Institute of Space Systems
University of Stuttgart

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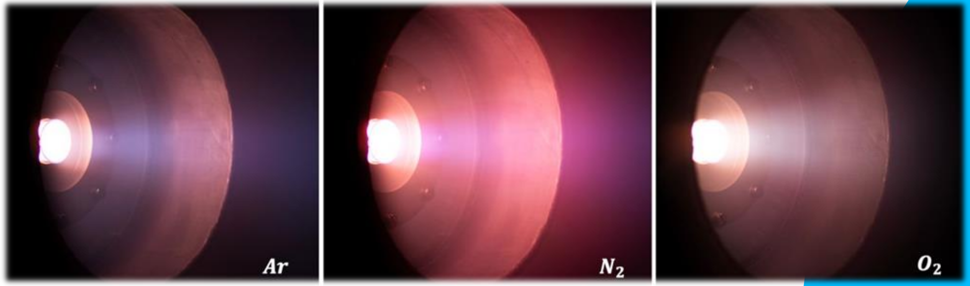
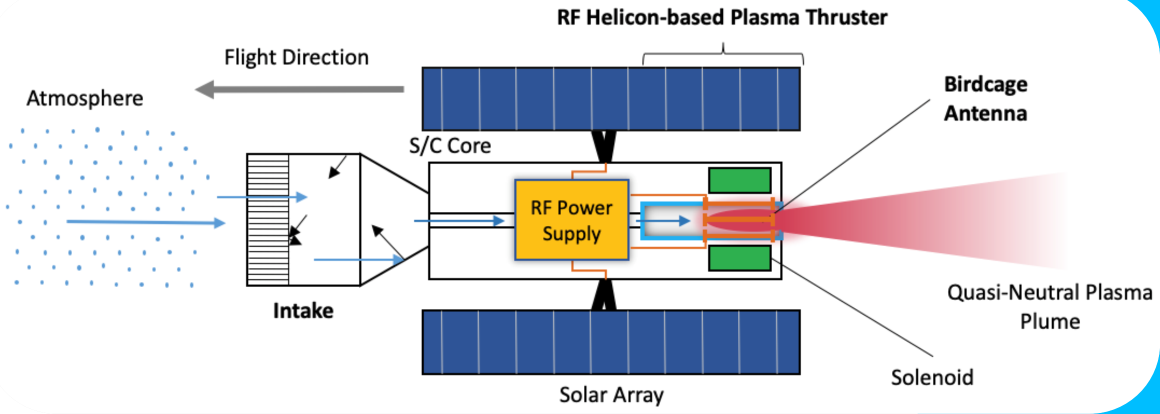




Current Status of the ABEP Developments

F. Romano, G. Herdrich, K. Papavramidis, J. Skalden, P. Maier

Final DISCOVERER General Assembly Meeting, 8-10 Feb. 2022

Brief Presentation Overview

- Atmosphere-Breathing Electric Propulsion (ABEP)
- Intake Principle of Operation and Designs
- Development and Test of the advanced RF Helicon Plasma Thruster

DISCOVERER

The path until today …

Prime: U. of Manchester
4 ¼ Years + 1 (due to pandemic)
5.7 M€
8 partners, 5 countries
www.discoverer.space

January 2017

Today

EU H2020 DISCOVERER: Development of the ABEP system

Scholarship

Ph.D. Development of an Electrodeless Plasma Thruster for an ABEP system

April 2015

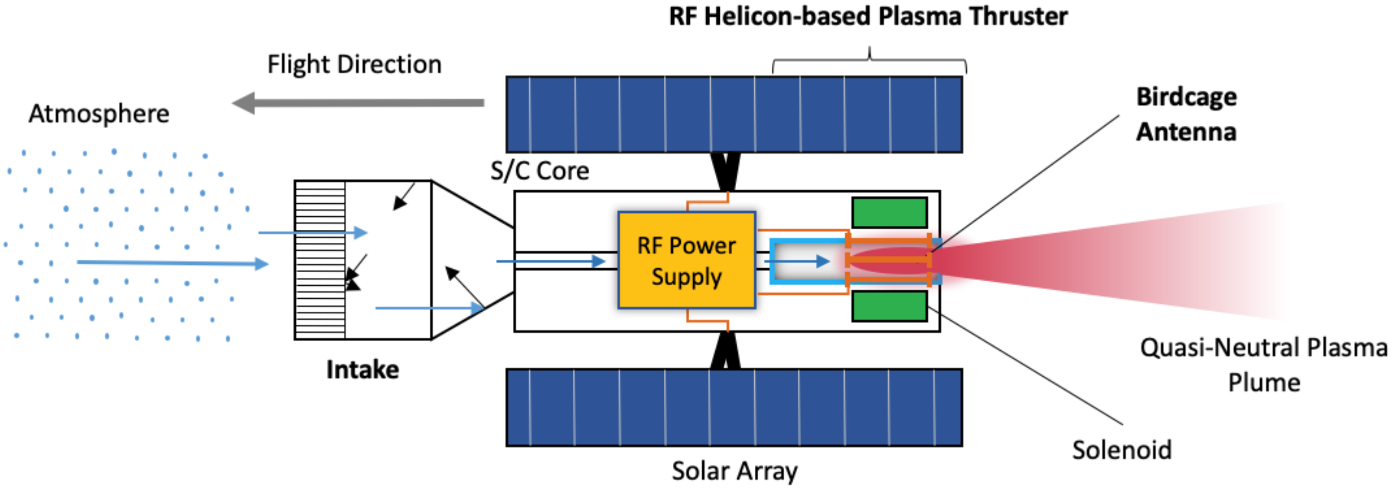
Time

Research Questions

1. *What are the main driving parameters and their ranges for designing an ABEP-based mission?*
2. *What is the principle of operation of an ABEP-intake and how can the (system) efficiency be maximized?*
3. *How to design an efficient electrodeless plasma thruster that operates on atmospheric propellant?*
4. *How can the more or less complex plasma physics-driven phenomena be approved i.e. how can we approve that our advanced Helicon is a Helicon?*
5. *What impact can application (e.g. EO or telecommunication), launcher and ABEP in general have referring to the platform design (i.e. the design of the satellite)?*

Atmosphere-Breathing Electric Propulsion (ABEP)

- Orbit at low altitudes and use the residual atmosphere as propellant, no tank required
- **Intake** collects the residual atmosphere, electric **thruster** ionizes and accelerates it to produce thrust
- Applicable to any celestial body with atmosphere

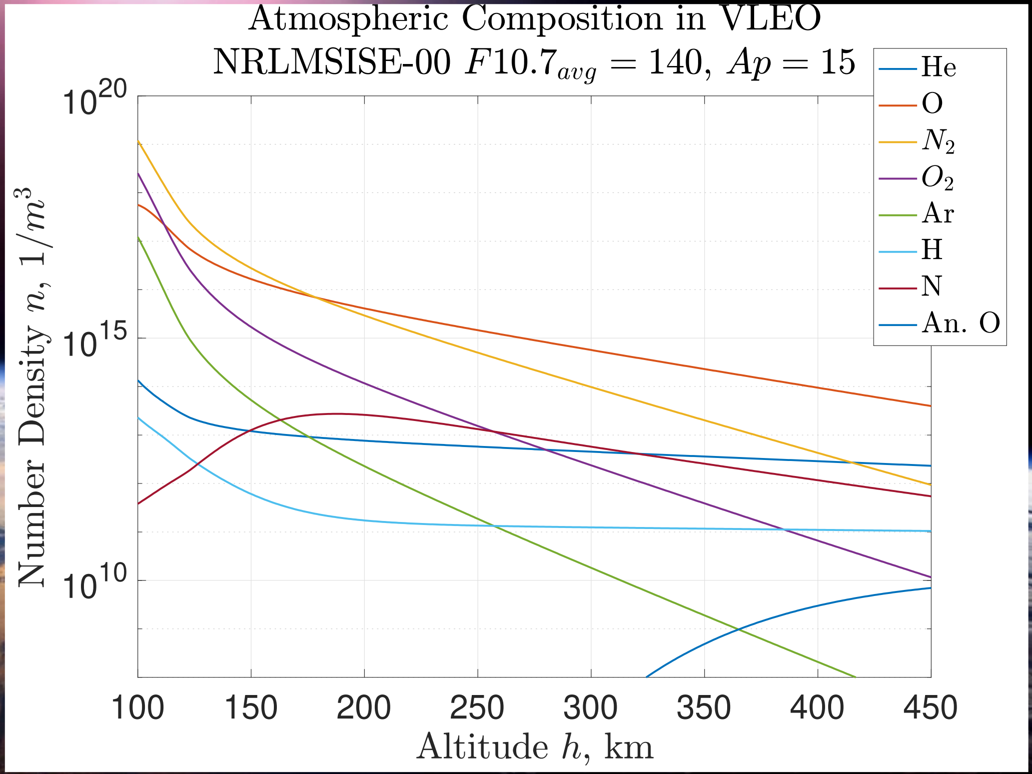


F. Romano, Y.-A. Chan, G. Herdrich, P.C.E. Roberts, et al. "RF Helicon-based Inductive Plasma Thruster (IPT) Design for an Atmosphere-Breathing Electric Propulsion system (ABEP)", Acta Astronautica 176: 476-483, November 2020, ISSN 0094-5765, DOI: 10.1016/j.actaastro.2020.07.008.

Very Low Earth Orbit (VLEO)

$h < \ 450 \text{ km},$ aerodynamics not negligible

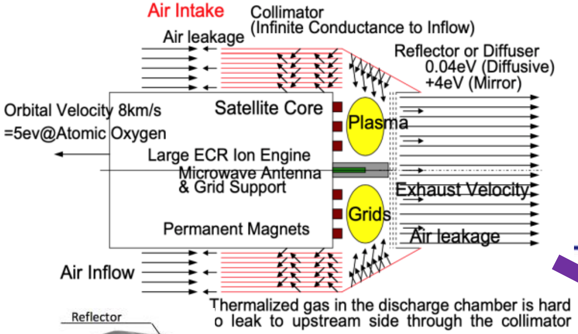
- Mostly Atomic Oxygen (AO) and N_2
- Atmospheric properties changes over time, location, solar activity, and altitude

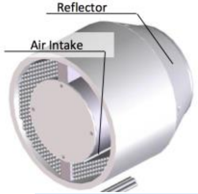


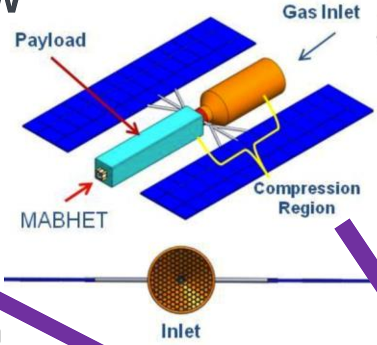
Advantages vs LEO

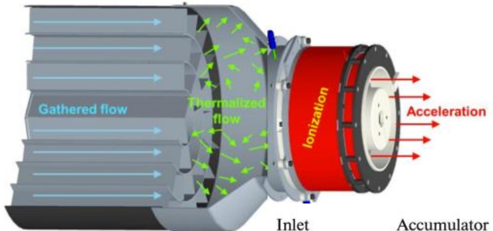
- Less complex optics
- Reduced antenna size and power
- Use of standard components, less radiation
- Reduced collision risk
- Self End-of-Life satellite disposal

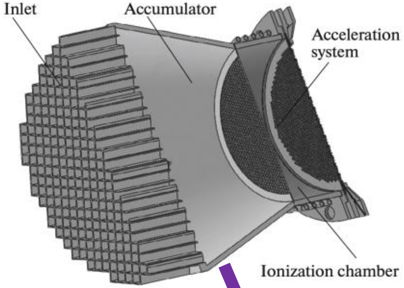
ABEP Literature Review

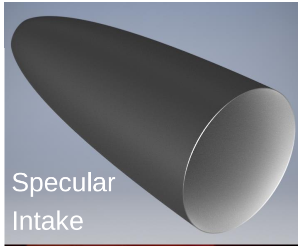


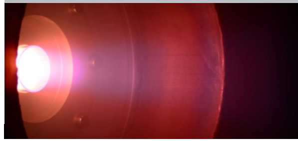












	ABCHT ECR + HET	Michigan RPT/ HHT	ABIE - ECR + Acc. Grid	BUSEK HET	RAM-EP HET	TsAGI / RIAME MAI RIT	USTUTT (IRS) HPT
$\eta_c, -$	0.35	0.9	0.46	$0.2 - 0.4$	$0.28 - 0.32$	$0.33 - 0.34$	$0.43 - 0.94$
$\eta_T, -$	0.25	0.25	NA	> 0.2	NA	$0.4 - 0.6$	> 0.2
A_{in}, m^2	0.25	0.25	0.48	0.15	0.126	1	$0.005 - 0.019$
h, km	> 220	200	$150 - 200$	$120 - 180$	$120 - 250$	$185 - 222$	$120 - 250$

Overview on RF Thrusters

Many designs of electrodeless thrusters have been proposed recently..

- A summary of helicon-type thrusters is shown in the table [1] below with respective KPI:
  - Specific impulse, Thrust efficiency, Thrust, Operational power
- Charactersitics motivating application of RF thrusters for ABEP
  - Quasineutral jet → no neutralizer needed
  - Flexibility in terms of propellant (composition) and density
  - No life time problems referring to electrodes (no electrodes)
  - Significant potential for comparably higher thrust efficiencies (example: “air”-driven HET: 15%)

Prototype	I_{sp} (s)	η_t (%)	Thrust	η_m (%)	Power	Reference
Mini helicon thruster experiment (mHTE)	1000–4000	18–20	10 mN	90	700–1100 W	[59]
Helicon plasma hydrazine combined micro (HPHCOM)	1200	13	1.5 mN	90	50 W	[85]
	422	13	0.5 mN	—	8 W	[86]
Permanent magnet expanding plasma (PMEP)	500	1	3 mN	<50	700 W	[87]
High power helicon thruster (HPHT)	4750 (H_2)	—	—	—	30 kW	[88]
Helicon double layer thruster (HDLT)	280	C1	1–2.8 mN	—	250–650 W	[89]
Permanent magnet helicon plasma thruster (PM-HPT)	2000	7.5	15 mN	—	2 kW	[90]

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

Literature review on RF Thrusters (2/4)

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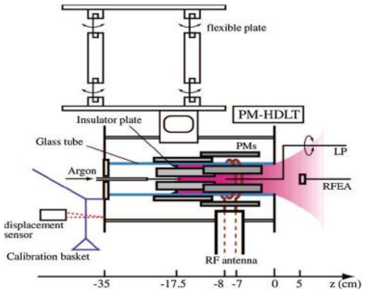
Tohoku University – Helicon Plasma Thruster (HPT) [2]

- Developed helicon plasma source for high power electric propulsion
- Use of permanent magnets
- Focus on high efficient device
- No ABEP application investigated

Thruster parameter	Value
Power	6000 W
Thrust	67 mN
Weight-specific impulse	3256 s
Thrust efficiency	17.8%
Propellant	Argon
Thruster length	350 mm
Plume potential	Quasi-neutral
Mass flow rate	2.1 mg/s



Australian National University – Helicon Double Layer Thruster (HDLT) [3]

- Developed new type of thruster -> HDLT
- Scalable in power and geometry
- Focus on system simplicity
- No ABEP application investigated

Thruster parameter	Value
Power	500 W
Exhaust velocity	15 km/s
Plasma density	10^{12} cm^{-3}
Operational pressure	$2{\cdot}10^{-4}$ - $2{\cdot}10^{-5}$ mbar
Propellant	Xenon
Discharge channel length	310 mm
Plume potential	Quasi-neutral
Mass flow rate	Not provided

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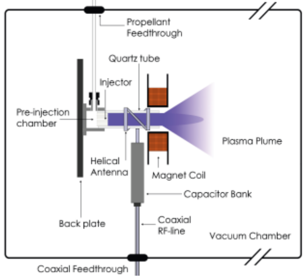
Literature review on RF Thrusters (3/4)

University Carlos III Madrid – Helicon Plasma Thruster (HPT) [4]

- Held studies on helicon plasma thruster – breadboard development
- Focus on increasing thruster‘s TRL
- Aim to provide complete EP system
- Target to LEO/MEO missions – design foresees tanks
- Diagnostics (LP, FP, RPA) used for perfomance assessment

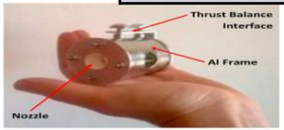


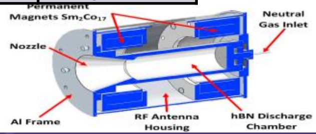
Thruster parameter	Value
Power	450 W
Thrust	5.6 / 7.9 mN
Specific impulse	1120 / 790 s
Thrust efficiency	9.1%
Propellant	Xenon, Argon
Discharge channel length	125-150 mm
Plume potential	Quasi-neutral
Flow rate	2.5-20 sccm, Argon 5-50 sccm, xenon

T4i – Magnetically Enhanced Thruster (MET) [5]

- Developed MET as part of REGULUS propulsion platfo
- Most advanced system wrt to TRL
- Support medium to large cubsats
- Orbits of 400km – use of onboard propellant

Thruster parameter	Value
Power	15 – 55 W
Thrust	0.3 – 0.85 mN
Specific impulse	300 – 850 s
Thrust efficiency	7%
Propellant	Xenon
Thruster length	120 mm
Mass flow rate	0.1 mg/s





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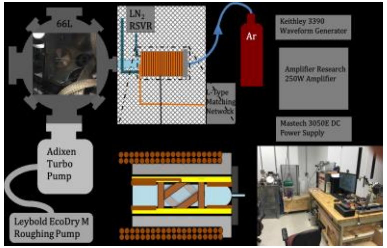
Literature review on RF Thrusters (4/4)

