

Disruptive Electric Propulsion at IRS

- Programmatic Overview
- Overview IRS Thrusters
- Tools: Diagnostics and Codes
- PPT
- AF MPD
- IEC
- TIHTUS

- ABEP (EU DISCOVERER, optional)

G. Herdrich, T.Binder, A. Boxberger, A. Chadwick, Y.-A. Chan, M. Ehresmann, N. Harmansa,
Ch. Montag, F. Romano, J. Skalden, St. Fasoulas, K. Komurasaki, T. Schönherr

Programmatic Overview (current activities)

PPT

- Collaboration with Uo Tokyo and RIAME + Kurtschatov Institute
- Harware-in-the-loop set-up for ADD-SIMPLEX/PETRUS
- Pulsed Electrothermal Thruster 3 years program (ESA NPI in context of CAPE)
- Inter laboratory comparison between ESA and IRS (procurement of balance and Mini PPT)

Arcjets

- Arcjets TALOS and VELARC within cooperation with Airbus D & S
- ESA Standardization project “Electrostatic probes” (Arcjet as reference)
- IRAS: Application of advanced manufacturing processes to further improve arcjets (DLR/IRS)

AF-MPD

- AF MPD (ESA TRP in coop. with Alta, quasi finalized)
- AF MPD numerical simulation (DAAD)



Programmatic Overview (current activities)

IEC

- IEC experimental investigation in coop. with ESA-ACT (numerical investigation) and Airbus D & S
- NEAT (linear IEC thruster) in cooperation with Gradel (ESA-Luxinno)

TIHTUS

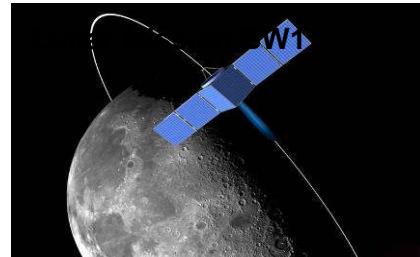
- Numerical Analysis and experimental Optimization of TIHTUS (DFG project)
- TIHTUS Alternative Propellants (U o Adelaide)

ABEP

- DISCOVERER: WP4 as main task of IRS → Atmosphere-Breathing Electric Propulsion

Water-based propulsion

- Secondary EP system developed within cooperation with Airbus D & S



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

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

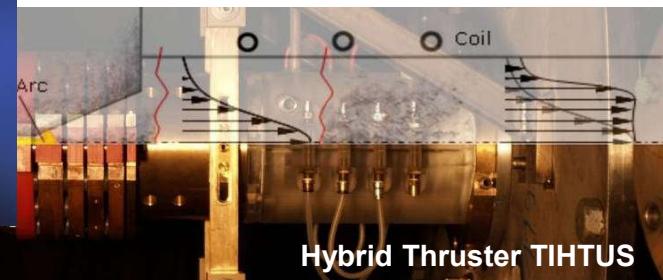
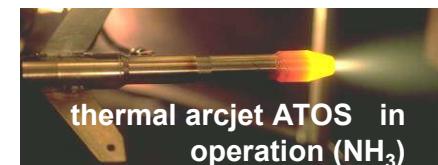
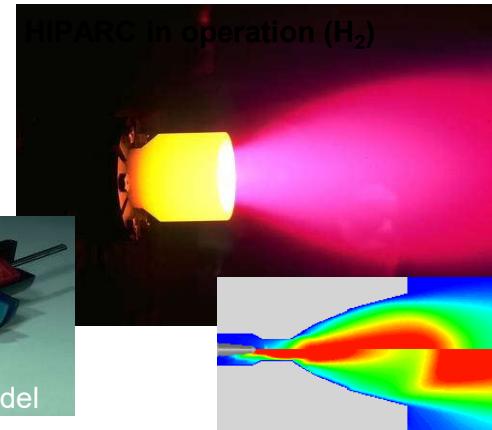
Magnetic flux density 140 mT
Voltage thruster 86 V
Current thruster 182 A
Power 15.6 kW
 $m_a = 72 \text{ mg/s}$
 $m_e = 24 \text{ mg/s}$

IRS AF-MPD SX3 in operation (Ar)

Electric Propulsion at IRS:

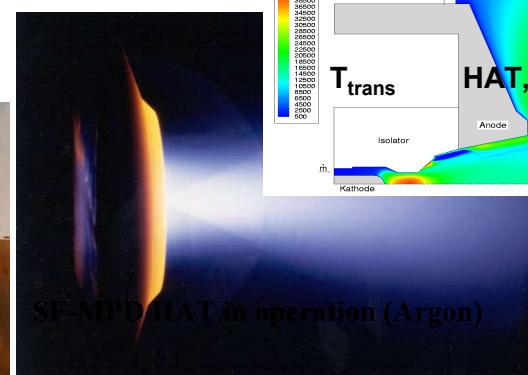
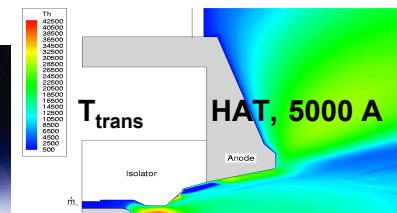
Development of

- Thrusters and
- propulsion systems



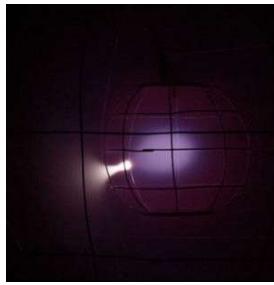
High power EP (50 kW up to MW) (Transport of large payloads)

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





IEC

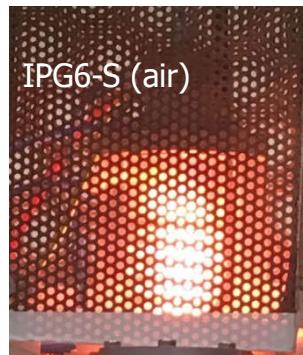


Star Mode, Ar

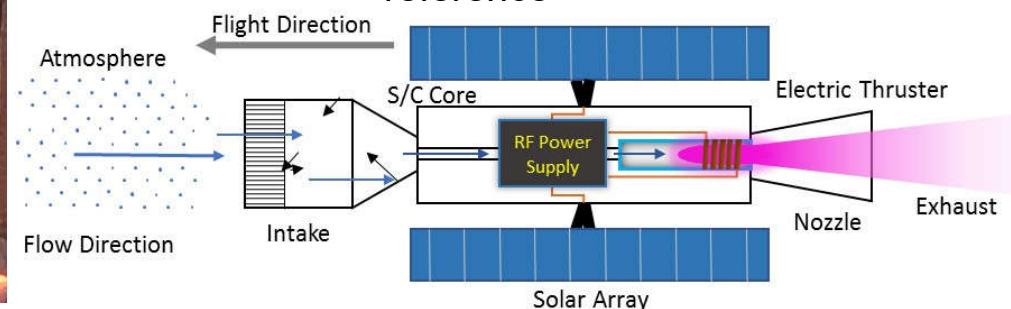


"Tight" Jet Mode, He

IPG6-S



IPG6-S (air)

