orbit: ISS
  - 400 km altitude
  - 51.56° inclination
- Downward spiralling manoeuvre
- Propulsion system: Pulsed Plasma Thruster (PPT):
  - 93 µN at 5.8 W (continuous)
  - 48 µN at 3.0 W (continuous operation with extra contingency 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







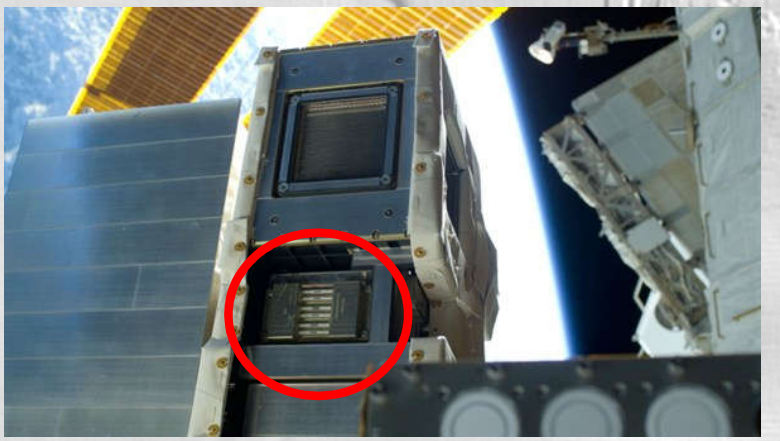
- Separation via LOTUS (Low Orbit Technical Unit Separator) spring-powered ejection mechanism
- High-performance ablator materials ZURAM considered as candidates for TPS
  → Flight qualification

# 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

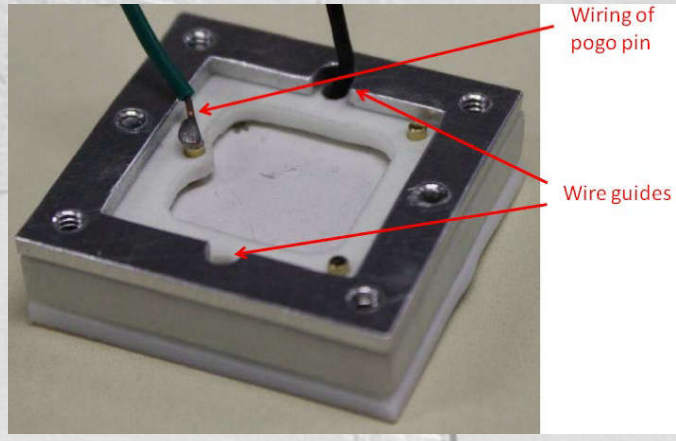
- In-situ measurement of atomic oxygen concentrations in lower thermosphere
- Successfully flown on ISS



(DLR)

## Piezo Dust Detectors

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



# 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**

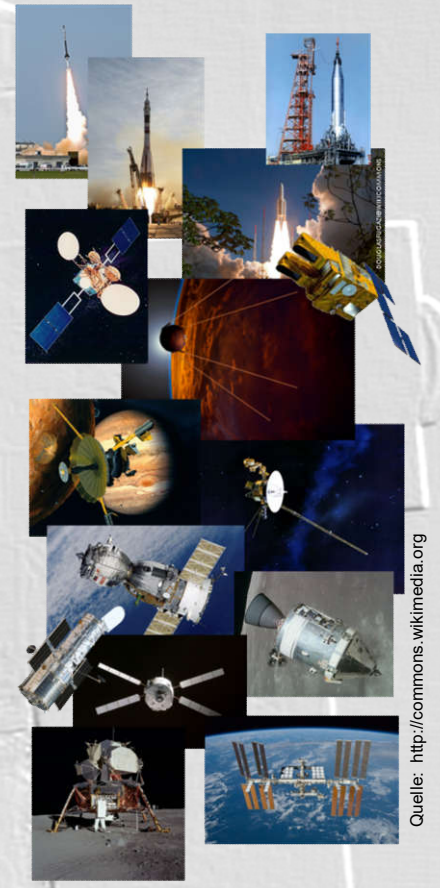
- Standardised platform for spatially and temporally resolved atmospheric measurements in general.
- Quantitative data of contamination of atmospheric gas sensor measurements through electric thruster exhaust.
- Micro return capsule data provides valuable reference scenario with direct application to 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 ouside its gravitation regime ✓/✗
  - Travel within our solar system ✓/✗
  - Interstellar flight ✗