University of Maryland – Superconducting Helicon Plasma Thruster (HPT) [6]

- Investigation on HPT incorporating superconducting magnets (SCM)
- Comparison with "conventional" HPT
- Better thrust efficiency
- Lower plasma densities and thrust (also Isp)
- Ignition achieved at very low power (7W)

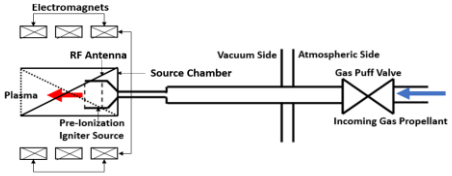


Thruster parameter	Value
Power	30 W
Thrust	0.2 mN
Specific impulse	220 s
Thrust efficiency	40%
Propellant	Argon
Discharge channel length	305 mm
Flow rate	3.1 sccm

University of Washington – High Power Helicon (HPH) [7]

- Developed high power helicon devices
- Cluster of thrusters
- Increase of exhaust velocity of 60%

Thruster parameter	Value
RF charge voltage	262.5 V
Magnetic field	350 G
Plasma density	$5 \cdot 10^{18}$ m^{-3}
Exhaust velocity	18.3 km/s
Specific impulse	1800 s
Propellant	Argon
Mass flow rate	Not provided



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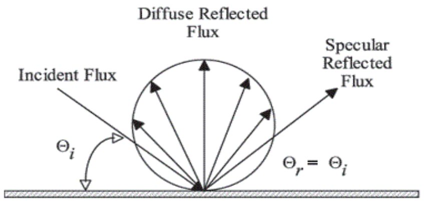
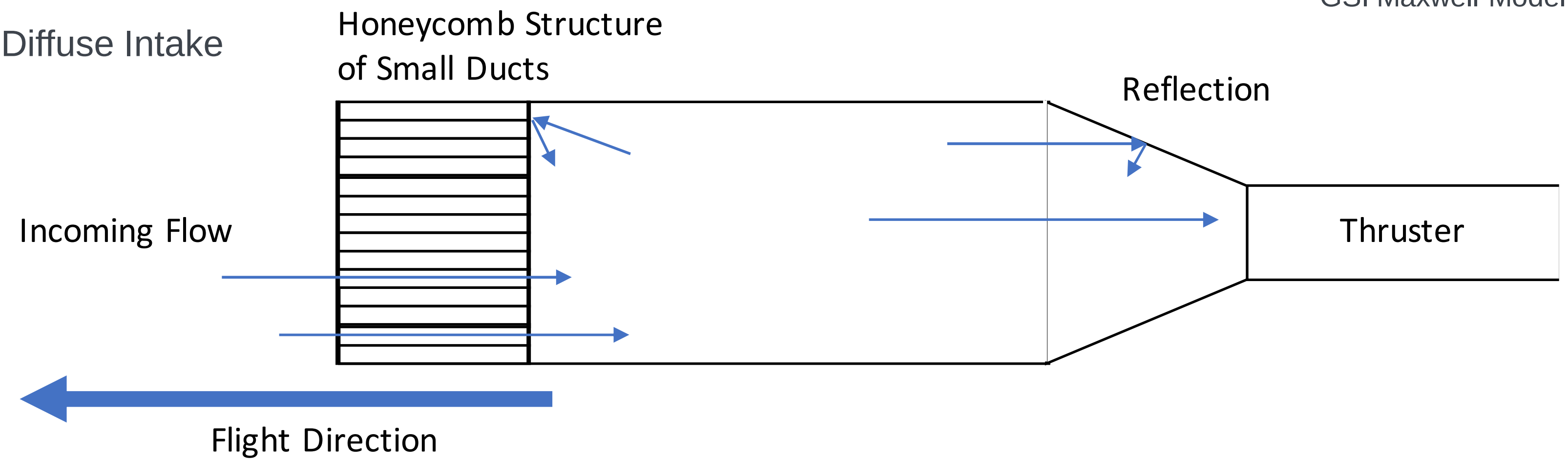
Intake: Principle of Operation

- Free Molecular Flow ➔ Design driven by gas-surface-interaction (GSI) properties
- Design based on in-house (verified) DSMC code PICLas
- Specular reflecting materials ➔ Optics/Telescope-like design
- Diffuse reflecting materials ➔ Molecular trap



GSI Maxwell Model

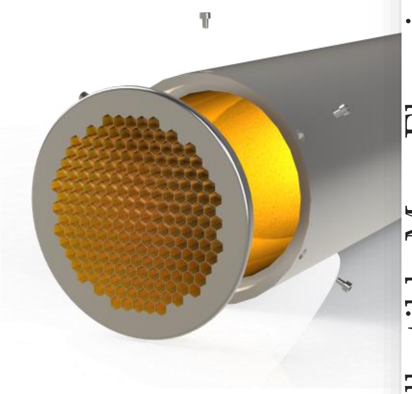
Diffuse Intake

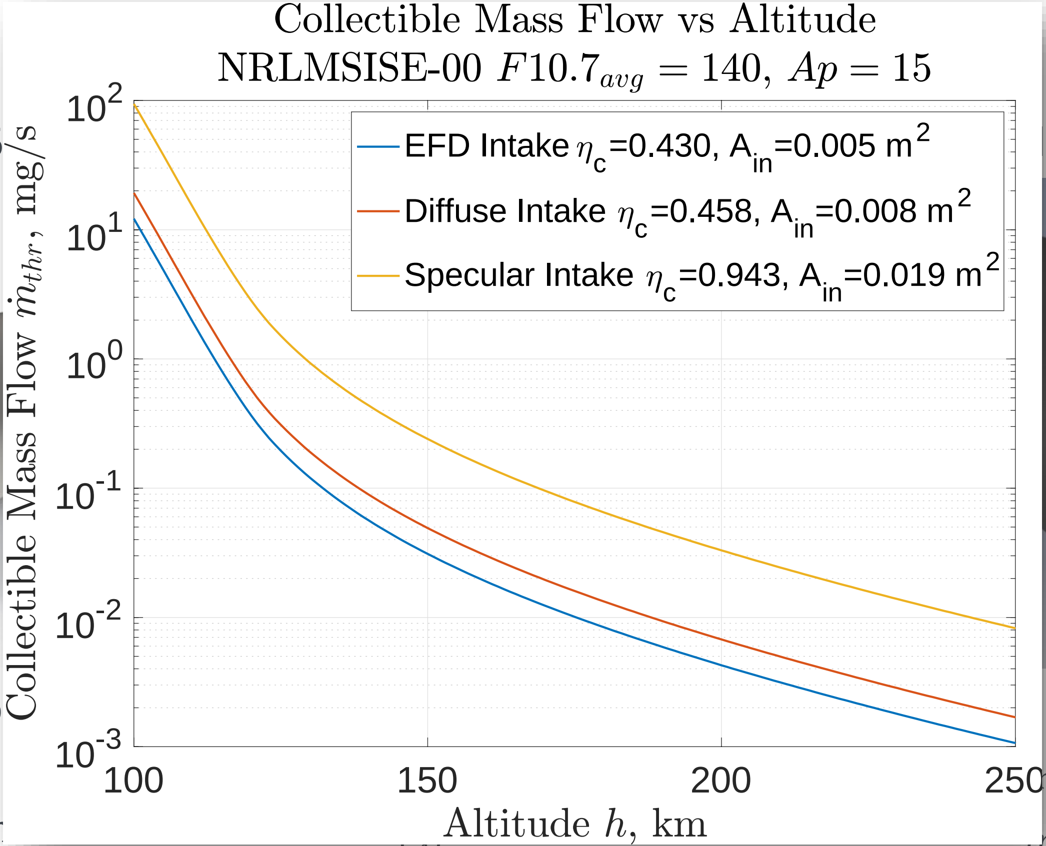


Intake Designs

EFD Intake (2015

ntake (2020-)





$\eta_C \sim 43$ %

$A_{in} \sim 0.00$

$D_{in} \sim 8$ cm

~ 94 %

~ 0.020 m^2

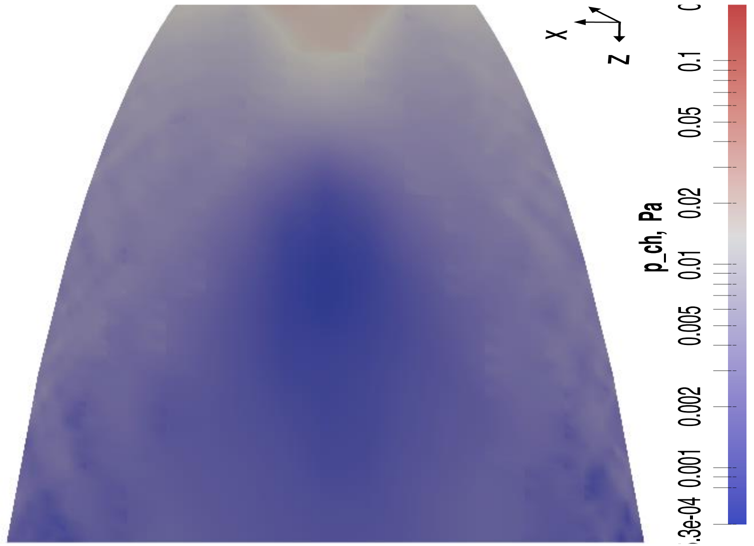
~ 16 cm

Specular Intake

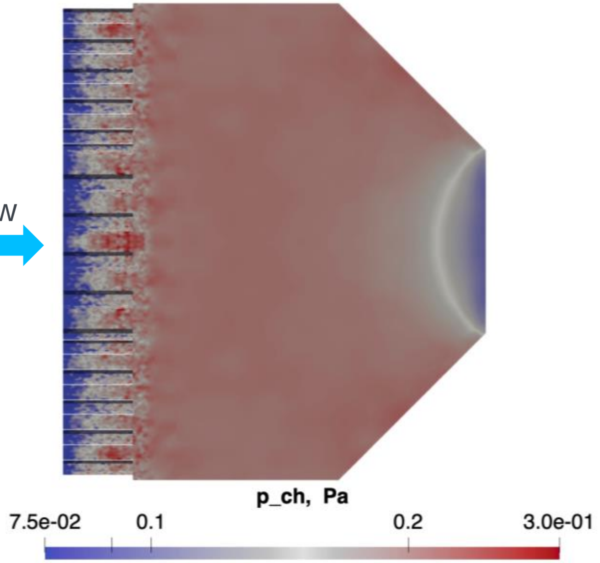
Pressure Distribution, PICLas Results, Figures not to scale

Diffuse Intake

Inflow



Inflow



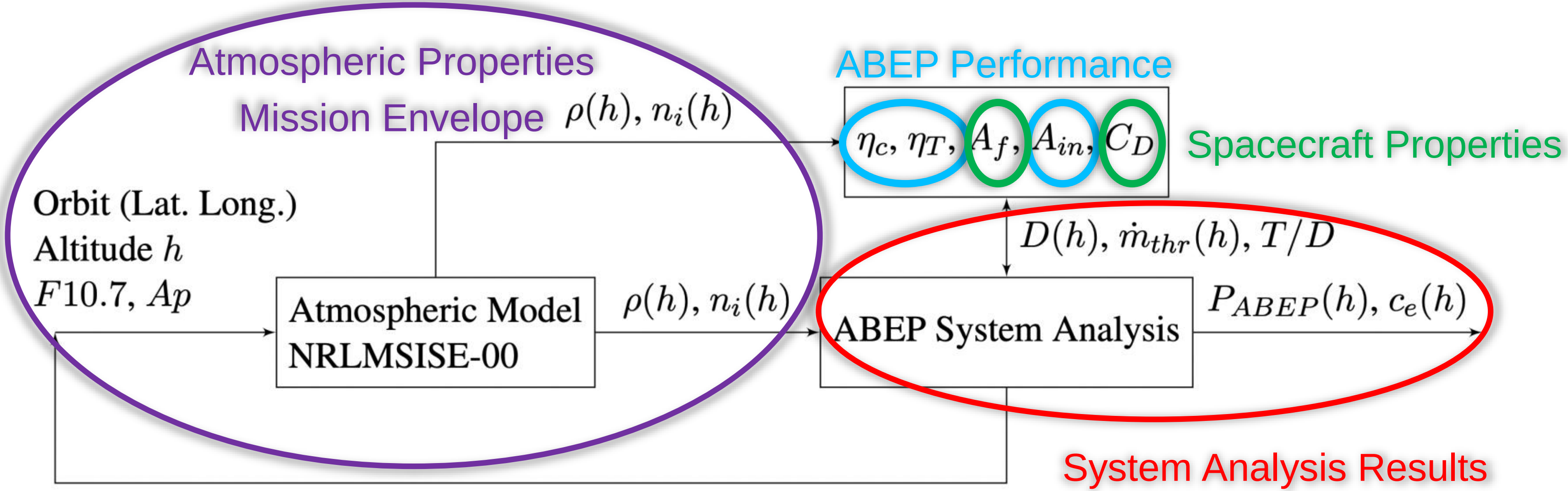
Flow Misalignment: for 5^o Specular Intake: $\Delta\eta_c$~0%, Diffuse Intake: $\Delta\eta_c$~17%
for 10^o Specular Intake: $\Delta\eta_c$~5%, Diffuse Intake: $\Delta\eta_c$~41%

F. Romano, J. Espinosa-Orozco, M. Pfeiffer, G. Herdrich, N.H. Crisp, P.C.E. Roberts, et al., “Intake design for an Atmosphere-Breathing Electric Propulsion System (ABEP)”, Acta Astronautica 187: 225-235, October 2021, ISSN 0094-5765,DOI: 10.1016/j.actaastro.2021.06.033.

System Analysis

Loop Link

Spacecraft's properties, ABEP performance (η_c, η_T), and atmospheric properties depending on the mission envelope: h, Lat., Long., duration (sol. act.), T/D required.



System Analysis

Aerodynamic Drag

$$D(h) = \frac{1}{2}\rho(h)v^2(h)C_D A_f$$

Collectible Mass Flow

$$\dot{m}_{thr}(h) = \rho(h)A_{in}v(h)\eta_c$$

ABEP Thrust

$$T(h) = \dot{m}_{thr}(h)\mathrm{c_e}(\mathrm{h})$$

Jet Power

$$\mathrm{P_{jet}}(h) = \frac{1}{2}\,\dot{m}_{thr}(h)\,c_e^2(h)$$

By Equaling

$$T(h) = D(h)$$

Along with the relation

$$P_{ABEP} = P_{jet}/\eta_T$$

Required ABEP Power

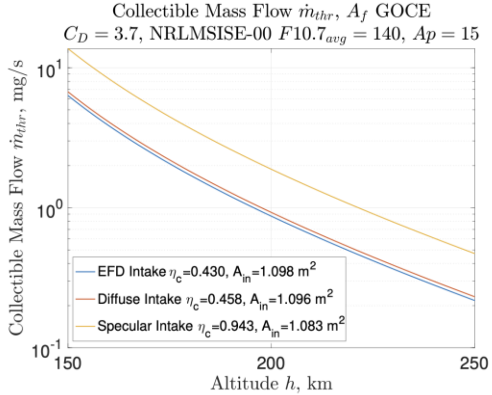
$$P_{ABEP} = \frac{1}{2}\rho(h)v^3(h)A_f^2C_D^2\frac{1}{A_{in}\eta_c\eta_T}$$

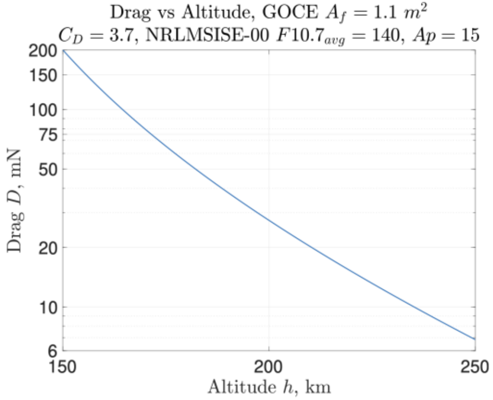
Atmospheric Properties and Mission Envelope