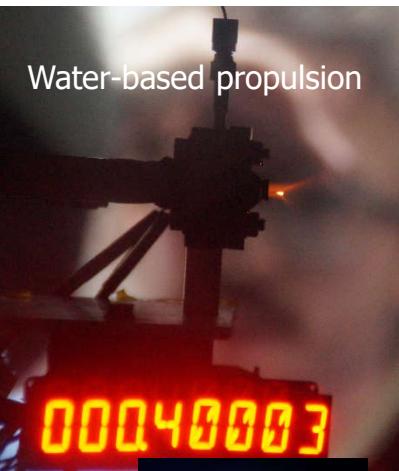


ABEP

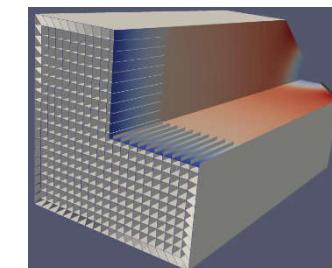
- Intake verification
- Intake design
- Inductive thruster as reference

Mini PPT

- PETRUS
- Thermal PPT
- Reliable, robust, cheap, ...
- CubeSat application



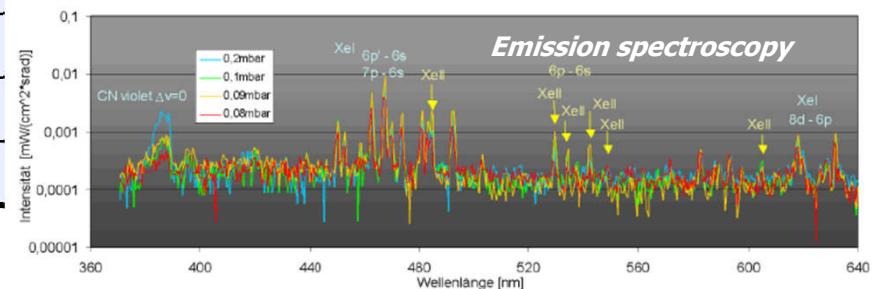
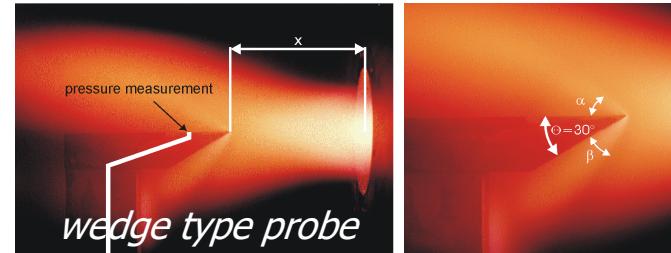
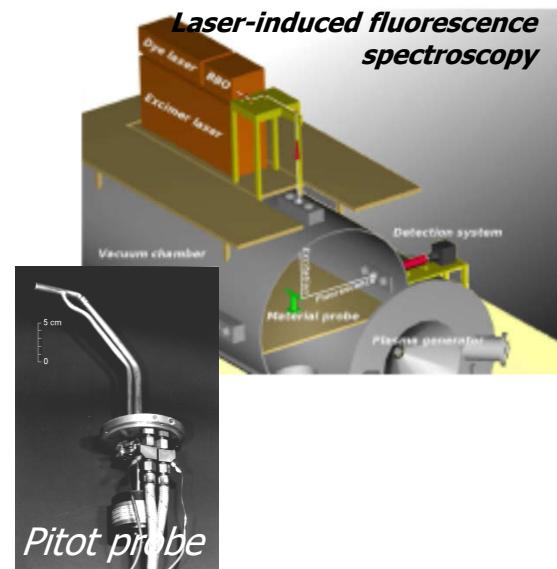
Water-based propulsion



DSMC simulation of adapted intake geometry

Diagnostics for EP Development

Probe-type	Value measured
Heat Flux Probe	heat flux
Pitot Probe	total pressure
Mass Spectrometer Probe	plasma composition
Wedge Type Probe	static pressure, Mach number
Enthalpy Probe	enthalpy
Electrostatic Probes	T_e , T_b , 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}



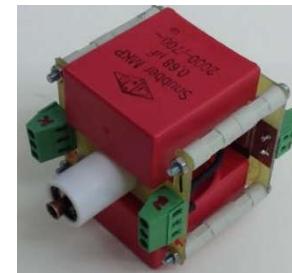
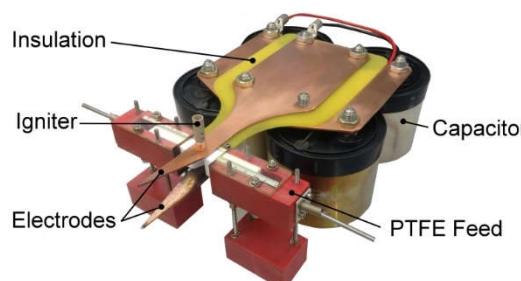
Numerical Codes for EP Development

URANUS (ATD)	SAMSA (ATD/EP)	SINA / ARCHE (ATD/EP)	PICLas (EP presently)
Navier-Stokes			particle method
continuum flow, thermal and chemical non-equilibrium			rarefied plasmas, strong non-equilibrium
re-entry	SF and AF MPD , magnetic probes	TLT, IPG, PWK	PPT, Ion thruster,...
2D rotational symm. / 3D	2D rotational symmetric		3D
fully implicit	explicit		
fully coupled		loosely, iteratively coupled	
structured multiblock grids	unstructured, adaptive grids	structured multiblock grids	unstructured grids
Air, CO ₂	Ar, air, CO ₂	air, N ₂ , H ₂	Presently mono- and diatomic species
PARADE/HERTA gas-radiation coupling		HERTA gas-radiation coupling	
gaskinetic gas-surface interaction model with catalytic reaction schemes. CVCV mult. temperature gas-phase model		changeable chemical modules	