# Space Travel – a Resumé

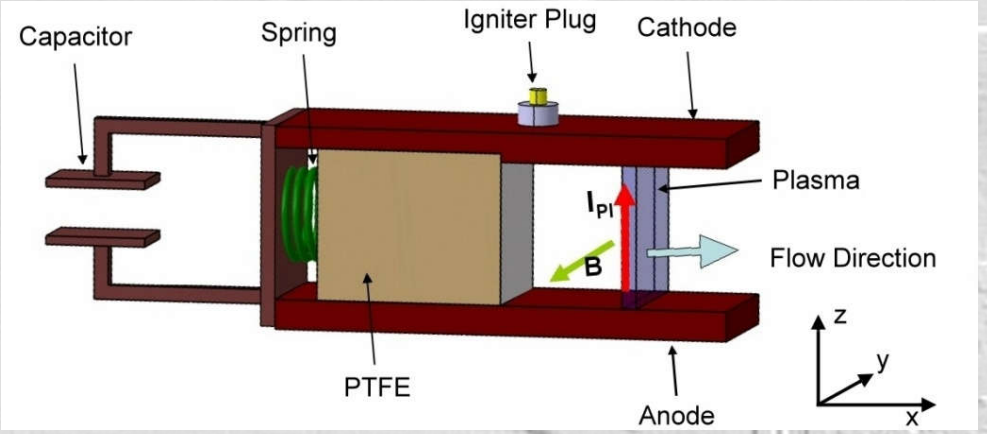
- Balance:
  - Space travel mostly in regime near Earth.
  - Most missions are un-manned.
- Examples:
  - Ballistic launchers, satellites, probes
  - manned launchers, space stations, moon landers
- Propulsion characteristics:
  - Launch with chemical high thrust systems, energy limited → limited effective exhaust velocities $c_e$.
  - Either impulsive orbit maneuvres applying low $c_e$ or un-/pulsed low thrust spiralling applying high $c_e$ systems.