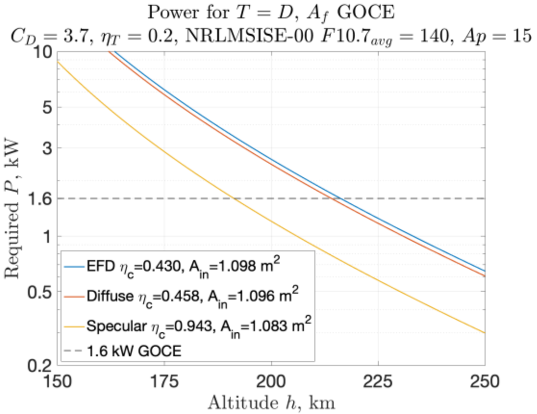
Spacecraft Properties

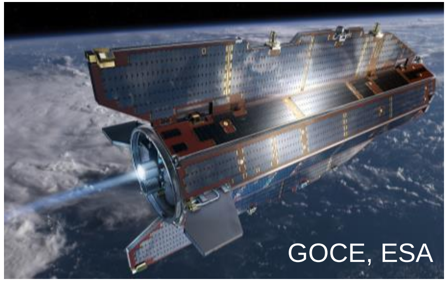
ABEP Performance

System Analysis applied to a GOCE-like Satellite








GOCE, ESA

GOCE Satellite Main Properties

$A_f = 1.1\ \mathrm{m}^2$

$C_D = 3.7$

$P = 1.6\ \mathrm{kW}$

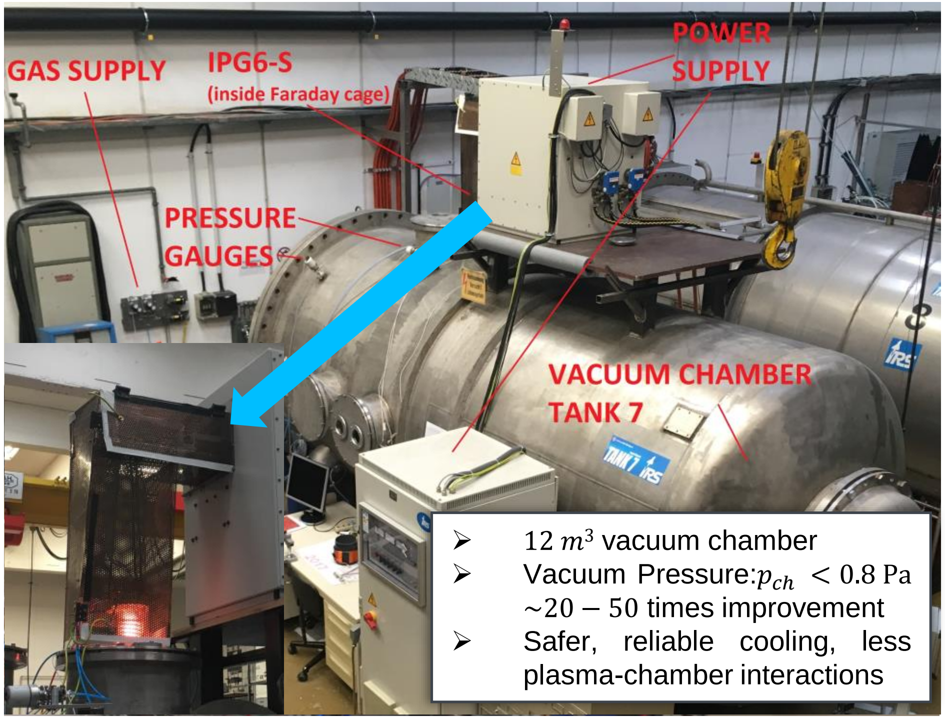
For the ABEP Performance

η_c —	η_T —
$0.43, 0.46, 0.94$	0.2

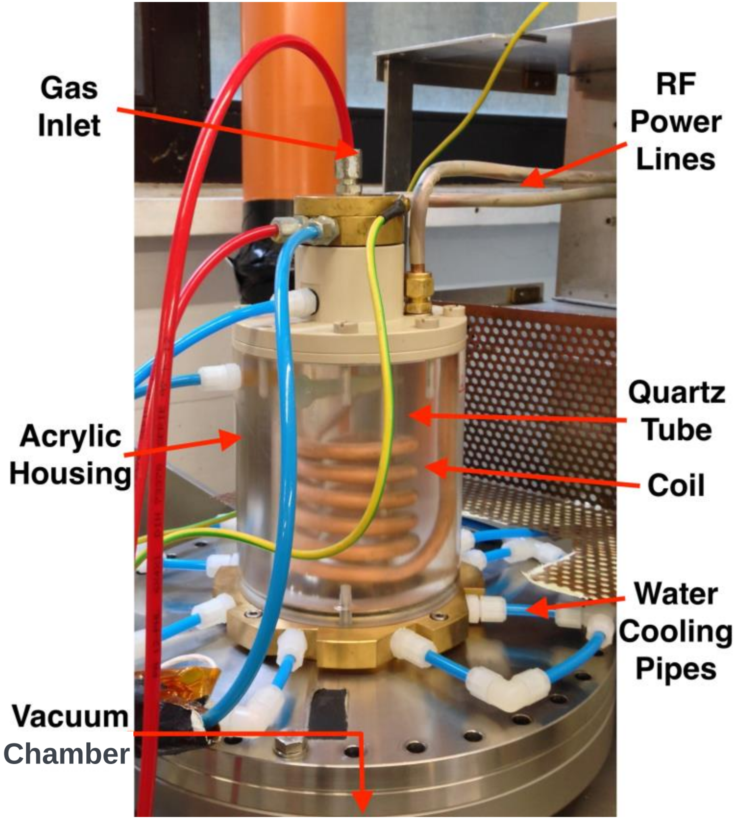
GOCE-like ABEP-based in VLEO

P_{ABEP} kW	h km	T/P mN/kW	I_{sp} $\times 10^3$s	C_D —
$1.6 - 0.3$	$190 - 250$	$10 - 24$	$1.5 - 3.0$	3.7

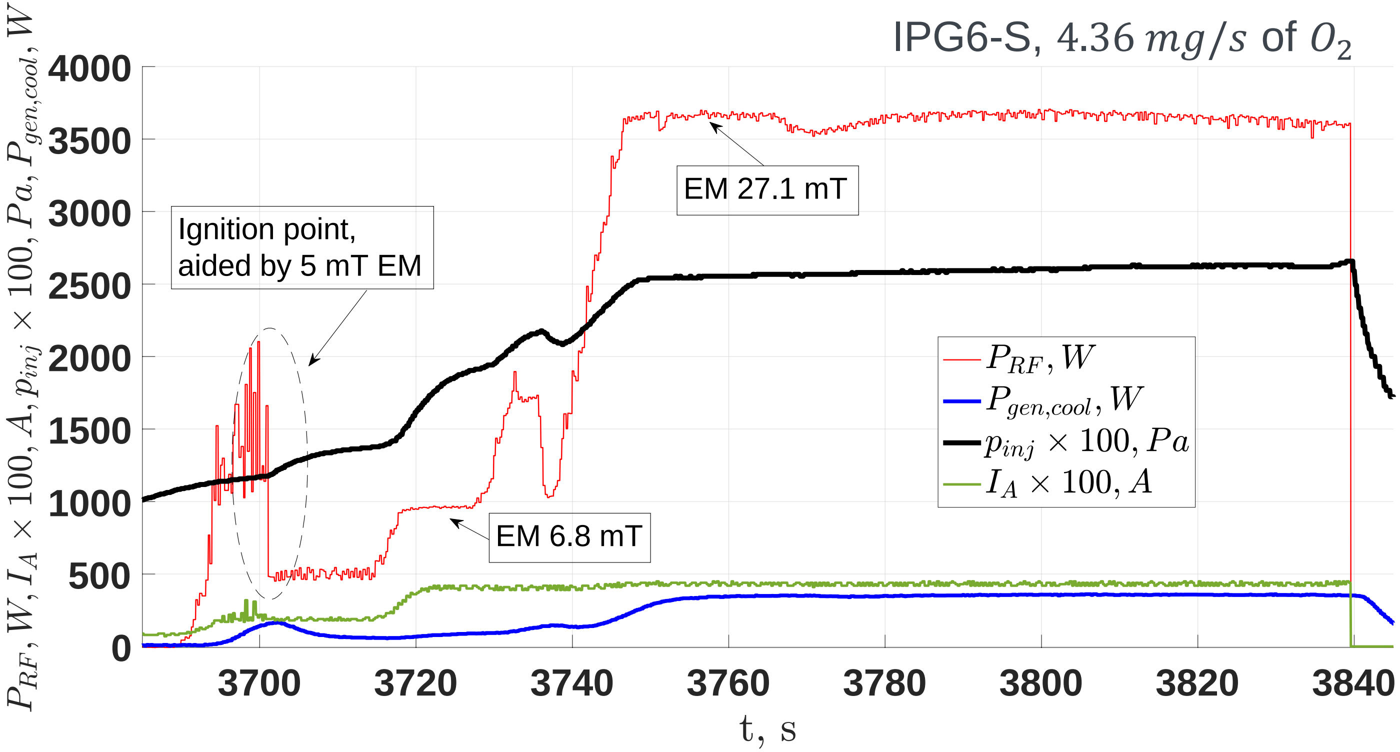
Experimental Activity with IPG6-S



- $12\ m^3$ vacuum chamber
- Vacuum Pressure: $p_{ch} < 0.8$ Pa $\sim 20-50$ times improvement
- Safer, reliable cooling, less plasma-chamber interactions



Testing IPG6-S with applied magnetic field.



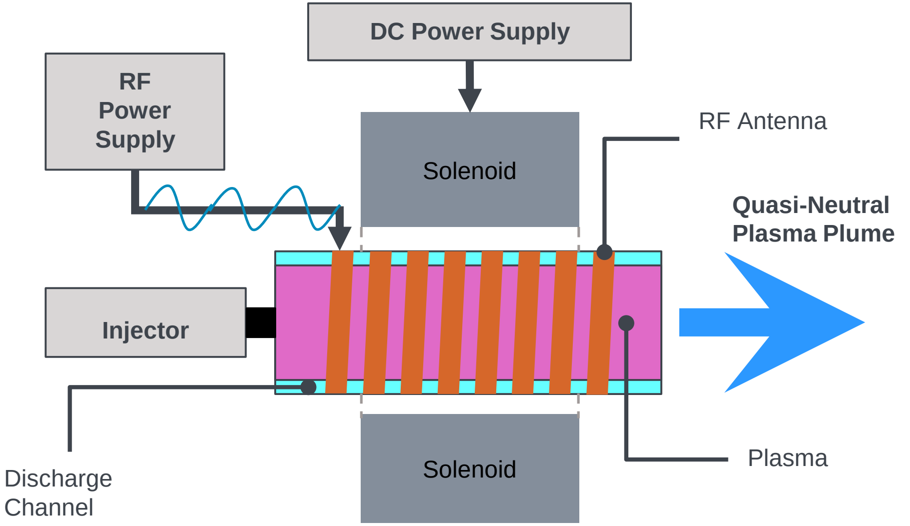
Effects of applied B-field

- Reduction of power oscillations, increase of absorbed power
- Hints to Helicon mode and/or significant inductivity change

F. Romano, G. Herdrich, T. Binder, A. Boxberger, C. Traub, S. Fasoulas, T. Schönherr, P. Roberts, et al., "Effects of applied magnetic field on IPG6-S, test-bed for an ABEP-based inductive plasma thruster (IPT)", Space Propulsion 2018, Seville, Spain, 14-18/05/2018, SP2018 00412.

Electric Thruster

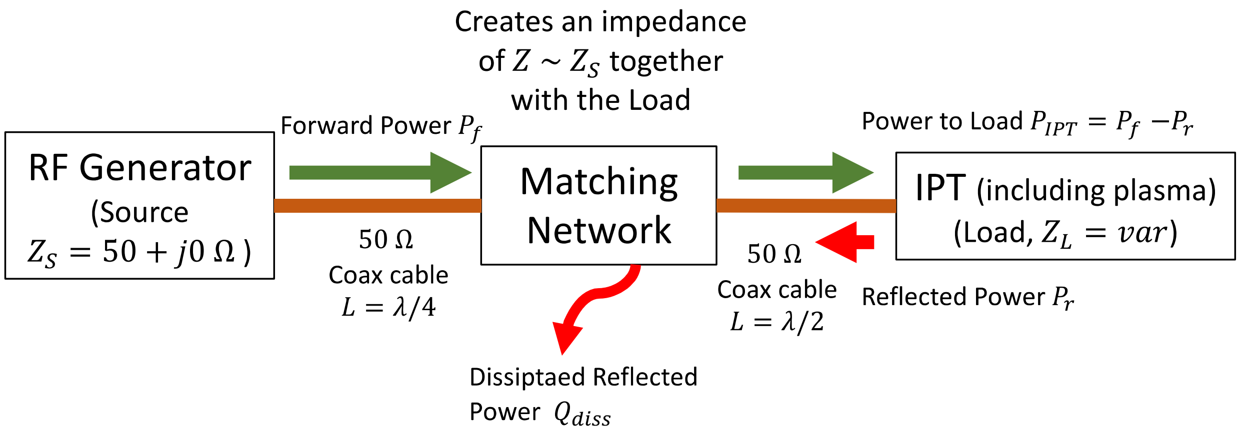
- Large I_{sp} ➔ efficient, low thrust, scalable
- Conventional thrusters operating on $\mathrm{N_2/O_2}$:
  - Erosion of accelerating grids, discharge channels
  - Need of a neutralizer
  - Atmosphere is not a uniform environment
    - Variable pressure, composition, and density
- Electrodeless plasma thruster:
  - No electrodes, no neutralizer, propellant variability



Thruster Design

The new electrodeless plasma thruster design started using HELIC and ADAMANT codes

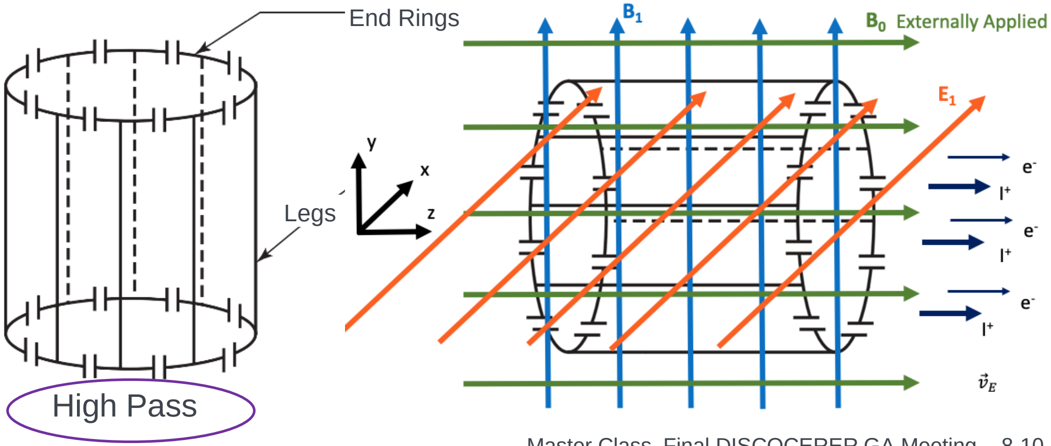
- Maximize exhaust velocity ➔ high ionization degree ➔ helicon plasma
- Easy (re)-ignitions, $n_e > 1 \times 10^{17} m^{-3}$
- $f > 27.12$ MHz, applied B-field $B_0 = 30 - 70\ mT$ ➔ Acquired 40.68 MHz RF Generator, solenoid
- Seek better antennae, RF circuit needs optimization



Birdcage Antenna

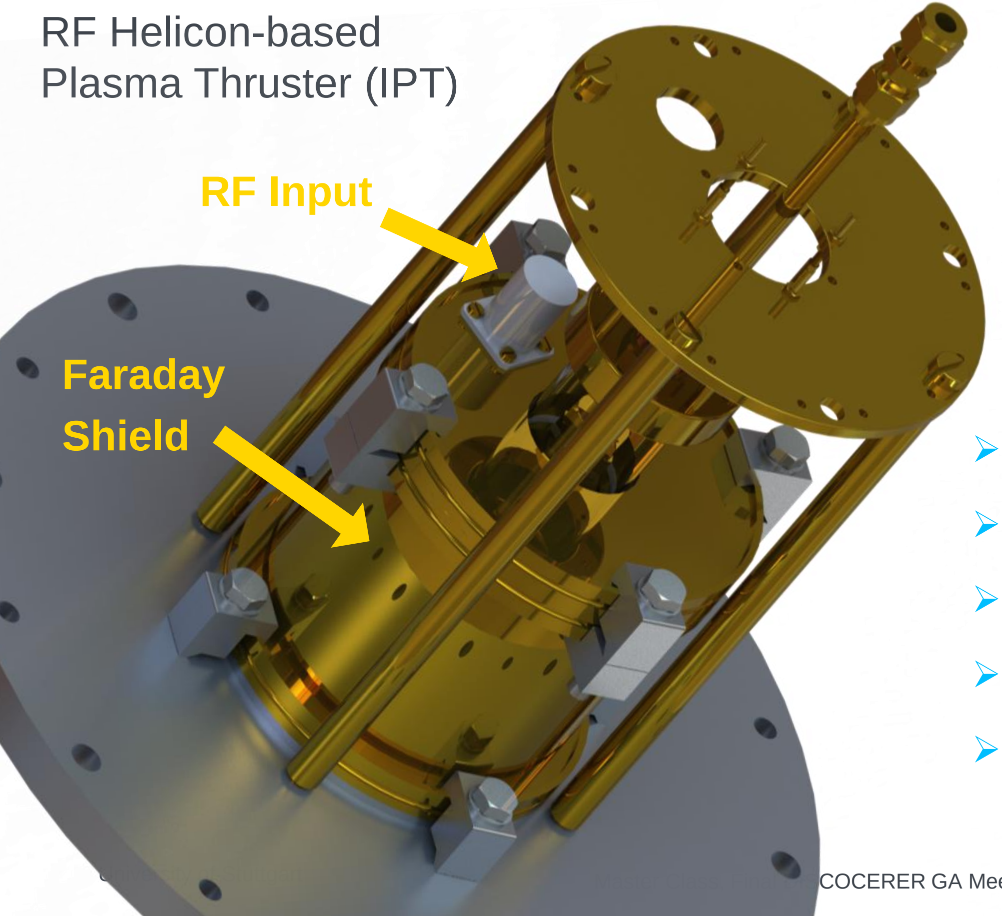
- Created for Magnetic Resonance Imaging (MRI)
- Operates at **resonance frequency** ➔ Partially matched load: $X = 0\,\Omega$ ➔ **Electrical efficiency**
- **Sinusoidal** distribution of the current around a cylinder ➔ Homogenous transversal lin. polarized B-field
- Field configuration ➔ Drift velocity to ions and electrons along same direction
- Divergence of applied B-field at the exhaust ➔ Thrust