Performance Overview of PPTs at IRS

	ADD SIMP-LEX	PET	PETRA	PETRUS 2.0
Type	iMPD	Electro thermal	Electro thermal	Electro thermal / iMPD
Design	Parallel plate.	coaxial	coaxial	coaxial
Geometry	370 x 240 x 120 mm	Ø 32 x 55 mm	Ø 17 x 29.1 mm	Ø 12 x 50 mm
Mass	6.5 kg	489 g	180.72 g	≤ 500 g (incl. PPU)
Propellant	PTFE	PTFE	PTFE	PTFE
Propellant mass	Up to 43 kg	4 g	1.825 g	3.7 g
Capacitance	80 µF	1.5 µF	1.36 µF	4 µF
Charge voltage	1300 V	2500 V	2000 V	1600 V
Energy	67.6 J	3 J	2.72 J	5.12 J
Pulse frequency	1 Hz	1 Hz	1 Hz	0.25 - 1Hz
Mbit	53.38 µg	43.4 µg	47.76 µg	2.1 µg (theor.)
Ibit	1373 µNs	61.7 µNs	72 µNs	26.5 µNs (theor.)
Number of pulses	More than 2 mio.	100000	38211 (theor.)	1761900 (theor.)
Isp	≤ 2718 s	140 s	154 s (theor.)	< 1282 s (theor.)
Thrust per pulse	1.373 mN	0.0617 mN	0.072 mN	0.0265 mN (theor.)
Power	~ 70 W	< 4 W	< 4 W	5 - 8 W



Design of PETRUS 2.0 and Preliminary Test Results of a Breadboard Model



Breadboard of
PETRUS 2.0



Front view: 2 J and 5.12 J

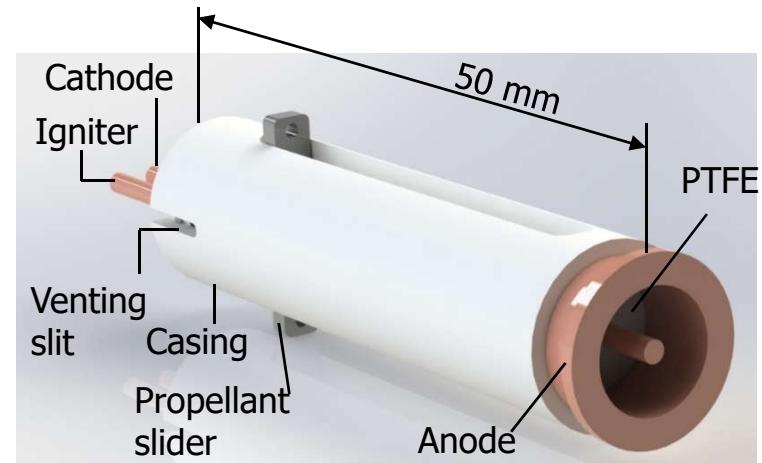


Breadboard model after ~ 2000 pulses



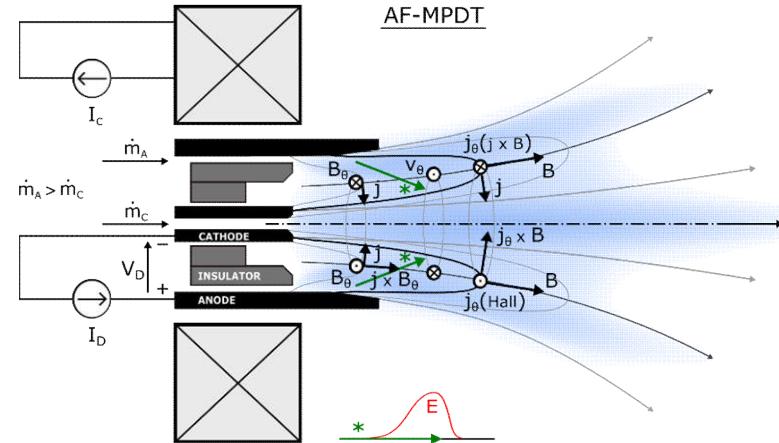
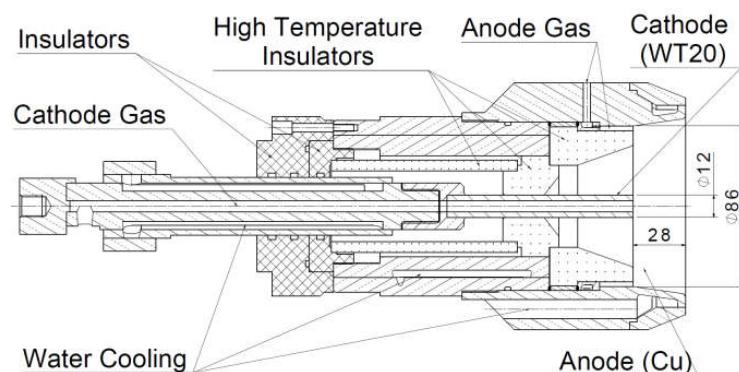
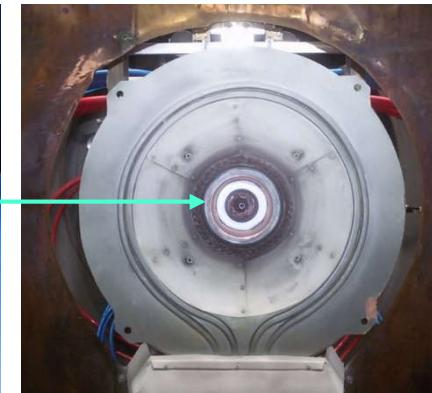
Side view: 2 J and 5.12 J