Quelle: http://commons.wikimedia.org

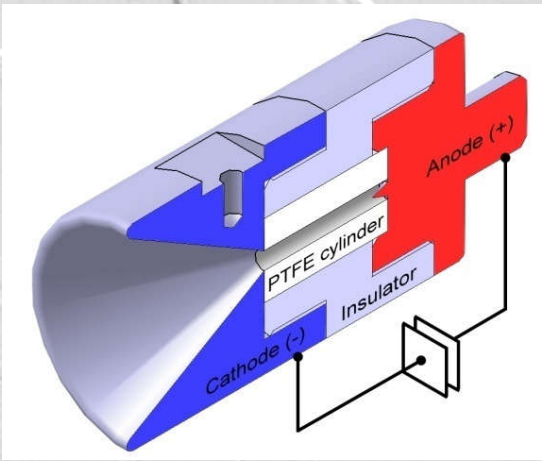
# Function of iMPD and PET

## iMPD



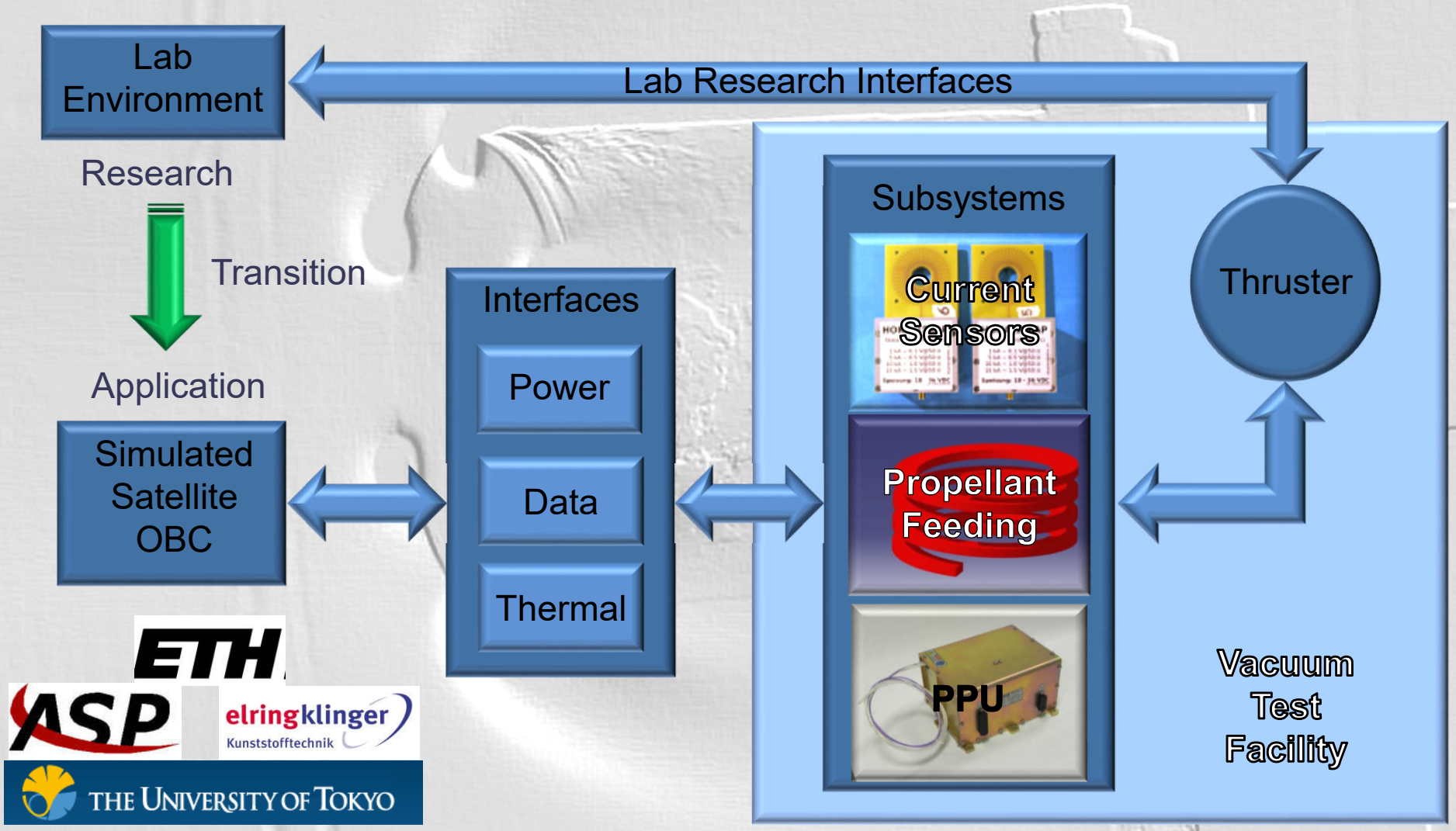

- Discharge ablates PTFE
- MHD-based acceleration
- ⇨ **Thrust: µN - mN**

## PET

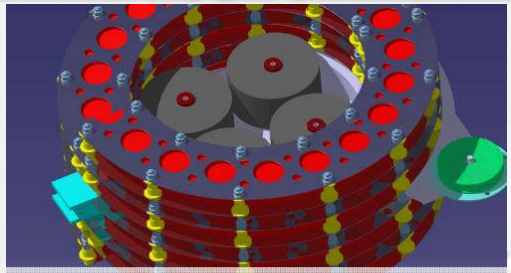



- Discharge ablates PTFE
- Gas dynamic acceleration
- ⇨ **Thrust: nN - µN**

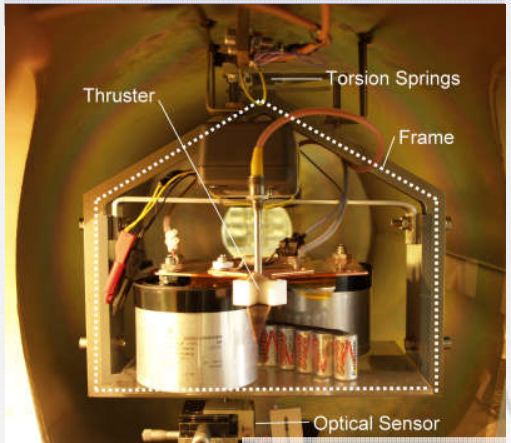
# Thruster System Design Strategy



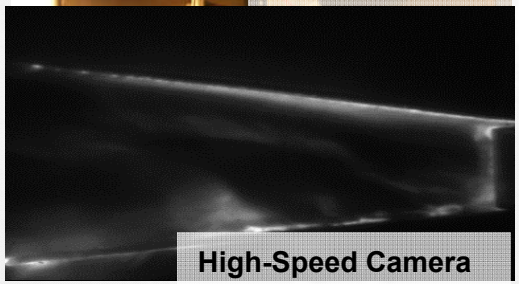