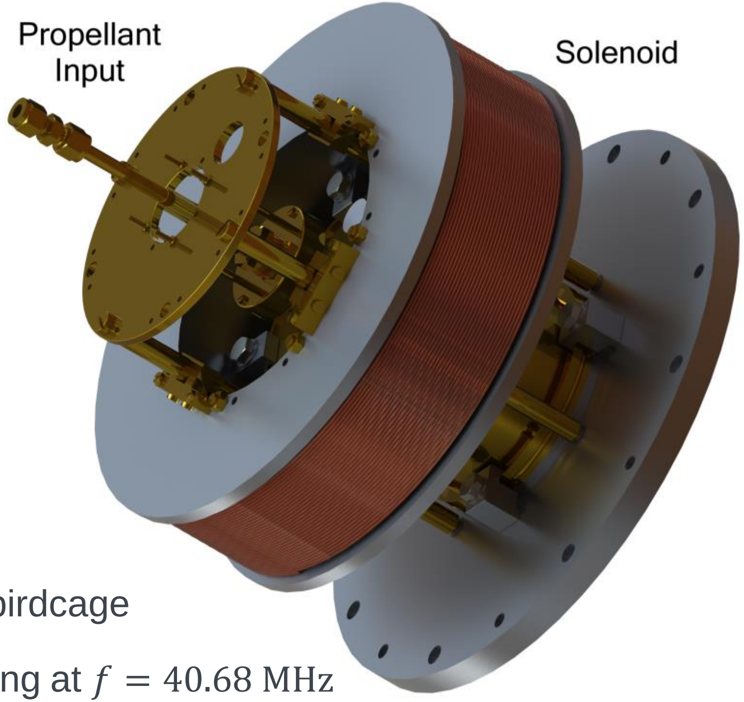
➔ **Propulsion**



$$\vec{v}_E = \frac{1}{\vec{B}^2}\left\|\begin{matrix}\hat{x} & \hat{y} & \hat{z}\\ E_1 & 0 & 0\\ 0 & B_1 & B_0\end{matrix}\right\| = \frac{1}{{B_0}^2 + {B_1}^2}\left\{\begin{matrix}0\\ -E_1B_0\\ E_1B_1\end{matrix}\right\}$$

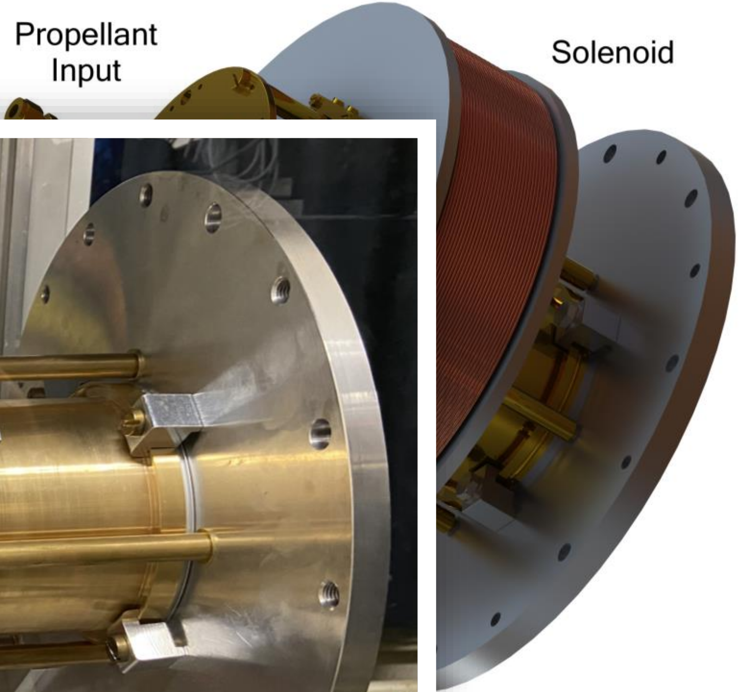
RF Helicon-based Plasma Thruster (IPT)

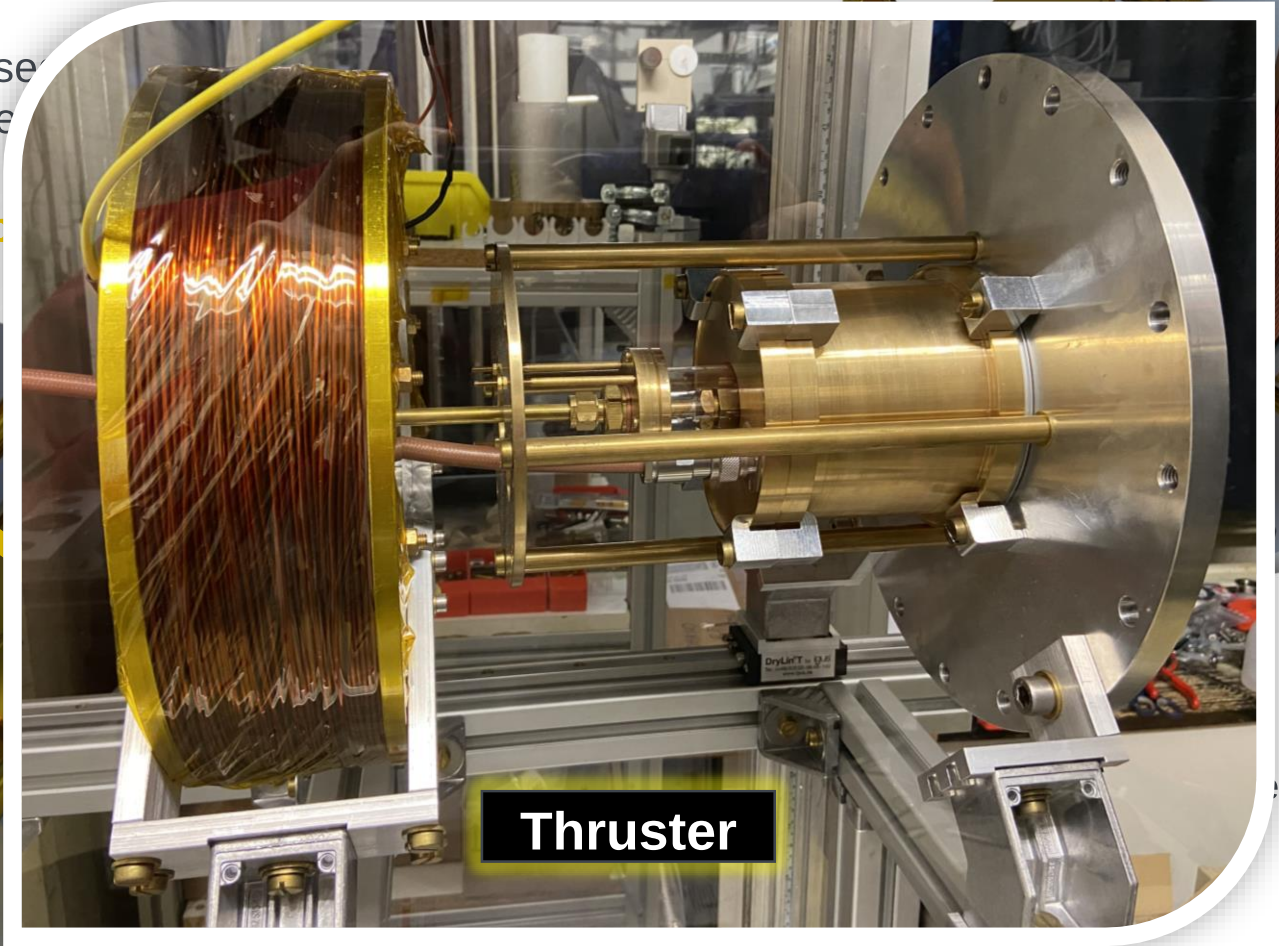




- 8 legs birdcage
- Operating at $f = 40.68$ MHz
- Injector for fine tuning
- $P_{in} < 1\ kW$
- XFdtd® software to extract required capacitance

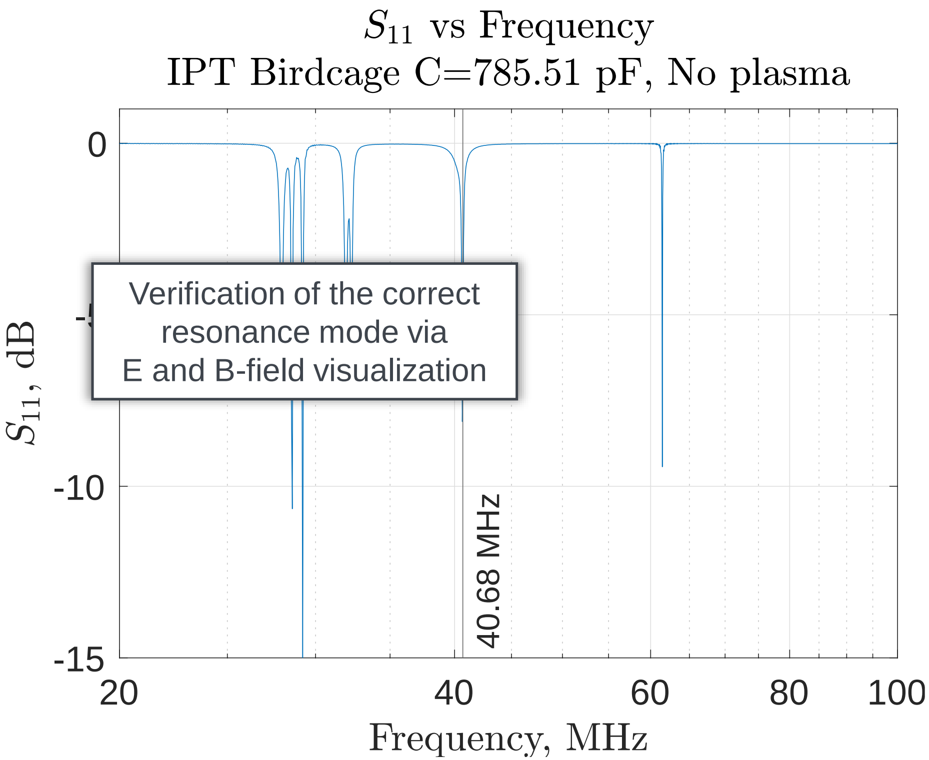
RF Helicon-base
Plasma Thruste



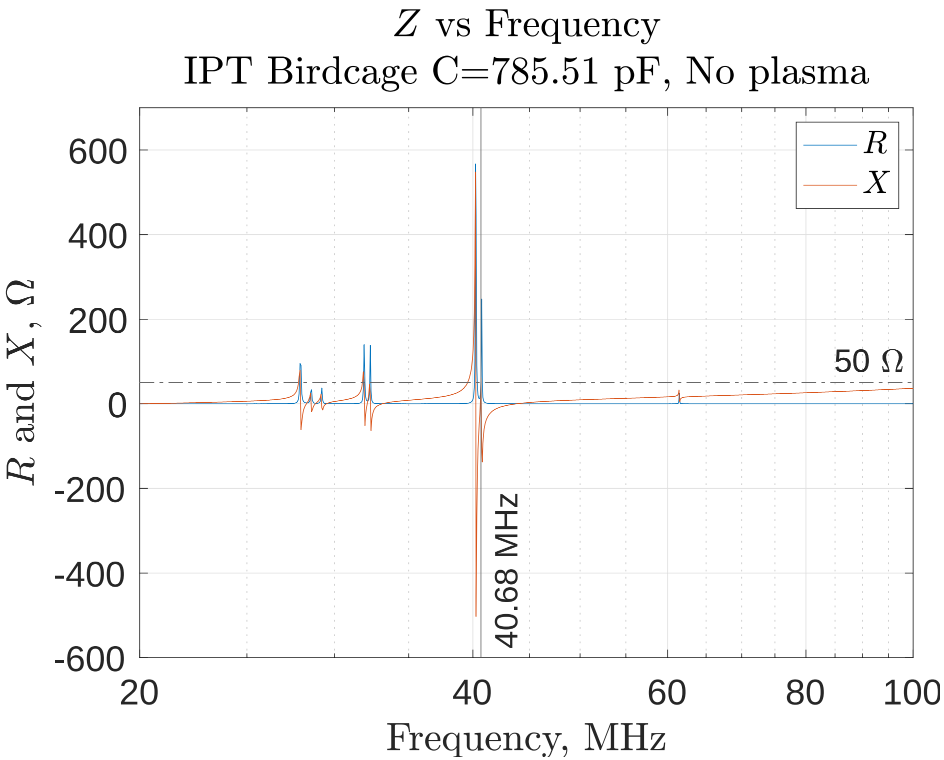


ed capacitance

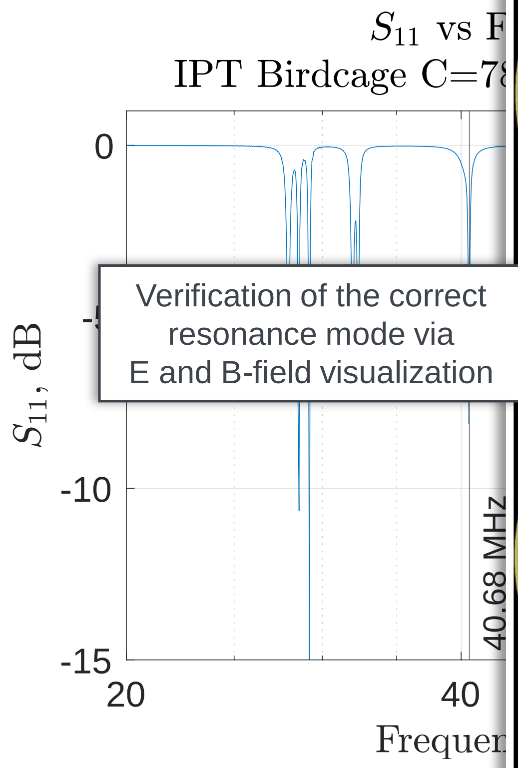
Simulation Results: Thruster Frequency Response



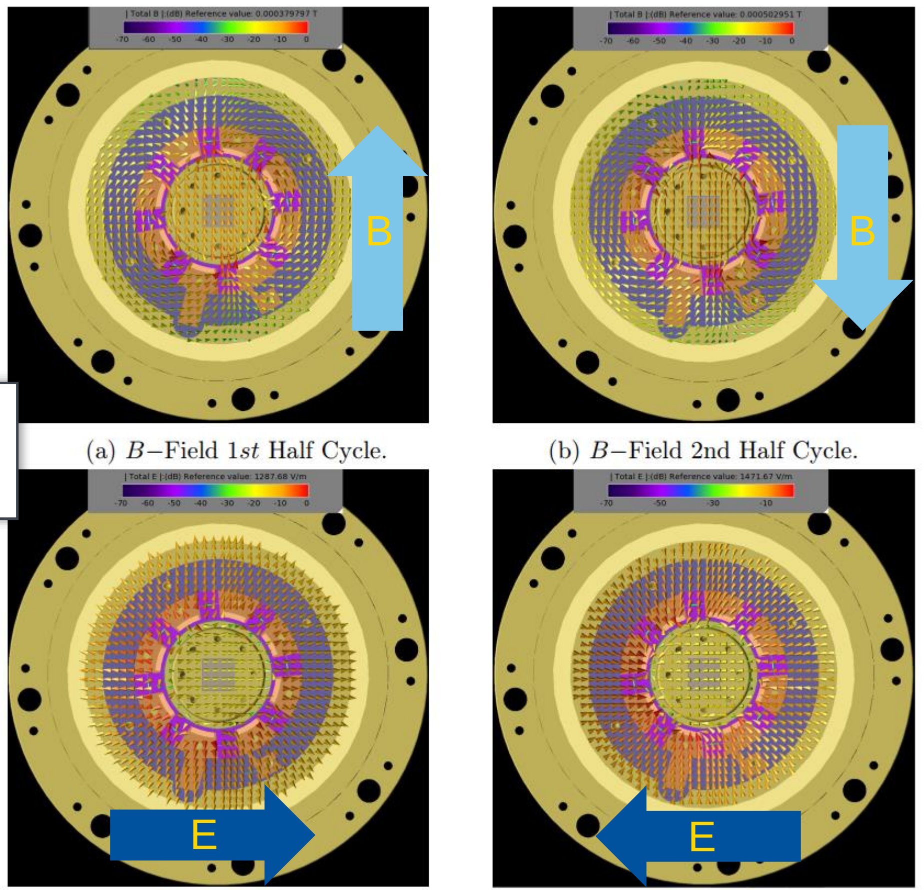
Verification of the correct resonance mode via E and B-field visualization



Simulation Results



Verification of the correct resonance mode via E and B-field visualization

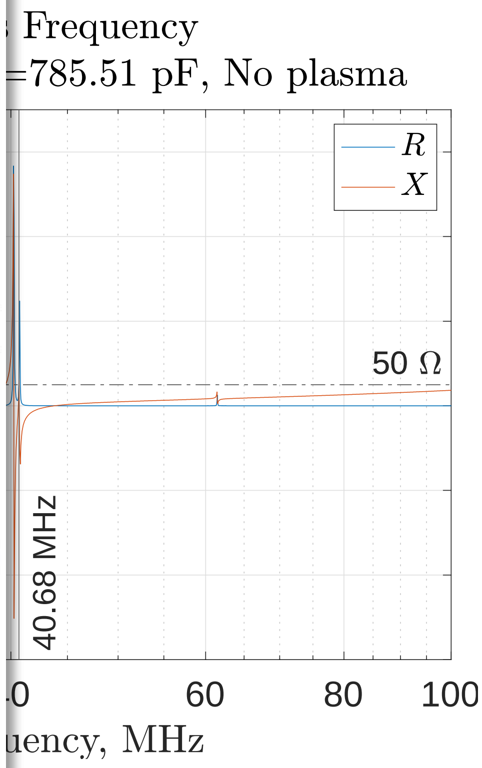


(a) $B-$Field 1st Half Cycle.