Isom. view: 5.12 J



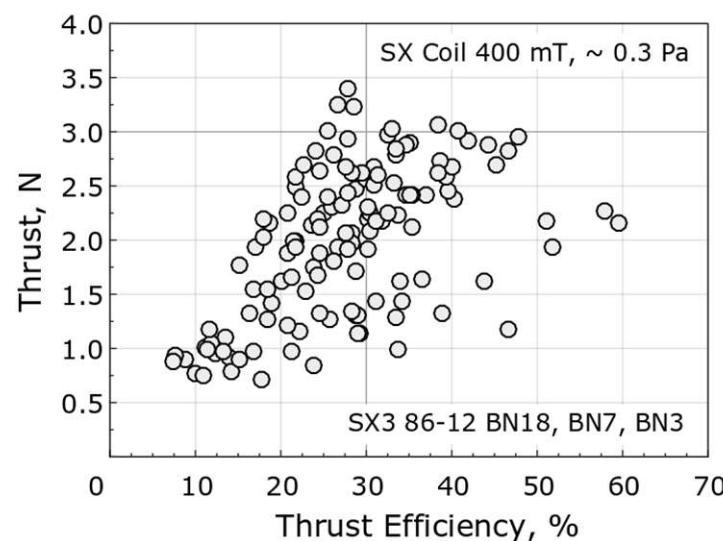
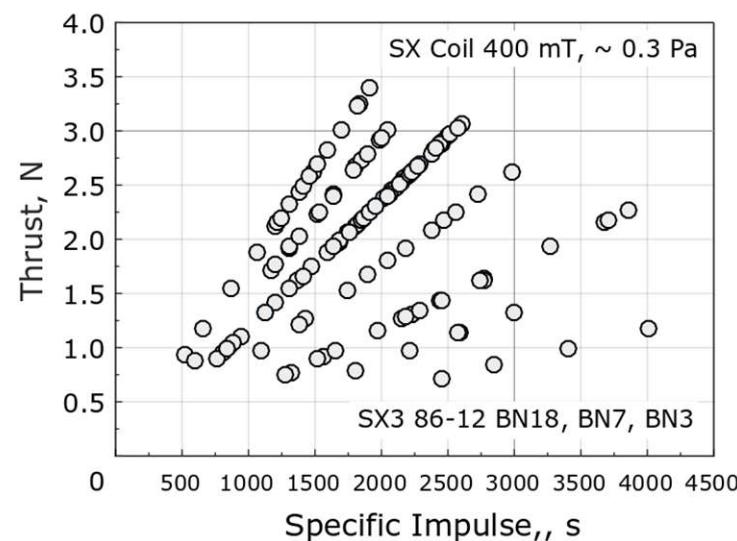
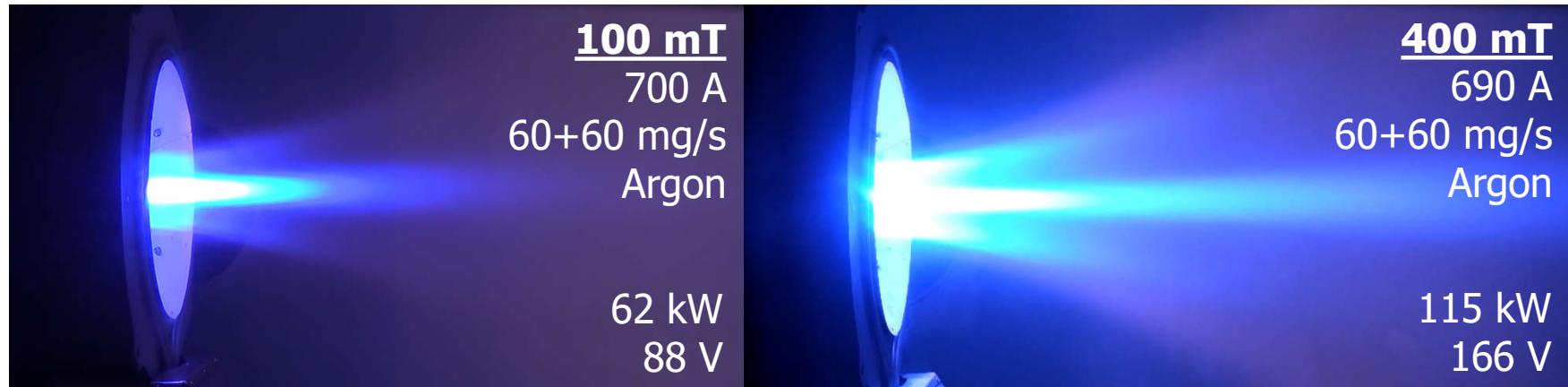
Final design of PETRUS 2.0

Steady State AF-MPD SX3 Thruster (100 kW class)



- Cost efficient laboratory model
- Applied field up to 400 mT, arc current up to 1kA
- Anode + cathode gas injection (argon)

100 kW Class Applied-Field MPD SX3 Thruster: Performance





Inertial Electrostatic Confinement: Plasma Extraction Modes

IEC Configuration:

- Longitude: 8 wires, Latitude: 5 wires
- D_{cathode} : 5 cm, D_{anode} : 15 cm

Tight jet mode:

1. High energy electron beam (*EB*)
2. Confined jet contour
3. Lower current value (1 ~ 50 mA)

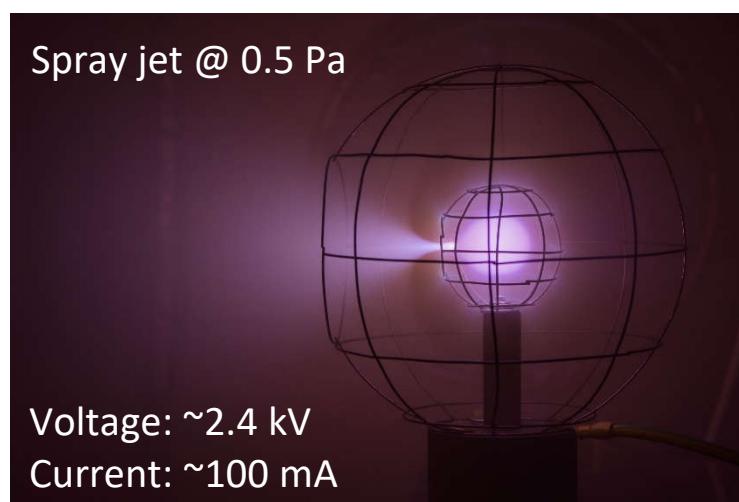
Spray jet mode:

1. Diffused ion plume
2. Higher current value (> 50 mA)
3. High luminosity from core region

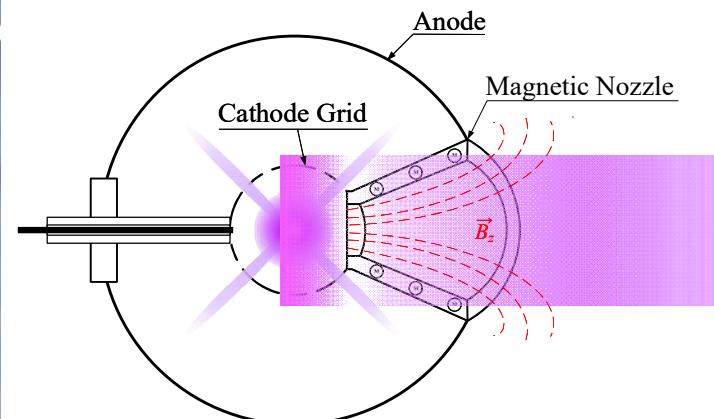
Tight jet @ 0.5 Pa



Spray jet @ 0.5 Pa

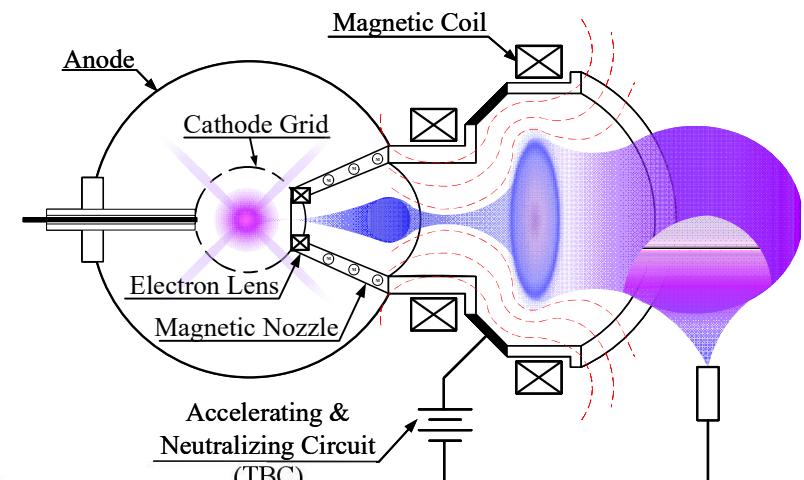


Inertial Electrostatic Confinement: Potential Thruster Concept and Application

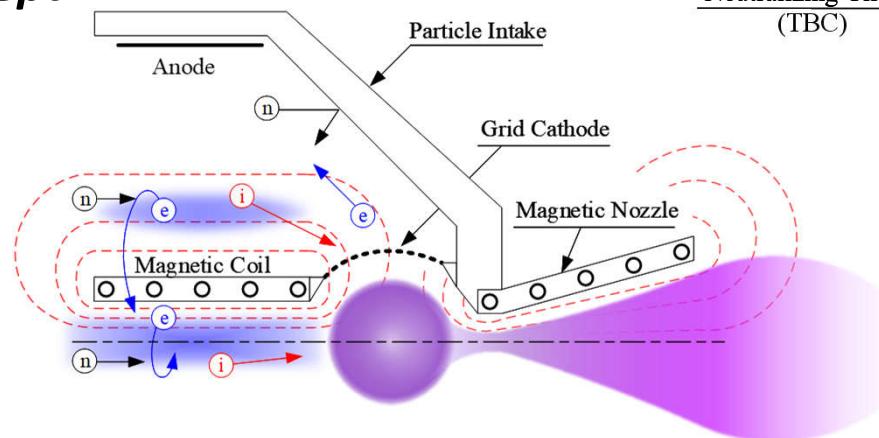


IEC Ion Thruster Concept

IEC ABEP Concept



IEC HET Concept



Inertial Electrostatic Confinement: Application Vision

IEC ABEP Concept:

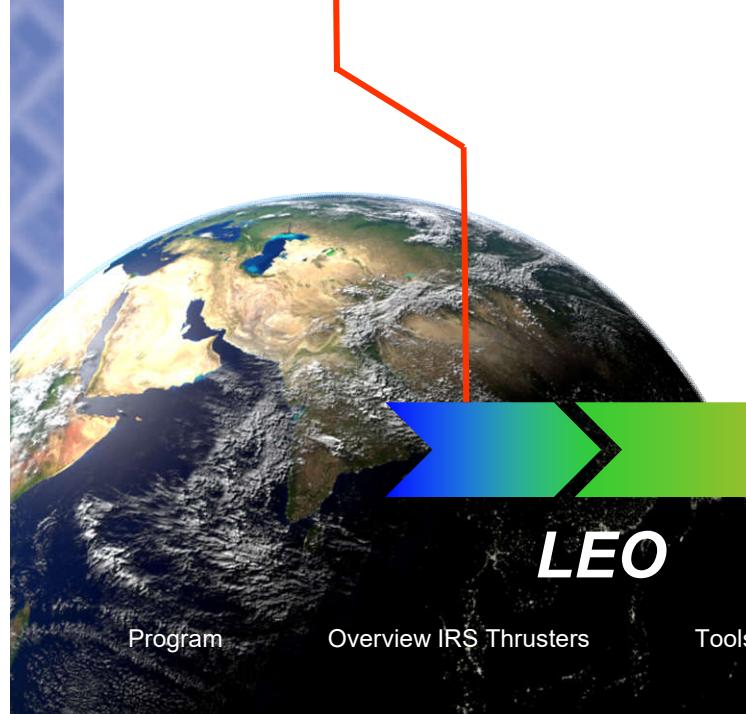
- Planet observation
- Space experiment

IEC Plasma Thruster Concept:

- Communication satellite
- GPS Navigation
- Astronomy

IEC Fusion Concept:

- Inter-planet traveling
- Deep-space exploration
- Manned mission

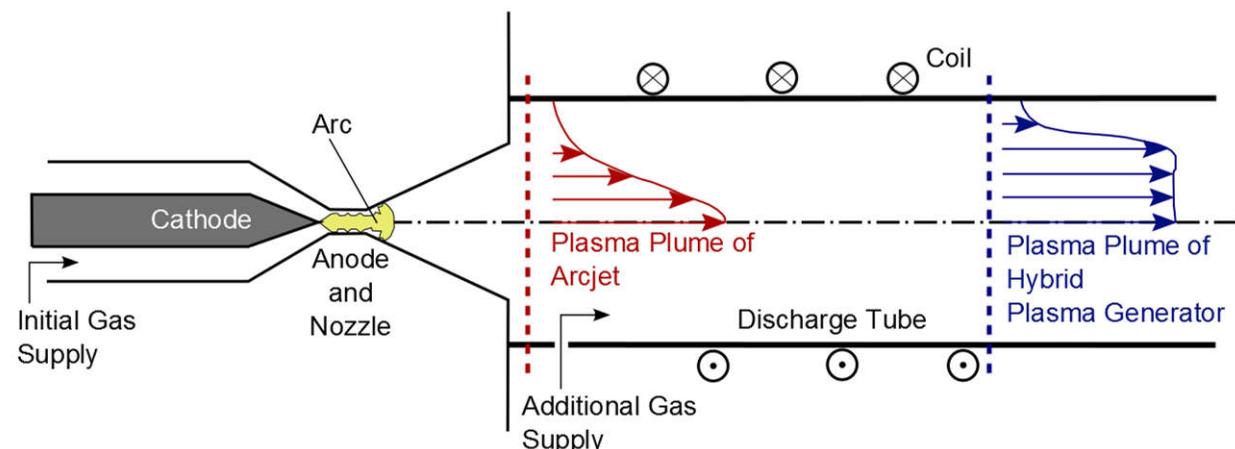
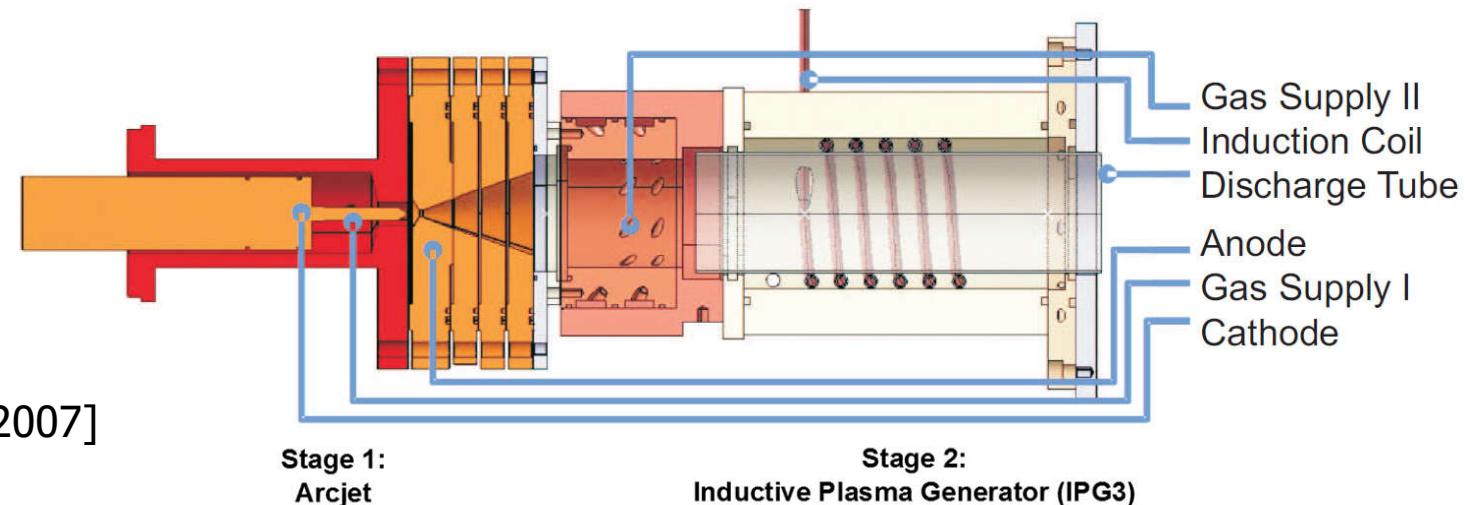