# ADD SIMP-LEX for Satellite Missions



Propellant Feeding System
Dupont Award 2007




Thrust Balance



High-Speed Camera

- 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
  - **Succesful System Approach (with ASP GmbH)**

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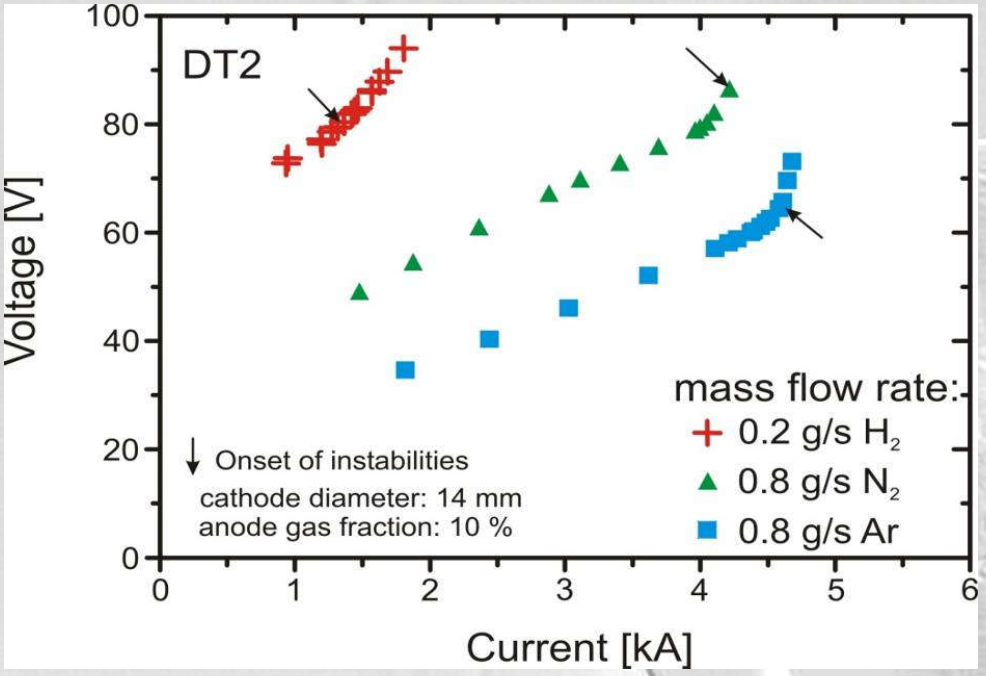
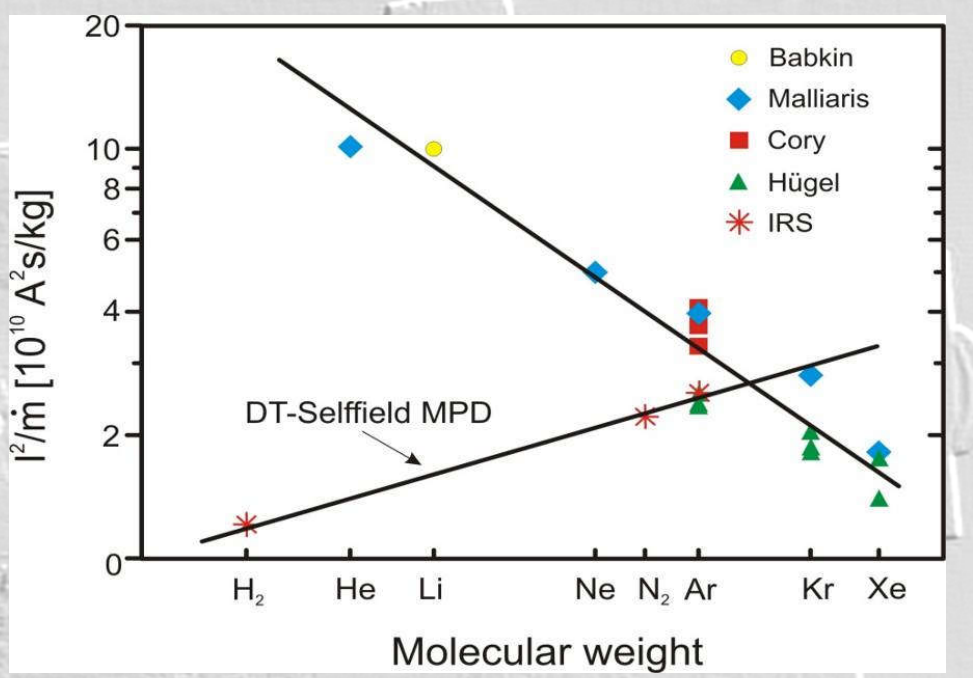
# SF-MPD Nozzle-Type Thrusters (DT) – Plasma Instabilities