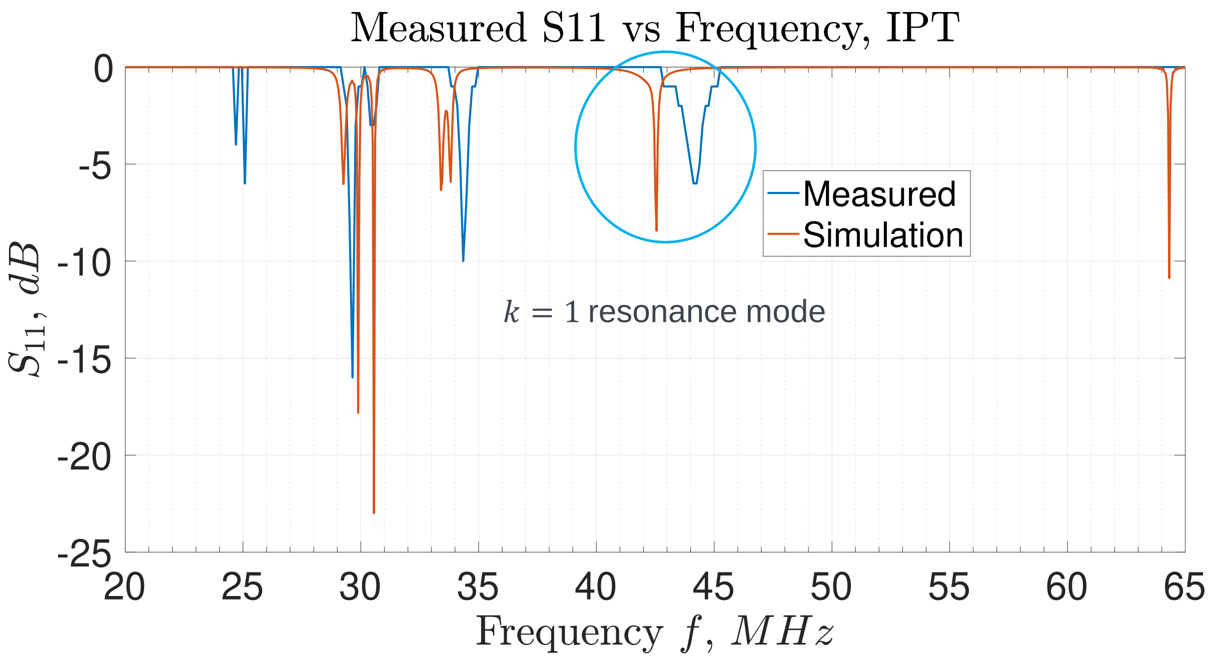
(b) $B-$Field 2nd Half Cycle.

(c) $E-$Field 1st Half Cycle.

(d) $E-$Field 2nd Half Cycle.



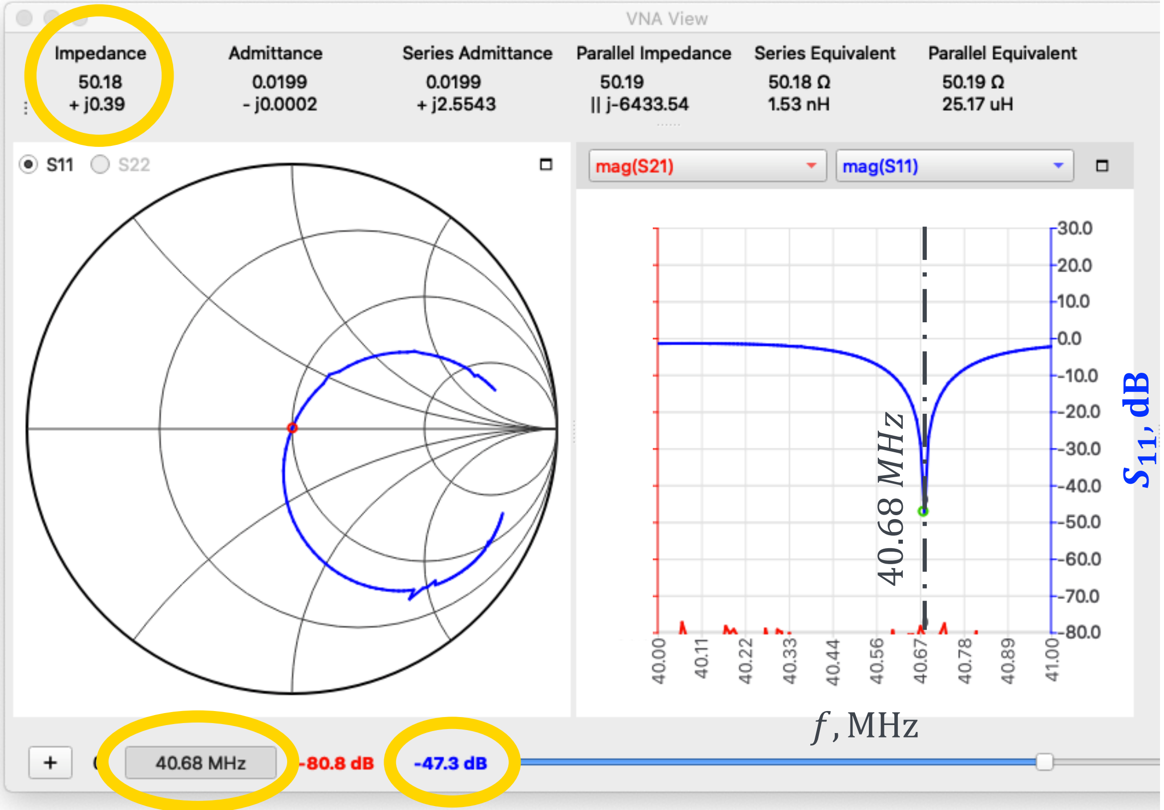
From Simulation to Experiment: Thruster Before Tuning



	Simulation (S) Experiment (E)	Relative Difference (S) vs (E)
f, MHz	42.55 (S) 44.25 (E)	3.84%
S_{11}, dB	−8.4 (S) −6.0 (E)	28.5%

Deviation justifiable with manufacturing tolerances, integration, non ideal components.

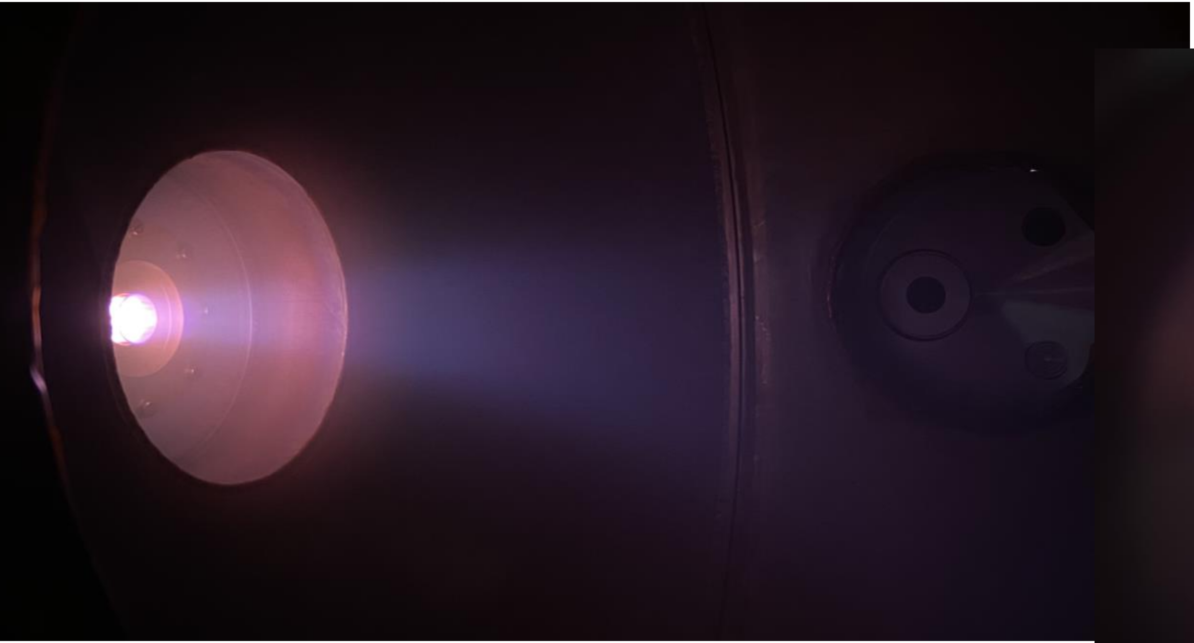
After Tuning: Network Analyzer Results

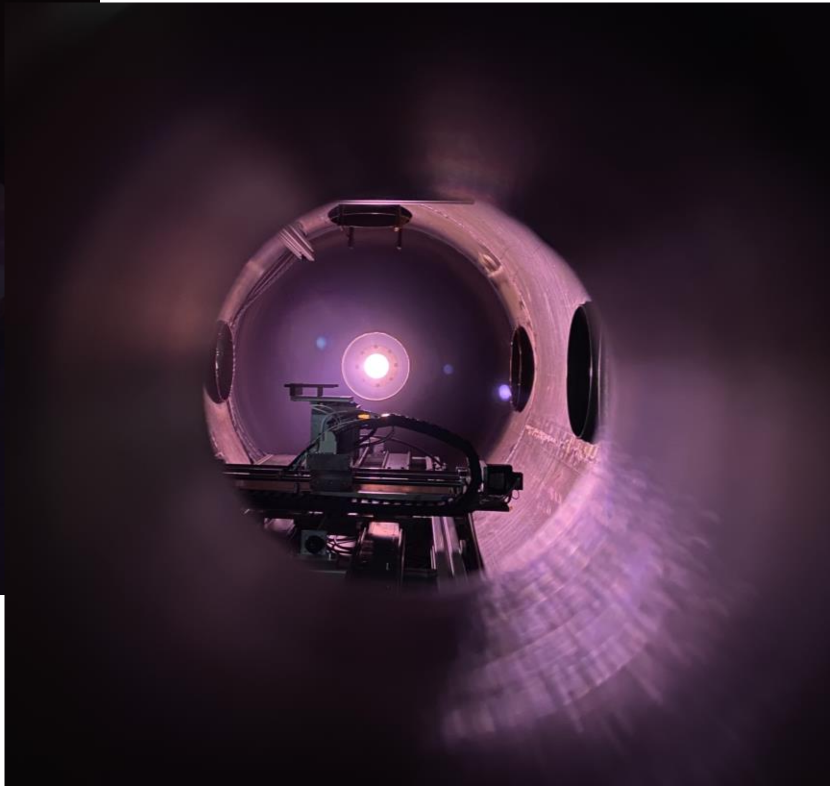


f is fine tuned, relative position of RF Input and Ground adjusted:

$$S_{11} = -47.3 \text{ dB}$$
$$Z = 50.18 + j0.39\Omega$$
$$f = 40.68 \text{ MHz}$$

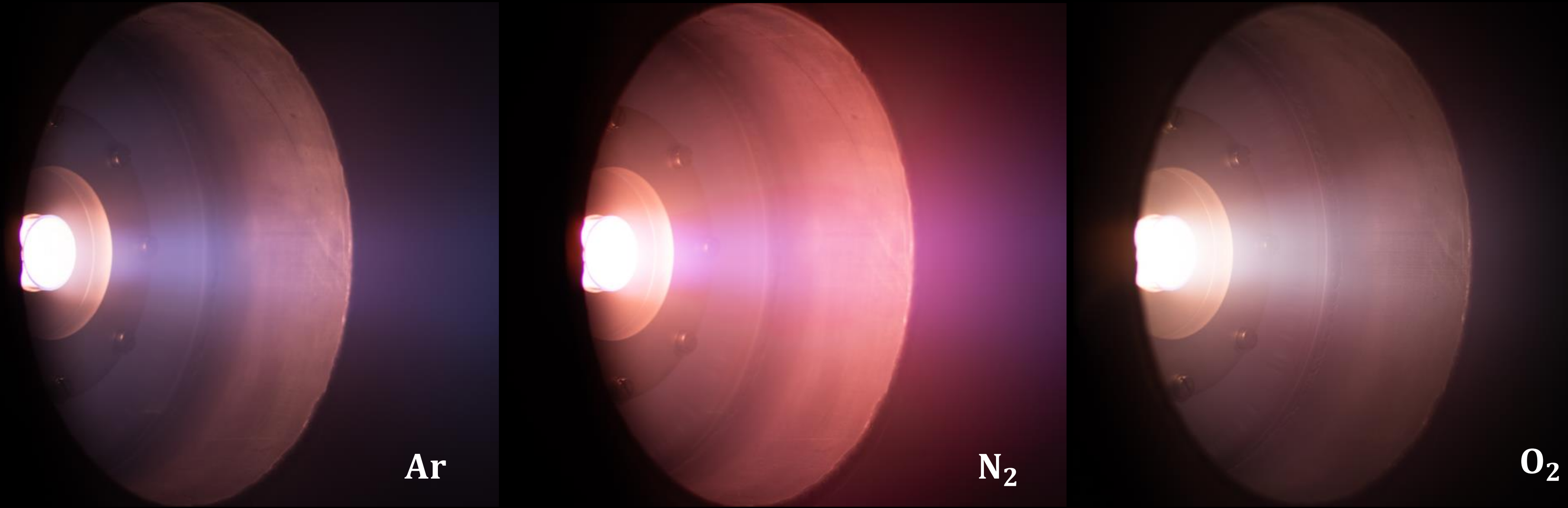
Correct resonant mode, at the required f and matched: ready for testing!





First ignition on Argon!

Proof of Concept: Operation on Argon, Nitrogen, and Oxygen



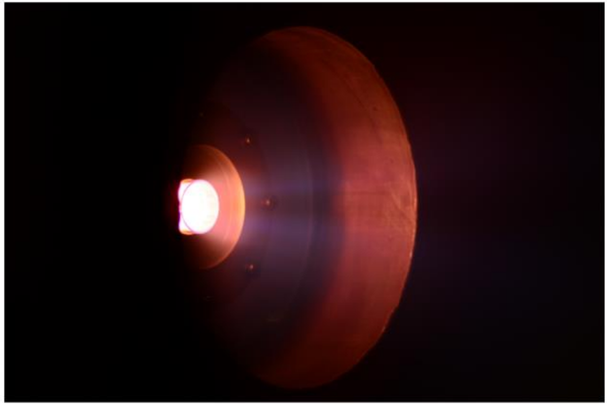
$$P_f = 60\ \mathrm{W}, \qquad I_S = 6.7\ \mathrm{A}, \qquad B_0 \sim 30\ \mathrm{mT}, \qquad \dot{N} = 20.30\,\frac{1}{s}, \qquad p_{ch} = 0.12 - 0.23\ \mathrm{Pa}$$

Decreasing B-field

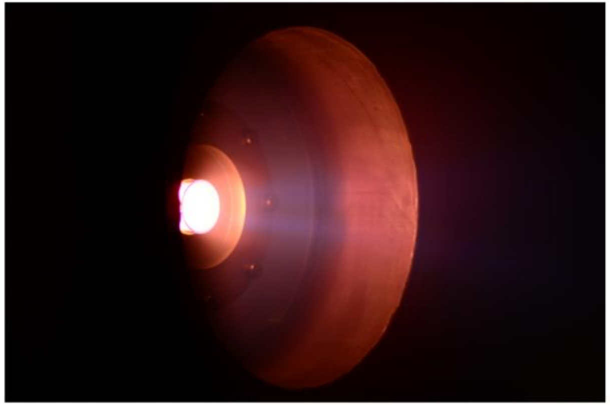
Argon:

$\dot{m} = 1.2\ \mathrm{mg/s}$

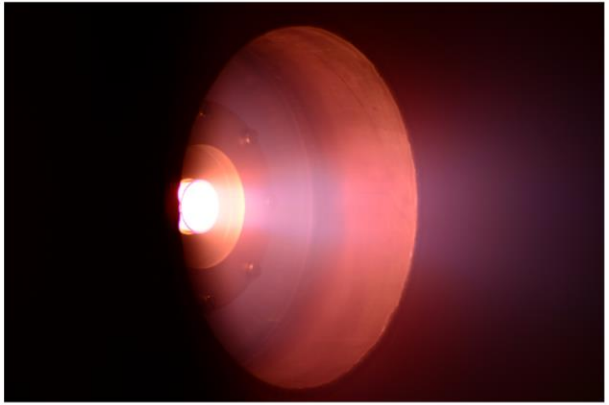
$P_f = 60\ \mathrm{W}$



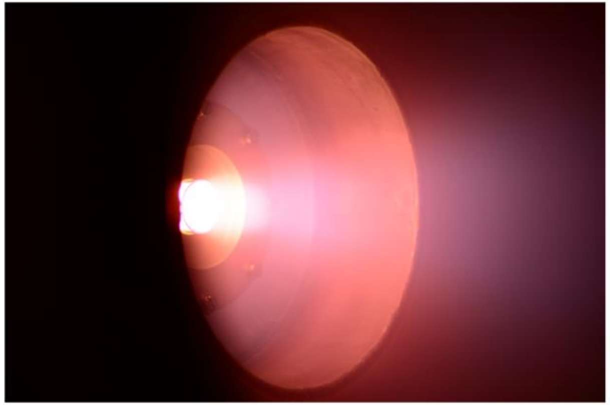
(a) $I_S = 10.07\,\mathrm{A},\ P_r = 1 - 6\,\mathrm{W}$



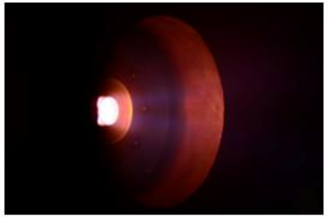
(b) $I_S = 6.7\,\mathrm{A},\ P_r = 10 - 17\,\mathrm{W}$