LEO

MEO

HEO & beyond

TIHTUS: Thermal-Inductive Hybrid Thruster of U o Stuttgart



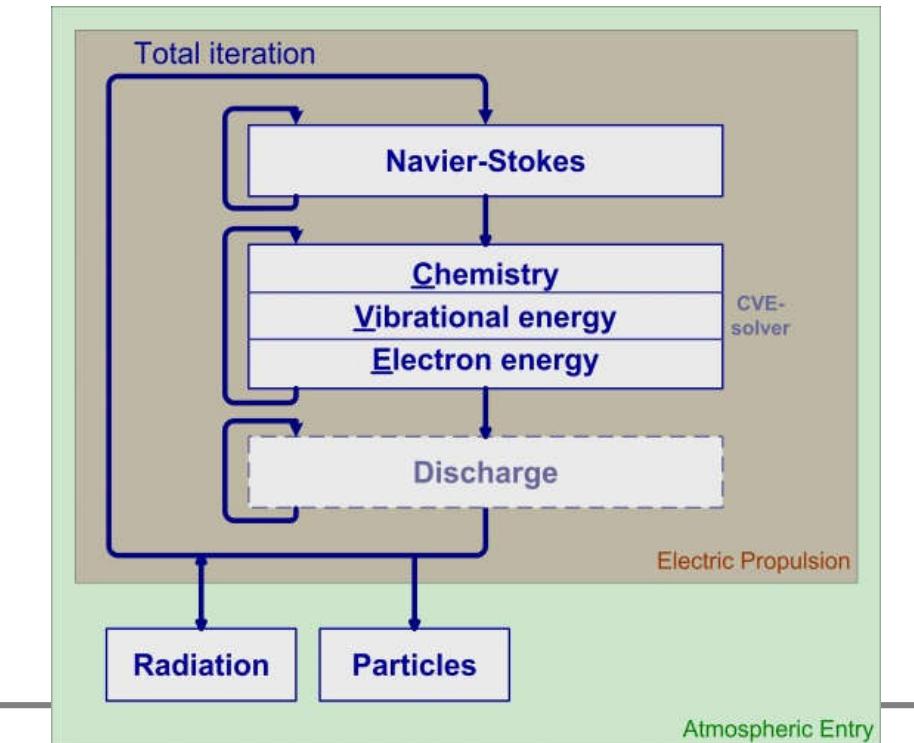


SINA - Simulation of plasma flows with discharges

Sequential Iterative Non-equilibrium Algorithm / Sequentieller Iterativer Nichtgleichgewichts-Algorimus

SINA:

→ Viscous plasma flows in chemical and thermal Nonequilibrium under consideration of discharges



Anwendungen:

- Atmospheric Entry
 - Erde (N_2/O_2), Mars (CO_2), Jupiter (H_2/He)
- Electric propulsion / Plasma wind tunnels
 - TLT, IPG, MPD (in Entwicklung)
- Two-phase flows
 - Plasma coating
 - Atmospheric Entry incl. Dust particles (e.g. Mars)



Development of TIHTUS

(exp.) Geometric
optimization, (num.)
Simulation



Efficiency increase,
Improvement of
understanding

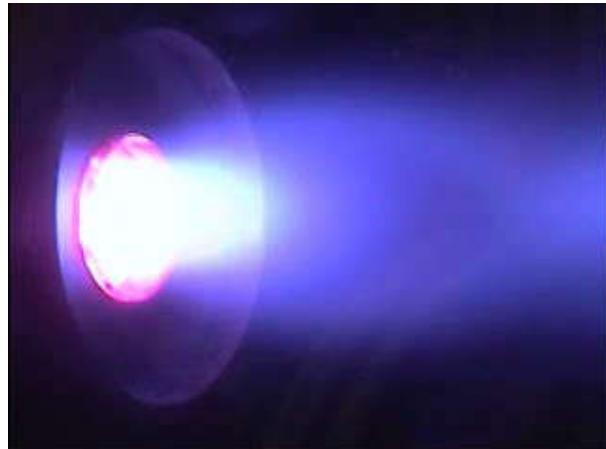


(exp.)
Alternative Propellants
→
Systemic Synergies:
2nd stage operation with
wastes (LSS), ISRU

DFG Deutsche
Forschungsgemeinschaft



THE SIR ROSS & SIR KEITH SMITH FUND





Summary

Promising candidates:

- PPT
- AF MPD
- IEC



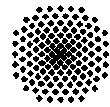
Summary: Thank you!