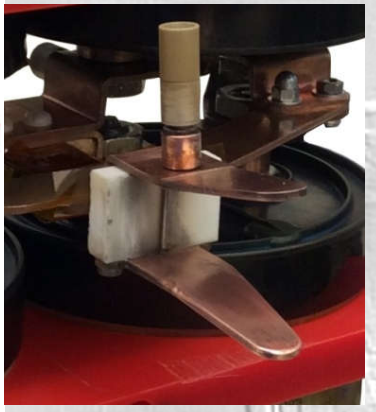



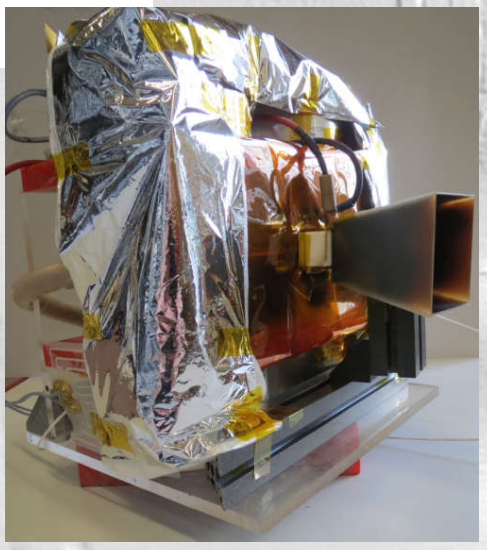

Scaling of Nozzle Equipped steady state SF MPD (Schmidt)

- Hydrogen data are significantly lower in power ($I_{max}$=1,35 kA)
- Argon data as shown here