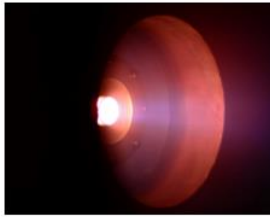
(c) $I_S = 6.5\,\mathrm{A},\ P_r = 17 - 27\,\mathrm{W}$



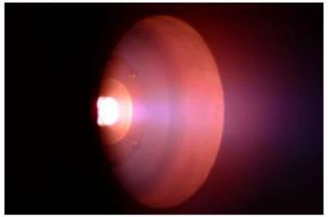
(d) $I_S = 6.3\,\mathrm{A},\ P_r = 11 - 28\,\mathrm{W}$



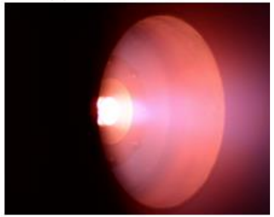
(a) $I_S = 10.07\,\mathrm{A}$, $P_r = 8 - 18\,\mathrm{W}$



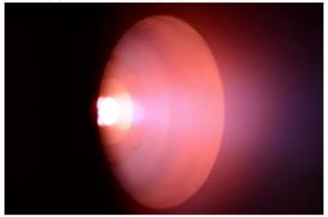
(b) $I_S = 6.7\,\mathrm{A}$, $P_r = 9 - 18$



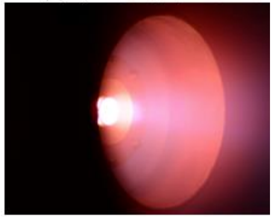
(c) $I_S = 6.5\,\mathrm{A}$, $P_r = 10 - 20\,\mathrm{W}$



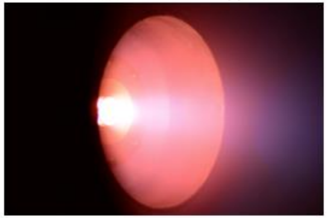
(d) $I_S = 6.3\,\mathrm{A}$, $P_r = 15 - 20$



(e) $I_S = 6.0\,\mathrm{A}$, $P_r = 16 - 25\,\mathrm{W}$



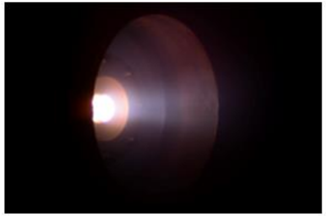
(f) $I_S = 5.7\,\mathrm{A}$, $P_r = 27 - 29$



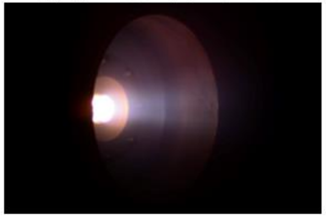
(g) $I_S = 3.5\,\mathrm{A}$, $P_r = 20 - 30\,\mathrm{W}$

Figure 2.27: $P_f = 60\,\mathrm{W}$, $\dot{m} = 0.6\,\mathrm{mg\,s^{-1}}$, Focal length 50 mm $f/4$ Exposur
1/5 s, Solenoid at 35 mm.

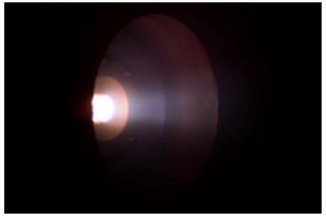
(a) $I_S = 10.07\,\mathrm{A}$, $P_r = 8 - 0\,\mathrm{W}$



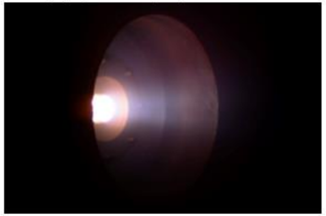
(b) $I_S = 6.7\,\mathrm{A}$, $P_r = 5 - 15\,\mathrm{W}$



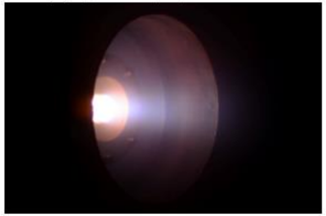
(c) $I_S = 6.5\,\mathrm{A}$, $P_r = 5 - 16\,\mathrm{W}$



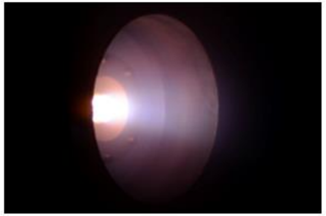
(d) $I_S = 6.3\,\mathrm{A}$, $P_r = 5 - 16\,\mathrm{W}$



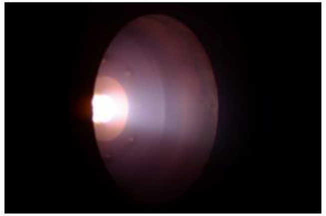
(e) $I_S = 5.7\,\mathrm{A}$, $P_r = 5 - 17\,\mathrm{W}$



(f) $I_S = 3.5\,\mathrm{A}$, $P_r = 4 - 16\,\mathrm{W}$

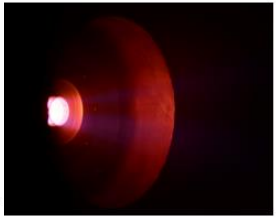


(g) $I_S = 2.5\,\mathrm{A}$, $P_r = 10 - 21\,\mathrm{W}$

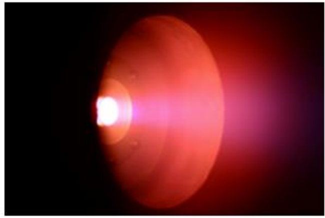


(h) $I_S = 2\,\mathrm{A}$, $P_r = 17 - 26\,\mathrm{W}$

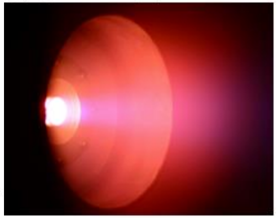
Figure 2.18: $P_f = 60\,\mathrm{W}$, $\dot{m} = 0.487\,\mathrm{mg\,s^{-1}}$, Focal length 50 mm $f/4$ Exposure time 1/5 s, Solenoid at 35 mm.



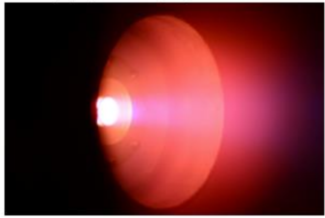
(a) $I_S = 10.07\,\mathrm{A}$, $P_r = 0\,\mathrm{W}$



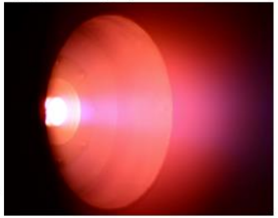
(b) $I_S = 6.7\,\mathrm{A}$, $P_r = 1 - 8\,\mathrm{W}$



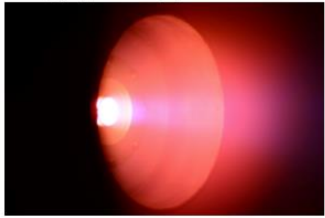
c) $I_S = 6.5\,\mathrm{A}$, $P_r = 0 - 10\,\mathrm{W}$



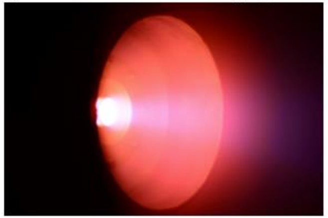
(d) $I_S = 6.3\,\mathrm{A}$, $P_r = 1 - 13\,\mathrm{W}$



e) $I_S = 6.0\,\mathrm{A}$, $P_r = 2 - 11\,\mathrm{W}$



(f) $I_S = 5.7\,\mathrm{A}$, $P_r = 2 - 13\,\mathrm{W}$

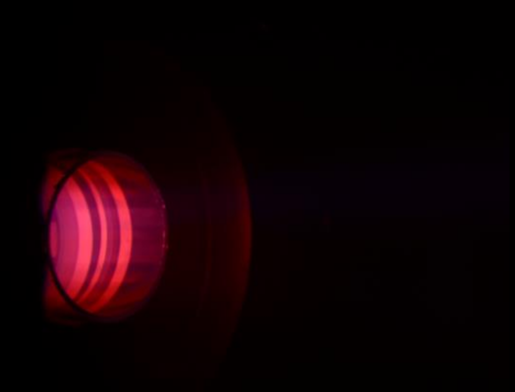


(g) $I_S = 3.5\,\mathrm{A}$, $P_r = 2 - 14\,\mathrm{W}$

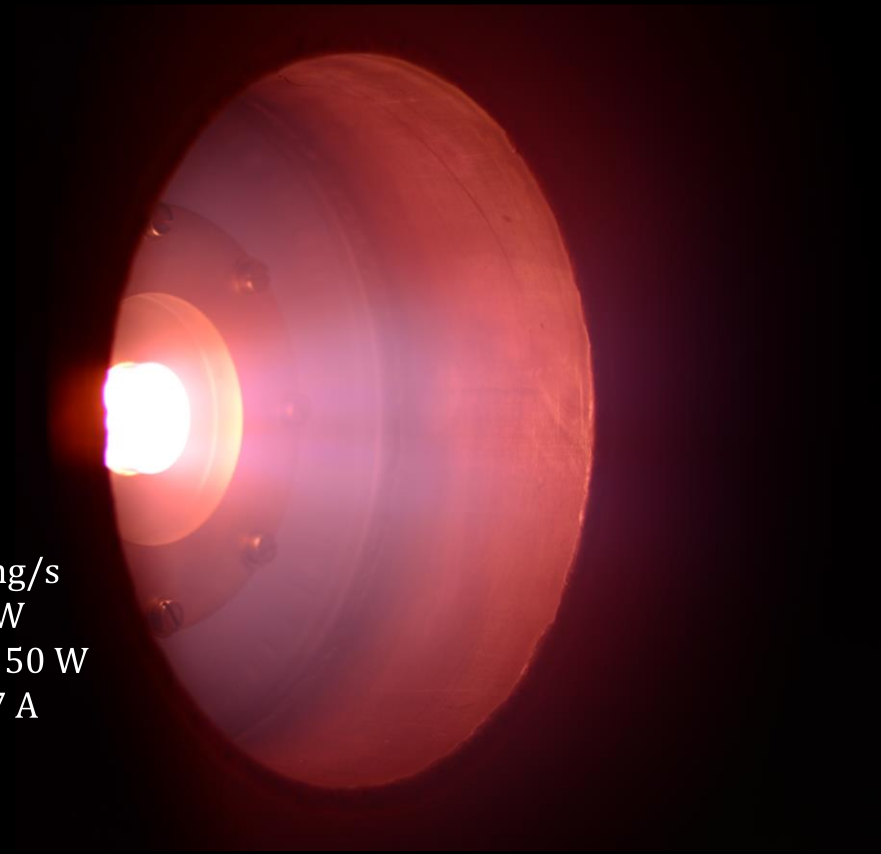
3.18: N_2, $P_f = 60\,\mathrm{W}$, $\dot{m} = 0.426\,\mathrm{mg\,s^{-1}}$, Focal length 50 mm $f/4$ Exposure time 1/5 s, Solenoid at 35 mm.

The Tested Limits!

Argon



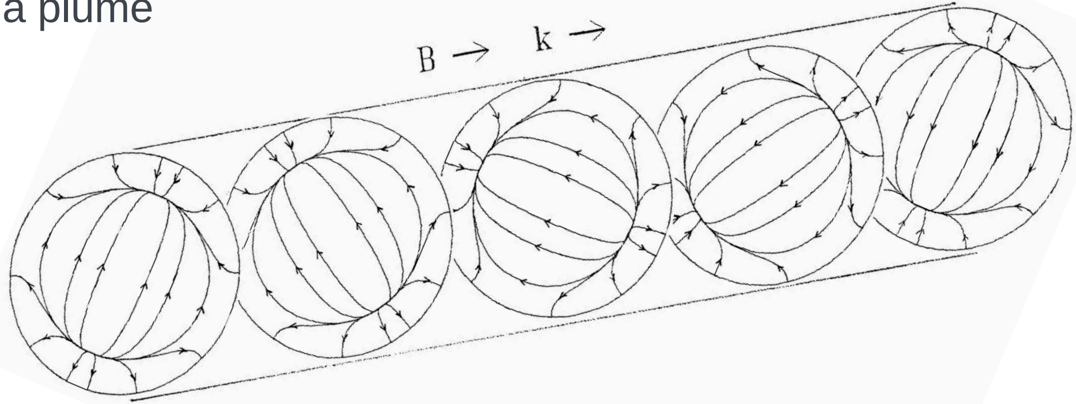
$\dot{m} = 0.4\ \mathrm{mg/s}$
$P_f = 10\ \mathrm{W}$
$P_r = 10\ \mathrm{W}$
$I_S = 6.7\ \mathrm{A}$



$\dot{m} = 0.6\ \mathrm{mg/s}$
$P_f = 300\ \mathrm{W}$
$P_r = 30 - 50\ \mathrm{W}$
$I_S = 10.07\ \mathrm{A}$

Helicon Waves (HW)

- Low frequency whistler waves, right-hand polarized ($m = +1$), confined in a cylinder
- HW increases the efficiency of the discharge ➔ Larger plasma density compared to "inductive" plasma discharges for a given input power
- Use of a magnetic inductive or B-dot probe to detect the rotating alternating magnetic field of the HW within the plasma plume

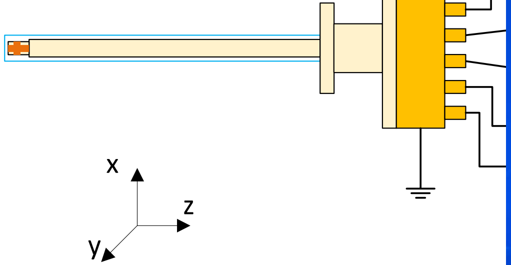


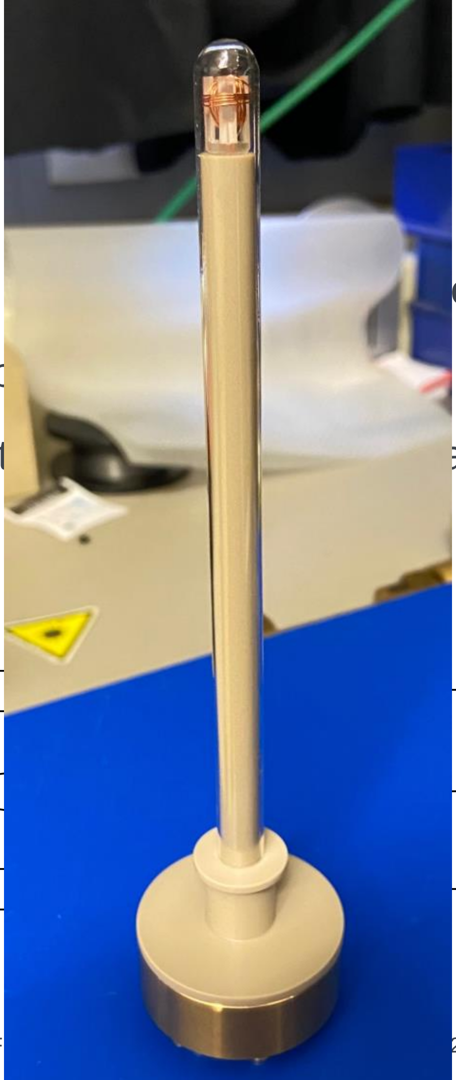
HW: E field pattern
$m = +1$, RH

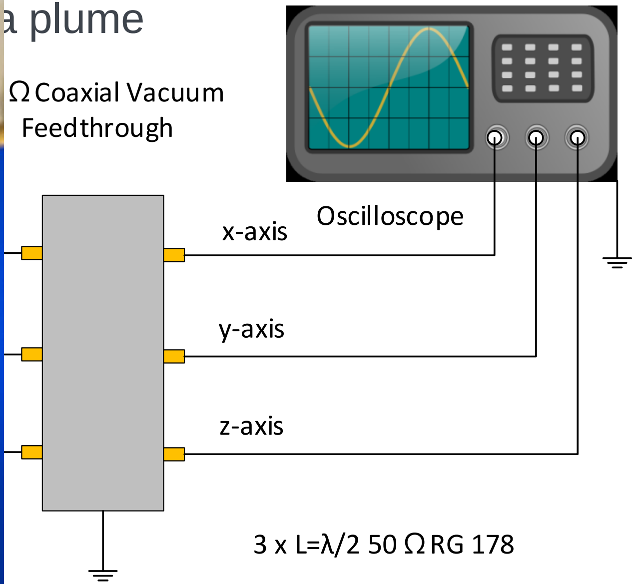
F. Chen, Helicon discharges and sources: a review, Plasma Sources Science and Technology 24 (1) (2015) 014001. doi:10.1088/0963-0252/24/1/ 014001.