- T. Schönherr, A. Nawaz, G. Herdrich, H.-P. Röser, M. Auweter-Kurtz, *Influence of the electrode shape on the performance of the pulsed MPD thruster SIMPLEX*, Volume 25, Number 2, pp. 380-386, *Journal of Propulsion and Power*, Mar. – Apr. 2009.
- G. Herdrich, U. Bauder, D. Bock, Ch. Eichhorn, M. Fertig, D. Haag, M. Lau, T. Schönherr, T. Stindl, H.-P. Röser, M. Auweter-Kurtz, *Activities in Electric Propulsion Development at IRS*, Invited Talk/Paper 2008-b-02, Selected papers from the 26th International Symposium on Space Technology and Science, *Transactions of Japan Society for Aeronautical and Space Sciences*, Space Technology Japan, Vol. 7, No. ists26, pp. Tb_5-Tb_14, (2009).
- D. Petkow, G. Herdrich, R. Laufer, R. Gabrielli, O. Zeile, *Comparative Investigation of Fusion Reactions for Space Propulsion Applications*, 26th International Space Symposium on Technology and Science, Hamamatsu, Japan, 1.-8. Juni 2008, Selected papers from the 26th International Symposium on Space Technology and Science, *Transactions of Japan Society for Aeronautical and Space Sciences*, Space Technology Japan, Vol. 7, No.ists26, pp.Pb_59-Pb_63, (2009).
- D. Haag, M. Auweter-Kurtz, M. Fertig, G. Herdrich, *Numerical Simulations and Accompanying Experimental Investigations of Magnetoplasmadynamic Thrusters with Coaxial Applied Magnetic Field*, 26th International Space Symposium on Technology and Science, Hamamatsu, Japan, 1.-8. Juni 2008, Selected papers from the 26th International Symposium on Space Technology and Science, *Transactions of Japan Society for Aeronautical and Space Sciences*, Space Technology Japan, Vol. 7, No. ists26, pp.Tb_19-Tb_28, (2009).
- O. Troll, L. Conde, E. Criado, J. M. Donoso, G. Herdrich, Measurements of Plasma Properties Using Fast Sweep Langmuir Probes in Unmagnetized Weakly Ionized Plasmas, *Contributions to Plasma Physics*, Vol. 50, No. 9, Seiten 819-823, 2010 / DOI 10.1002/ctpp.201010138
- T. Schönherr, K. Komurasaki, R. Kawashima*, Y. Arakawa*, and G. Herdrich**, *Effect of Capacitance on Discharge Behavior of Pulsed Plasma Thruster*, Department of Advanced Energy, The University of Tokyo, *Department of Aeronautics and Astronautics, The University of Tokyo, **Institute of Space Systems (IRS), Universität Stuttgart, *Journal of IAPS*, Vol. 18, Nr. 1, pp. 23-28, Juni 2010.
- G. Herdrich, M. Fertig, D. Petkow, S. Kraus, S. Löhle, M. Auweter-Kurtz, *Operational behavior and application regime assessment of the magnetic acceleration plasma facility IMAX*, *Vacuum* 85 (2010) pp. 563-568, doi:10.1016/j.vacuum.2010.08.012.
- H. Böhrk, M. Lau, G. Herdrich, H. Hald, H.-P. Röser, *A porous flow control element for pulsed plasma thrusters*, *CEAS Space Journal*, Springer, DOI: 10.1007/s12567-011-0019-5, Oktober 2011.
- T. Schönherr, A. Nawaz, M. Lau, D. Petkow, and G. Herdrich, Review of pulsed plasma thruster development at IRS, *Transactions of the Japan Society for Aeronautical and Space Sciences*, *Aerospace Technology Japan*, vol. 8, no. ists27, pp. Tb 11–Tb 16, 2010.



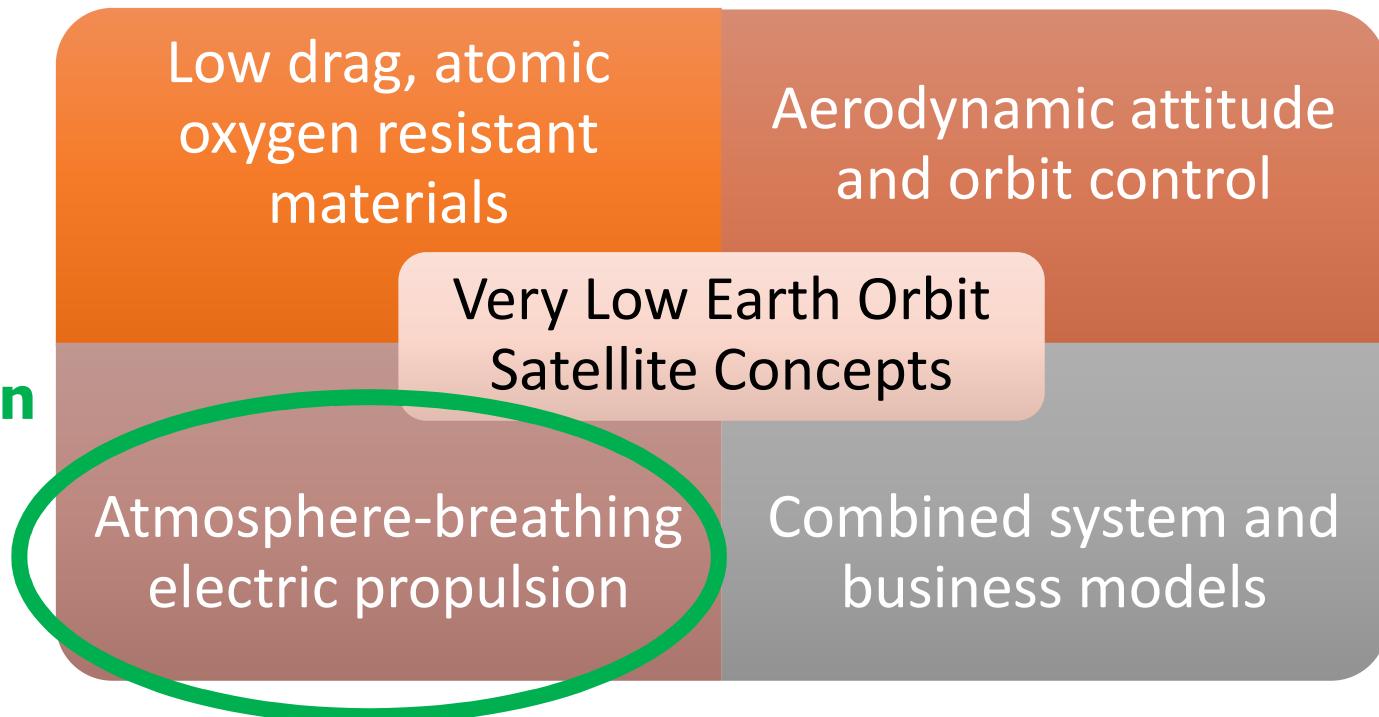
Summary: Thank you!