# ADD SIMP-LEX GSM (TRL = 7)

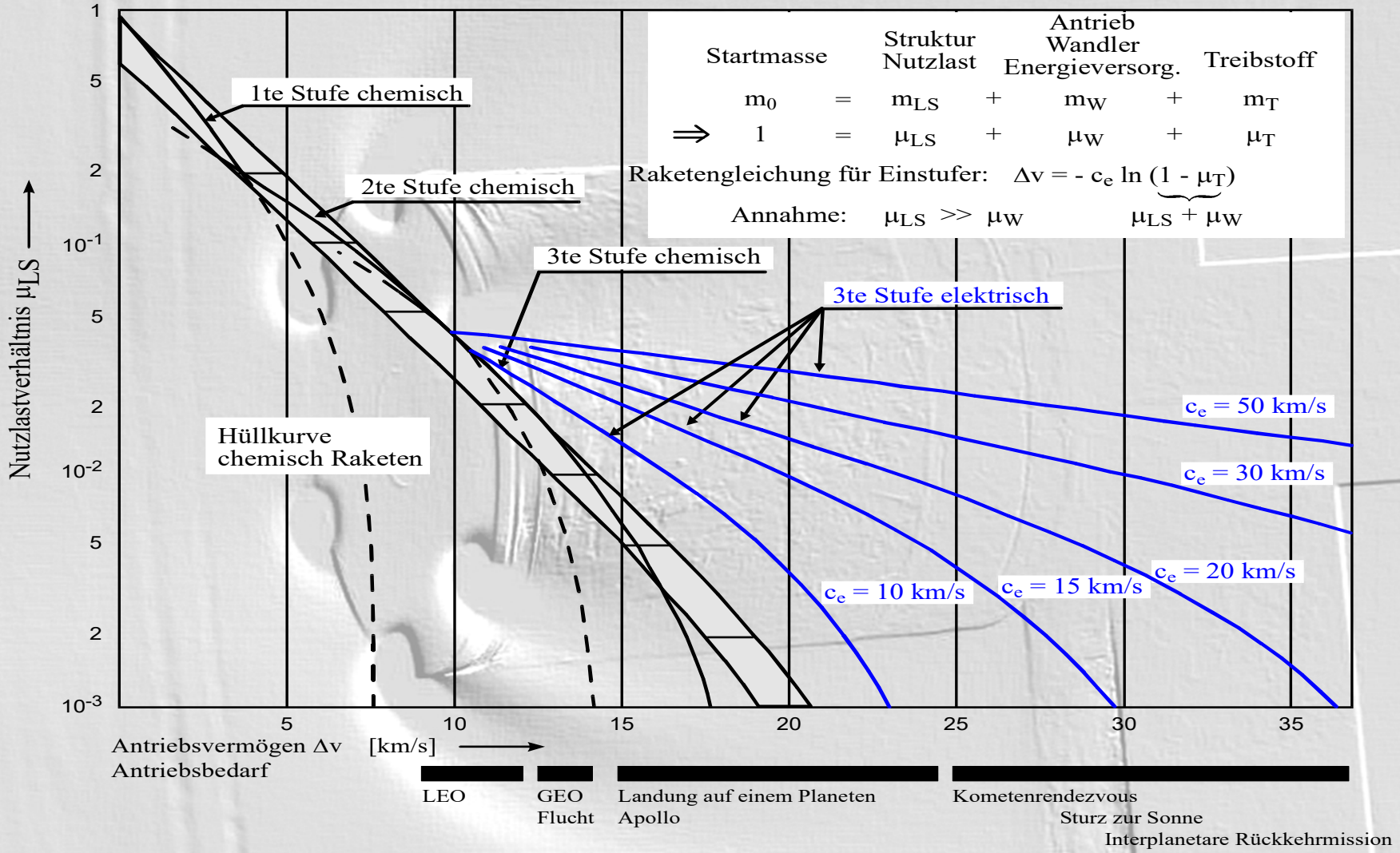
## Test of total system in DLR STG Facility (incl. PPU)





| Parameter | Unit | Value |
|---|---|---|
| Max. Capacitor Dry Mass | kg | < 6 |
| Max. Pulse Energy | J | 67.6 |
| Electrode gap (HxW) | mm | 21 x 20 |
| Propellant | - | Solid PTFE |
| Mechanical Feeding Type | - | Side-fed |
| Total Capacitance | µF | 80 (4 x 20) |
| Capacitor Type | - | Wound Mica Foil |
| Capacitor Voltage | V | 1300 |
| Igniter Insulation Material | - | $Al_2O_3$ |
| Igniter Voltage Capability | kV | Up to 20 |
| iMPD Power Consumption | W | < 85 |
| Impulse per Pulse | µNs | 1.5 |
| Specific Impulse | s | < 2650 |
| Mass per Pulse | µg | 60 |
| Thrust Efficiency | % | ~ 30 |
| Demonstrated Pulse Life | - | 2 Mio. |
| Demonstrated Total Impulse | Ns | 3000 |

# Electric Propulsion for interplanetary missions and orbit transfers




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

# Operational Satellites with Electric Propulsion