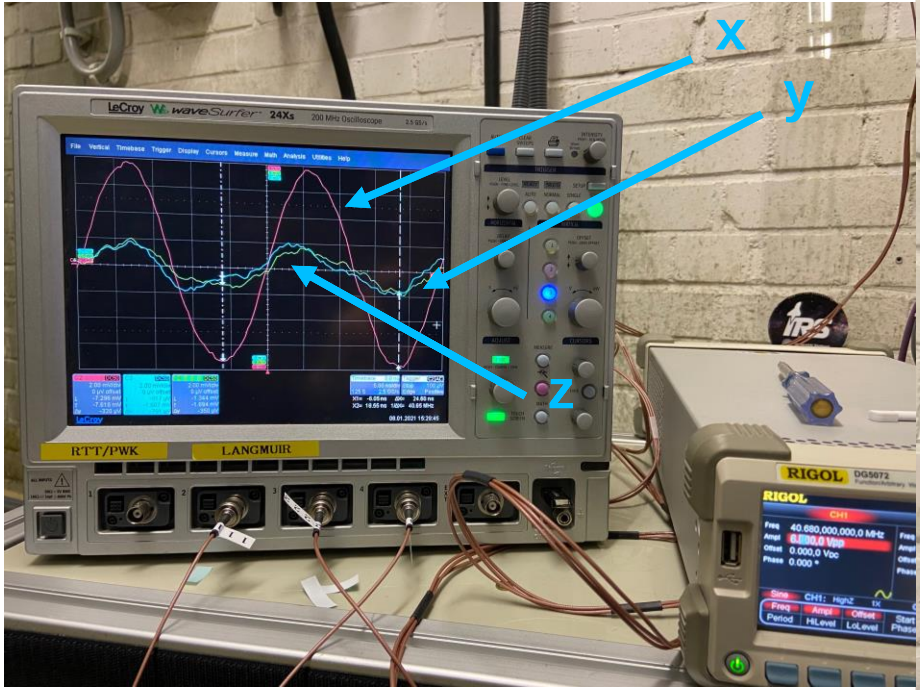
B-dot Probe

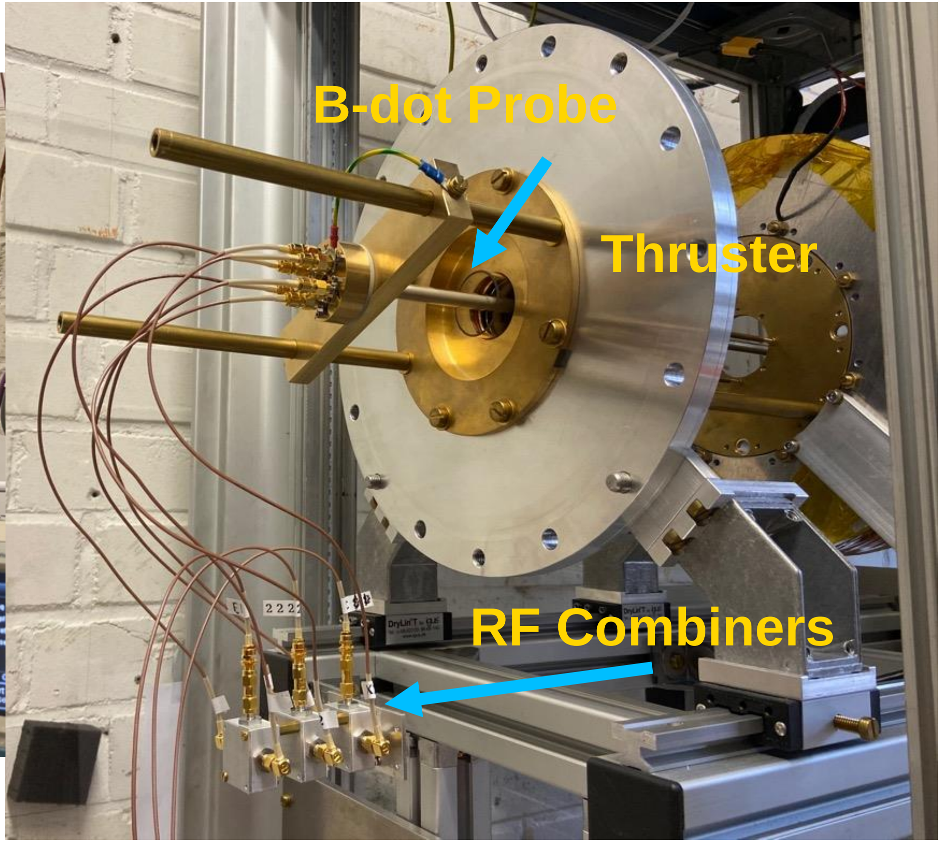
- A 3-axes B-dot probe is designed ed
- Measure B-field flux along x, y, z b
- Aiming to see the rotating alternat a plume







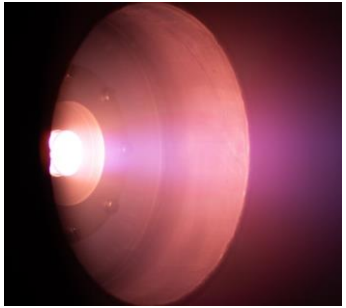

x
y
z
LeCroy
waveSurfer 24Xs
RTT/PWK
LANGMUIR
RIGOL

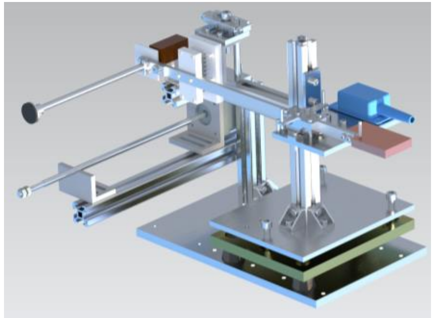

B-dot Probe
Thruster
RF Combiners

IPT – Thrust Measuring Technique

Measurement goal:

- ExB drift verification
- Determination of thrust efficiency
- Determination of weight-specific impulse
- Characterisation of momentum distribution in the plume



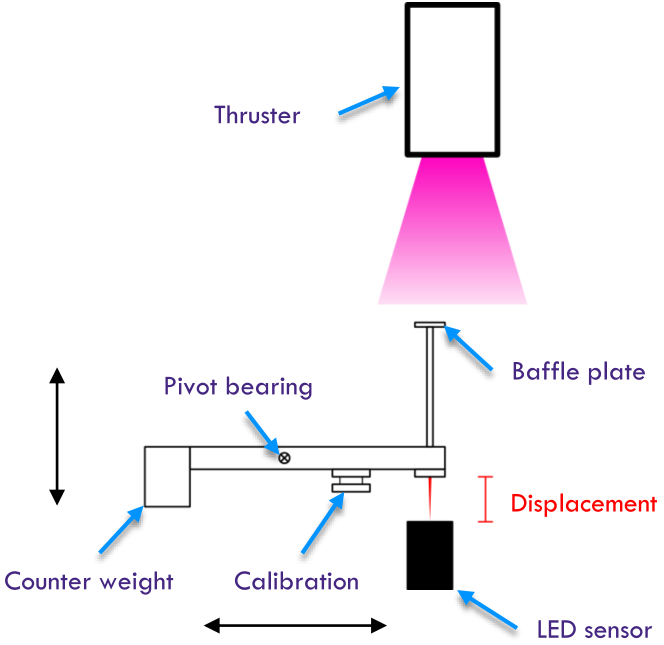


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 737183.

IPT – Thrust Measuring Technique

Momentum flux probe principle:

- Accelerated particles are absorbed by a baffle plate
- Particle momentum transferred to probe
- Resulting displacement measured via an LED sensor
- Frictionless rotation via pivot bearings in the pendulums centre of gravity
- Calibration with electrostatic comb
- Moveable setup



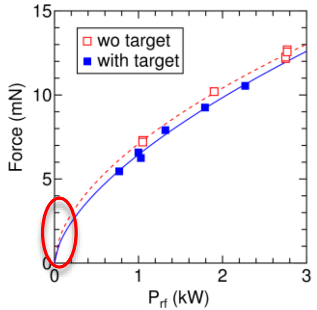
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 737183.

IPT – Thrust Measuring Technique

Comparison of pendulum mechanics:

- Expected force: ≤ 1 mN
- Influence of gravity critical

	Hanging Pendulum	Inverted Parallelogram Pendulum	Inverted Pendulum	Elastic Beam	Torsional Pendulum
Pros	• Simple principle • Gravity as stabilizing force	• Probably point of attack less relevant • no deflection of plate	• Simple principle	• No bearings • Less structure	• Gravity independent • Allows measurement close to thruster exit
Cons	• Long arm necessary →facility issues • Alignment • Plate deflection • Affected by gravity	• Complex structure • Requires a min. of 6 bearings → restoring force high • Affected by gravity	• Alignment • Plate deflection • Affected by gravity	• Long arm necessary →facility issues • Alignment	• Alignment • Plate deflection

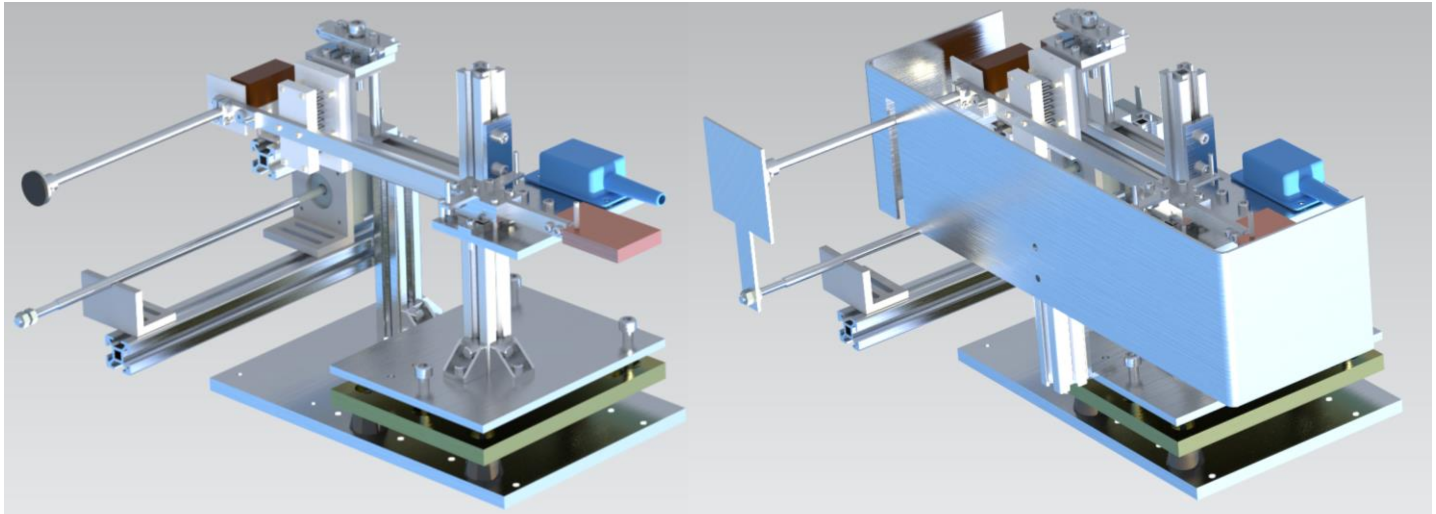


Kazunori Takahashi, Atsushi Komuro and Akira Ando, Rev. Sci. Instrum. **86**, 023505 (2015)

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

IPT – Thrust Measuring Technique

Final design



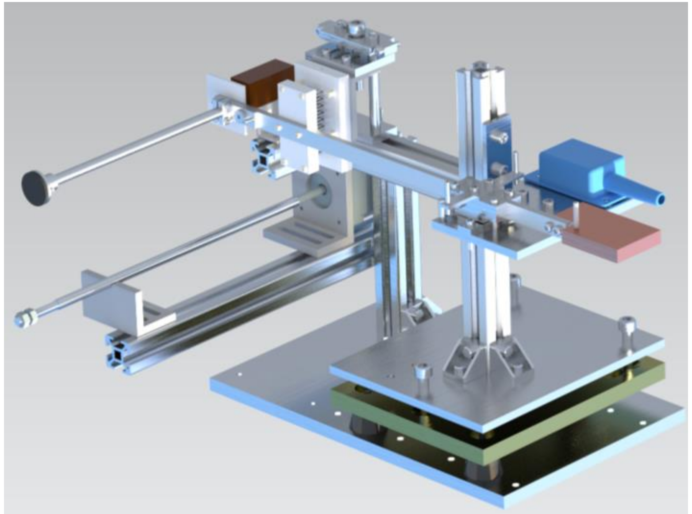
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 737183.

IPT – Thrust Measuring Technique

DISCOVERER

Final design

- Graphite baffle plate
- Alumina target plate for sensor
- Tilt control
- Copper counterweight also functions as Eddy current damper
- Electrostatic comb for calibration
- Shield to prevent particle influence
- Shutter mechanism in front of baffle plate

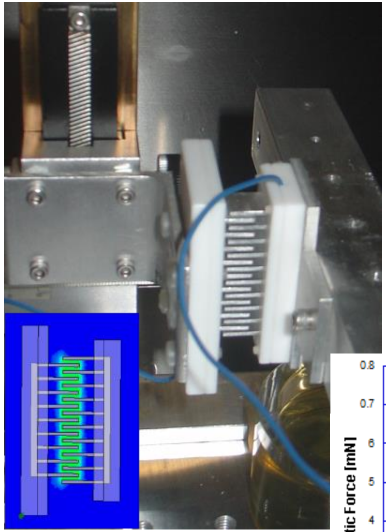


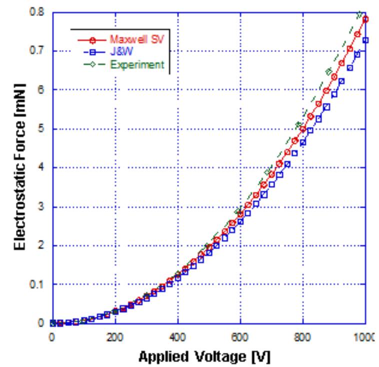
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 737183.

IPT – Thrust Measuring Technique

Calibration

- Correlation between measured displacement and applied force
- Electrostatic force between fins
- Non-intrusive application of force
- Accurate application of very low forces possible





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

Spacecraft Platform Considerations

Mission & Payload Envelope (ESA)

Orbit

- 150 to 250 km
- SSO, goal: 10:00 or 12:00 LTAN

Payload

- Optical payload, 390 mm x 270 mm x 270 mm (l x w x h) on nadir side
- Telecom payload, nadir side, shape & size uncritical

System Assumptions / Constraints

- Outer spacecraft surfaces made of diffusely reflecting material
- Maximal viable length of spacecraft (launcher): approx. 4 m

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Spacecraft Platform Considerations

Considered ABEP Components: IRS IPT & diffuse or specular intake

- Thruster efficiency: 0.2
- Diffuse intake efficiency: 0.46
- Specular intake efficiency: 0.94

ABEP System Constraints

- Realistic max. I_{SP}: approx. 2000 s
- Max. specular intake diam. to maintain length of 3 m: 0.5 m

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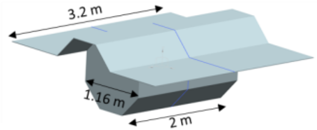
Spacecraft Platform Considerations

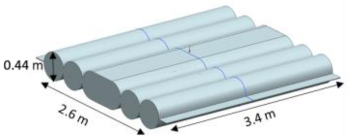
Considered Options

Slender body



- Payload requires body width of ca. 85 cm
  - with specular intake $\frac{A_{intake}}{A_{frontal}} \approx 0.59$
  - with diffuse intake $\frac{A_{intake}}{A_{frontal}} \approx 0.95$

Flat body



- Specular intake with high $A_{intake}/A_{frontal}$ ($\approx$ 0.9) possible → specular intake

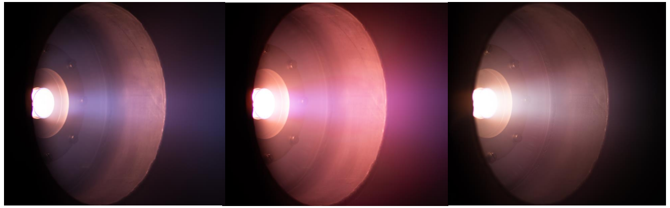
Conclusions

- I_{SP} requirement of flat body significantly lower (C_D is slightly higher, but particularly η_c is much higher)
- Required ABEP power of flat body significantly lower (again, penalty of slightly higher C_D compensated by much higher η_c

$$I_{SP} = \frac{1}{2}\frac{v(h)}{g}\frac{A_{frontal}}{A_{intake}\eta_c}C_D(h)$$

$$P_{ABEP} = \frac{1}{8}\rho(h)v^3(h)\,A_{frontal}^2 C_D^2 \frac{1}{A_{intake}\eta_c\eta_T}$$

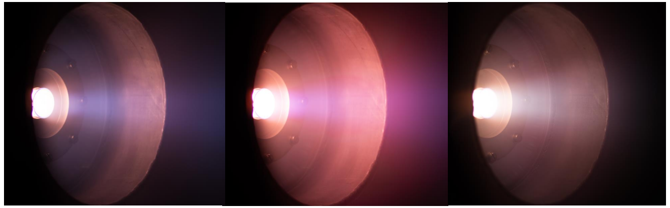
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 737183.