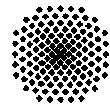
- M. Pfeiffer, D. Petkow, G. Herdrich, S. Fasoulas, Assessment of a numerical approach suitable for the M2P2 problem, *The Open Journal of Plasma Physics*, Volume 4, pp. 24-33, April 2011.
- D. Petkow, R. Gabrielli, G. Herdrich, R. Laufer, Generalized Lawson criterion for magnetic fusion applications in space, *Fusion Engineering and Design*, Volume 87, Issue 1, January 2012, pp. 30-38, [doi:10.1016/j.fusengdes.2011.08.008](https://doi.org/10.1016/j.fusengdes.2011.08.008)
- D. Petkow, G. Herdrich, M. Pfeiffer, A. Mirza, S. Fasoulas, M. Matsui, K. Komurasaki, On the probabilistic particle simulation of an arcjet flow expansion, *Vacuum Journal*, 02/2013; 88:58-62. DOI 10.1016/j.vacuum.2012.04.047
- G. Herdrich, U. Bauder, A. Boxberger, R.A. Gabrielli, M. Lau, D. Petkow, M. Pfeiffer, C. Syring, S. Fasoulas, Advanced plasma (propulsion) concepts at IRS, *Vacuum Journal*, 02/2013; 88:36-41. DOI:<http://dx.doi.org/10.1016/j.vacuum.2012.02.032>
- Tierno, S.P.; Domenech-Garret, J.L.; Donoso, J.M.; Jennewein, D.; Herdrich, G.; Fasoulas, S.; Conde, L., "Emissive Langmuir Probes in the Strong Emission Regime for the Determination of the Plasma Properties," *Plasma Science, IEEE Transactions on*, vol.41, no.4, pp.695,700, April 2013, doi: 10.1109/TPS.2013.2243760
- T. Schönherr, K. Komurasaki, G. Herdrich, Plasma front velocity and propellant utilization efficiency in a pulsed plasma thruster, submitted to the *Journal of Propulsion and Power*, Sept. 2012.
- B. Wollenhaupt, Q.H. Le, G. Herdrich, S. Fasoulas, H.-P. Röser, An Overview about International Thermal Arcjet Thruster Development, eingereicht beim *Journal of Propulsion and Power*, Okt. 2012.
- T. Schönherr, F. Nees, Y. Arakawa, K. Komurasaki, and G. Herdrich, Characteristics of plasma properties in an ablative pulsed plasma thruster, *Phys. Plasmas* 20, 033503 (2013); <http://dx.doi.org/10.1063/1.4794198> (8 pages).
- R. A. Gabrielli, D. Petkow, G. Herdrich, R. Laufer, H.-P. Roeser, Two Generic Concepts for Space Propulsion Based on Thermal Nuclear Fusion, *Acta Astronautica* 03/2014; 101:129.
- M. Lau, S. Manna, G. Herdrich, T. Schönherr, K. Komurasaki. Investigation of the Plasma Current Density of a Pulsed Plasma Thruster, *Journal of Propulsion and Power*, doi: 10.2514/1.B35131
- M. Lau, G. Herdrich, Plasma diagnostic with inductive probes in the discharge channel of a Pulsed Plasma Thruster, *Vacuum*, in Press, Available online 1 August 2014



This project has received funding from the European Union's Horizon 2020 research and innovation programme under agreement No 737183

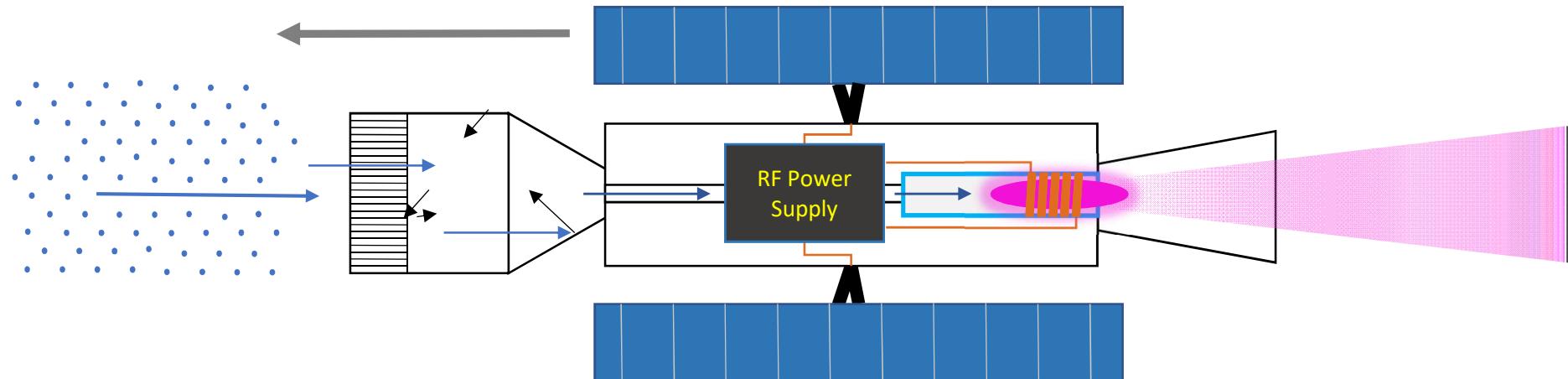
IRS Main Task

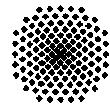




Atmosphere-Breathing Electric Propulsion (ABEP)

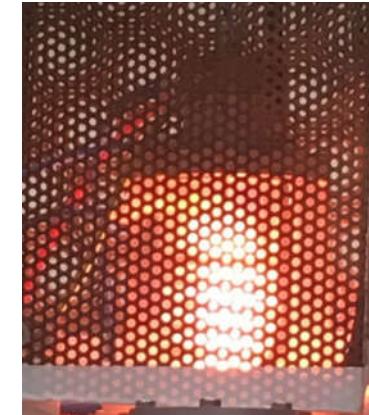
- Use of residual atmosphere as propellant for an electric thruster;
- Intake collects the atmosphere molecules and feeds the thruster;
- Thruster process and expel them through a nozzle to generate thrust.





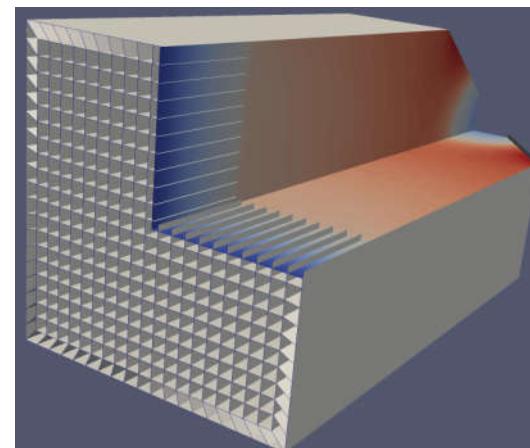
IRS is responsible to develop IPT and intake

- IPT:
 - Based on IPG6-S;
 - Passively cooled;
 - Optimized for ABEP related mass flow;
 - Optimized for input power 0.5 to 5.5 kW.



IPG6-S operating with N_2

- Intake:
 - Based on verified DSMC in-house code;
 - Analytical tool available;
 - Molecular trapping;
 - Optimized for IPT.



DSMC simulation of adapted intake geometry