Conclusions 1

- Literature assessment of both
  - ABEP R&D as well as
  - R&D in the field of electrode-less RF thrusters
- Main ABEP-mission parameter investigated: ABEP efficiencies, variability of atmospheric properties
- Investigated ABEP-intakes and developed designs
- IPG6-S experiments
  - Potential evidence of Helicon mode
  - Implementation support for needed measurement techniques for later designed IPT
- System and mission analyses to assess
  - Feasibility and corresponding sensitivity scenarios
  - Data base for operational parameters for designed intakes as well as IPT (e.g. mass flow rates)

Conclusions 2



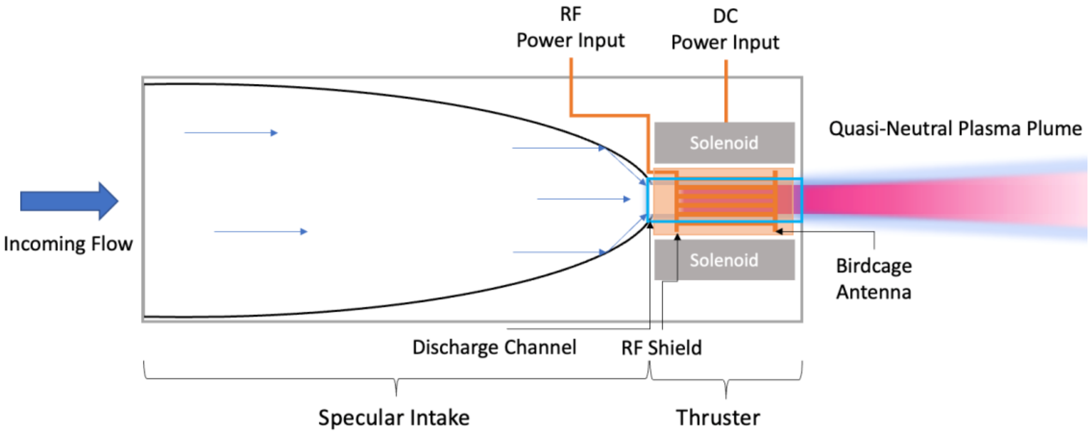
- New plasma thruster designed and tested based on a cylindrical birdcage antenna
  - Low operation power requirement ➔ $P_{in} \sim 60\ W$, tuned and matched load, shielded
  - Contact-less ➔ Propellant flexibility in composition and density, minimized erosion
  - Quasi-neutral plasma exhaust ➔ Charge-independent drift velocity, no neutralizer required
  - Proof of concept: tested on $\mathrm{Ar}, \mathrm{N_2}, \mathrm{O_2}$ and comparable ABEP particle flows
- Designed and integrated a magnetic inductive 3-axes B-dot probe for HW verification
- Designed a torsional thrust balance to assess thruster relevant parameters
- Assessment of advanced and alternative ABEP-based mission scenarios (not shown here)

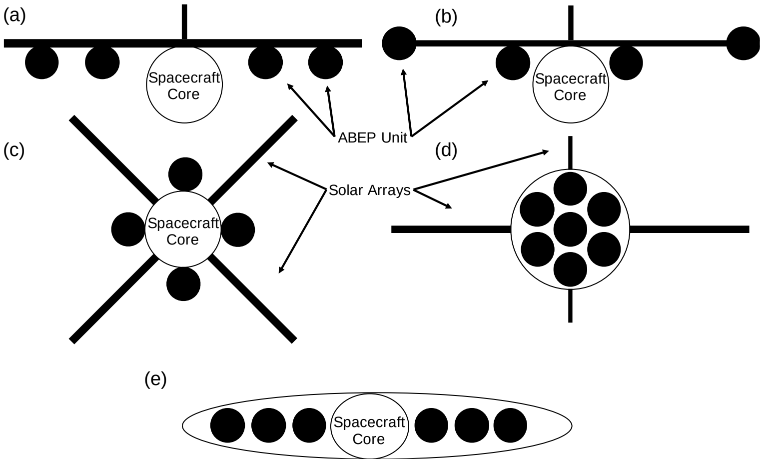
Beyond DISCOVERER

- Design requirements in ESA project fosters alternative design approaches

Outlook 1 (DISCOVERER)

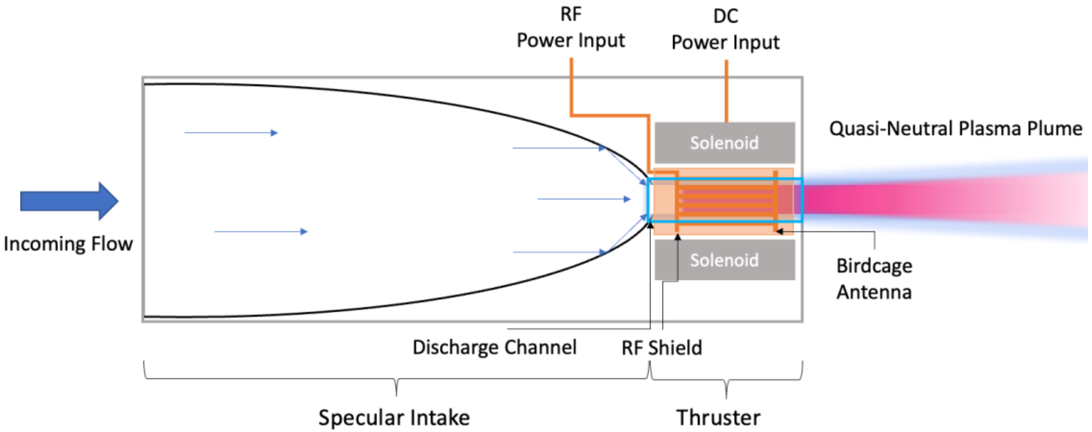
- Conclude B-dot probe calibration and perform tests for HW verification
- Extraction of thruster impedance during test for precise power measurement

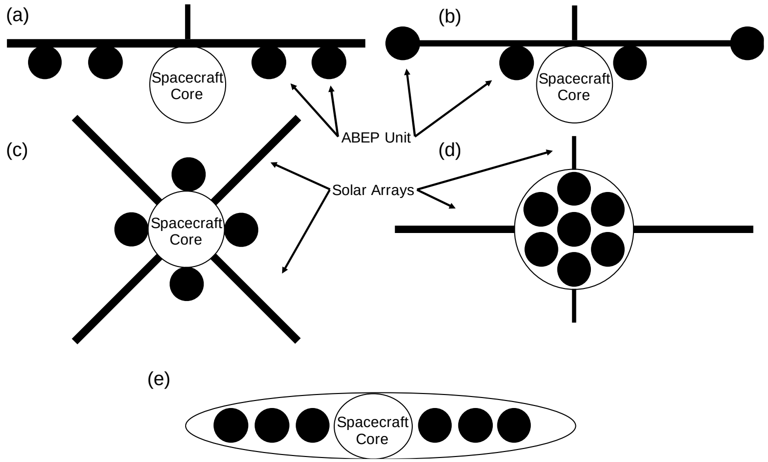




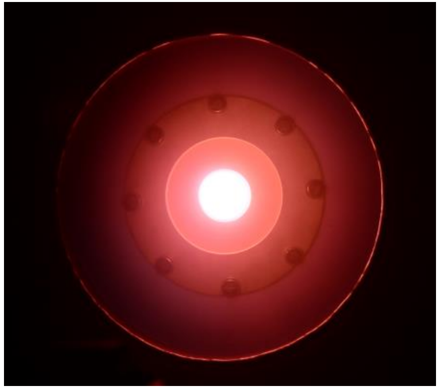
Outlook 2 (beyond DISCOVERER)

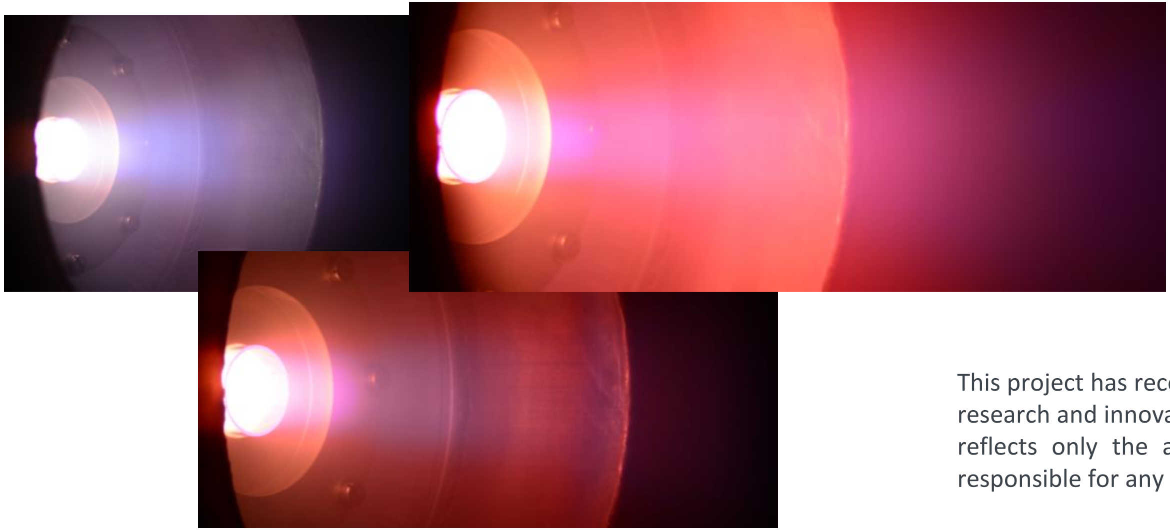
- Characterize by RF compensated plasma diagnostics: LP and FP probe at first, RPA and OES later
- Design the thruster for vacuum operation: perform direct thrust measurements, increase of TRL





Thank you for Listening!





This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 737183. This reflects only the author's view and the European Commission is not responsible for any use that may be made of the information it contains.

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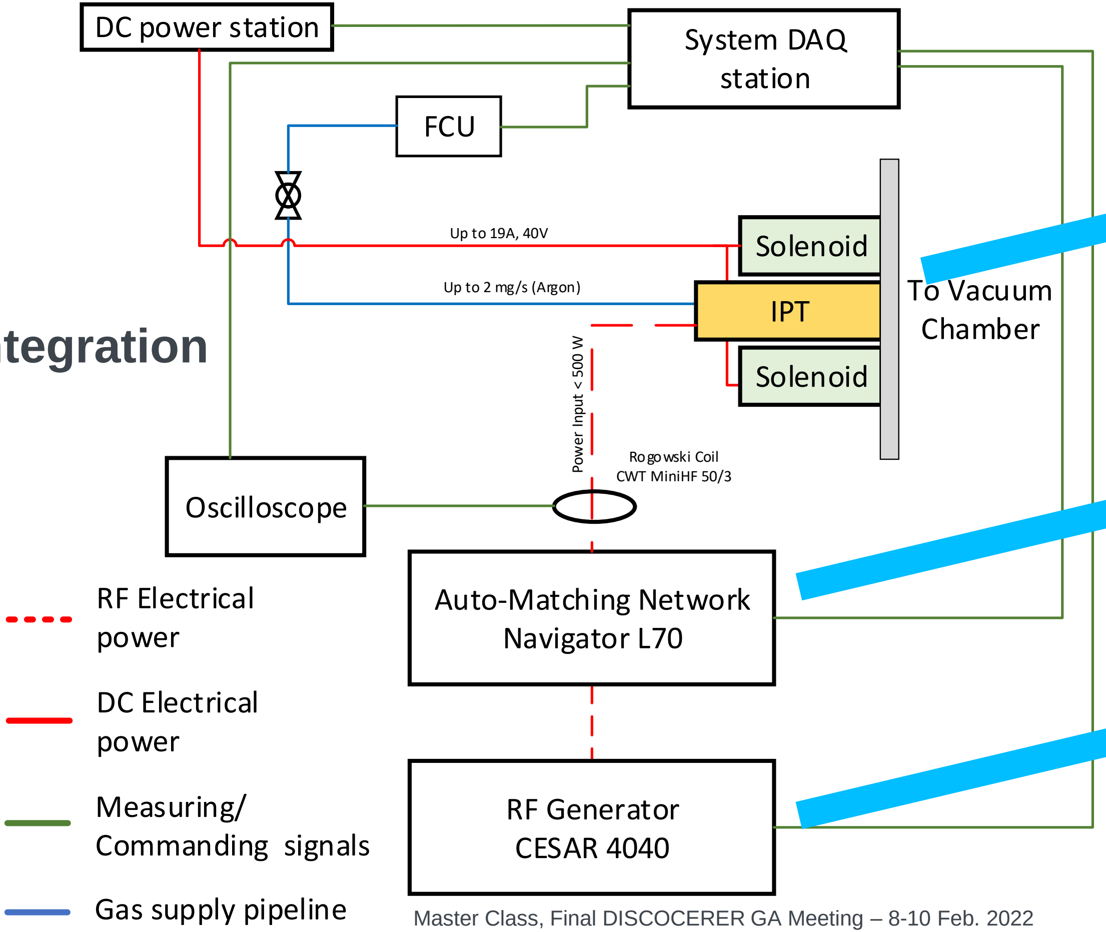
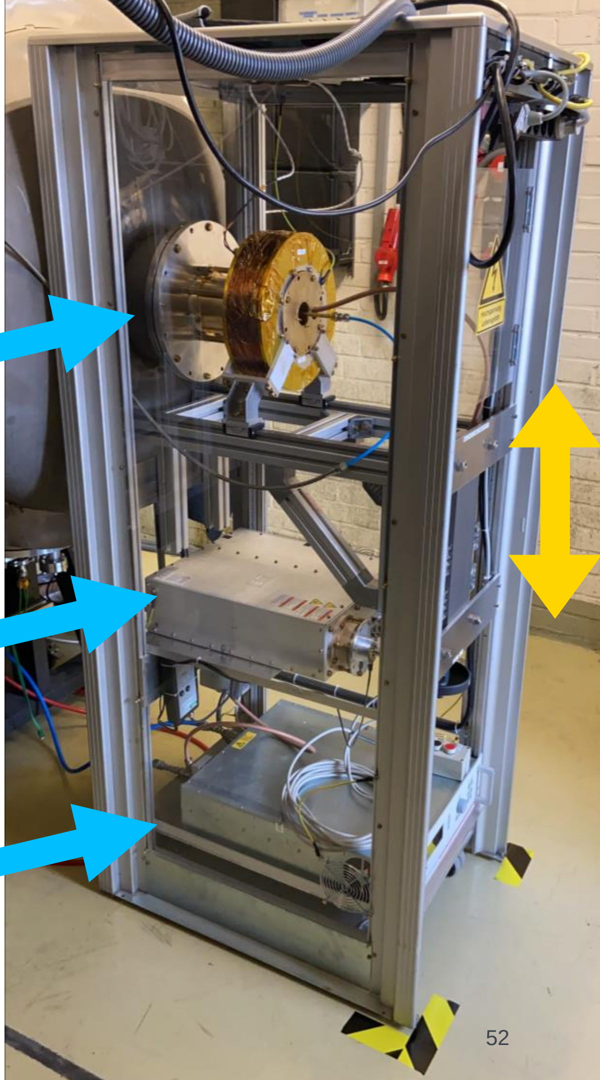
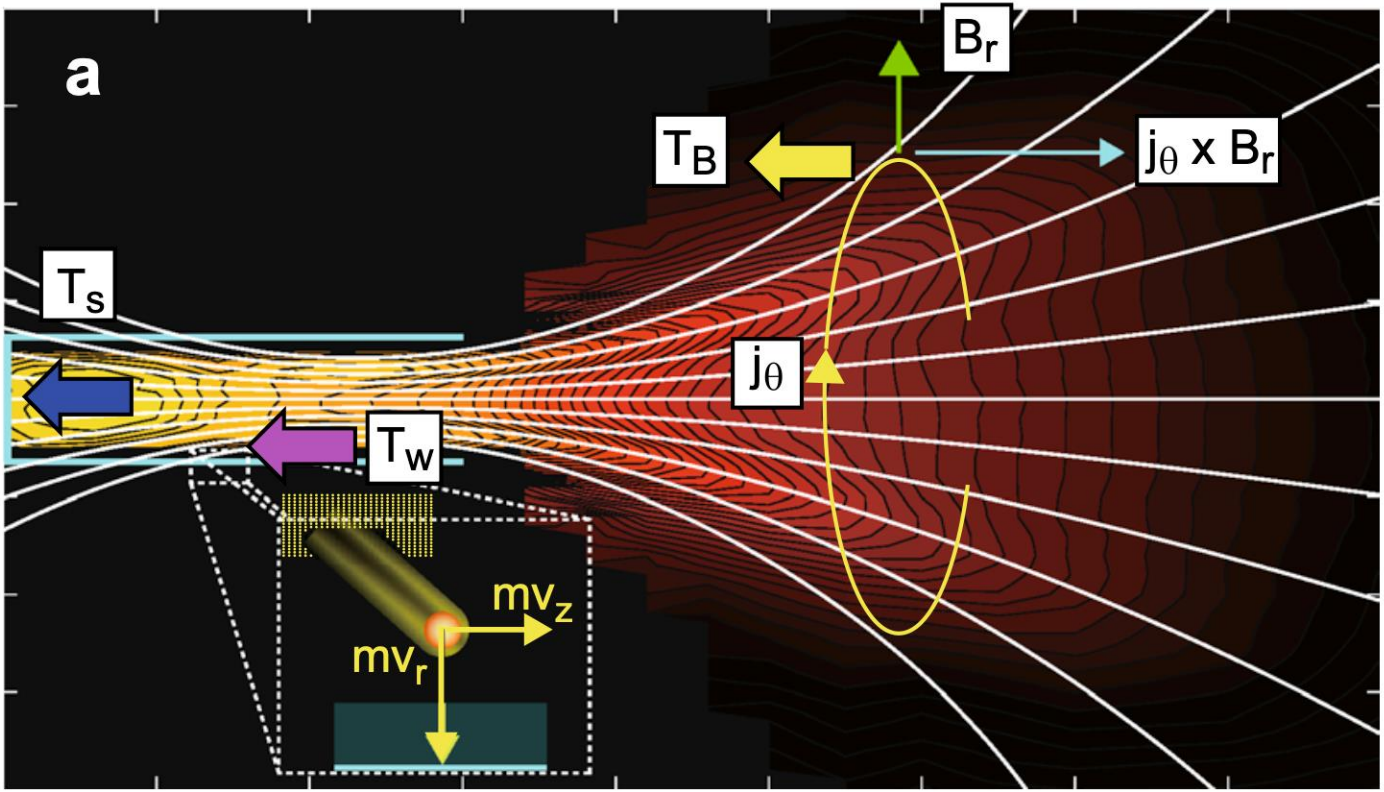
Rack Integration

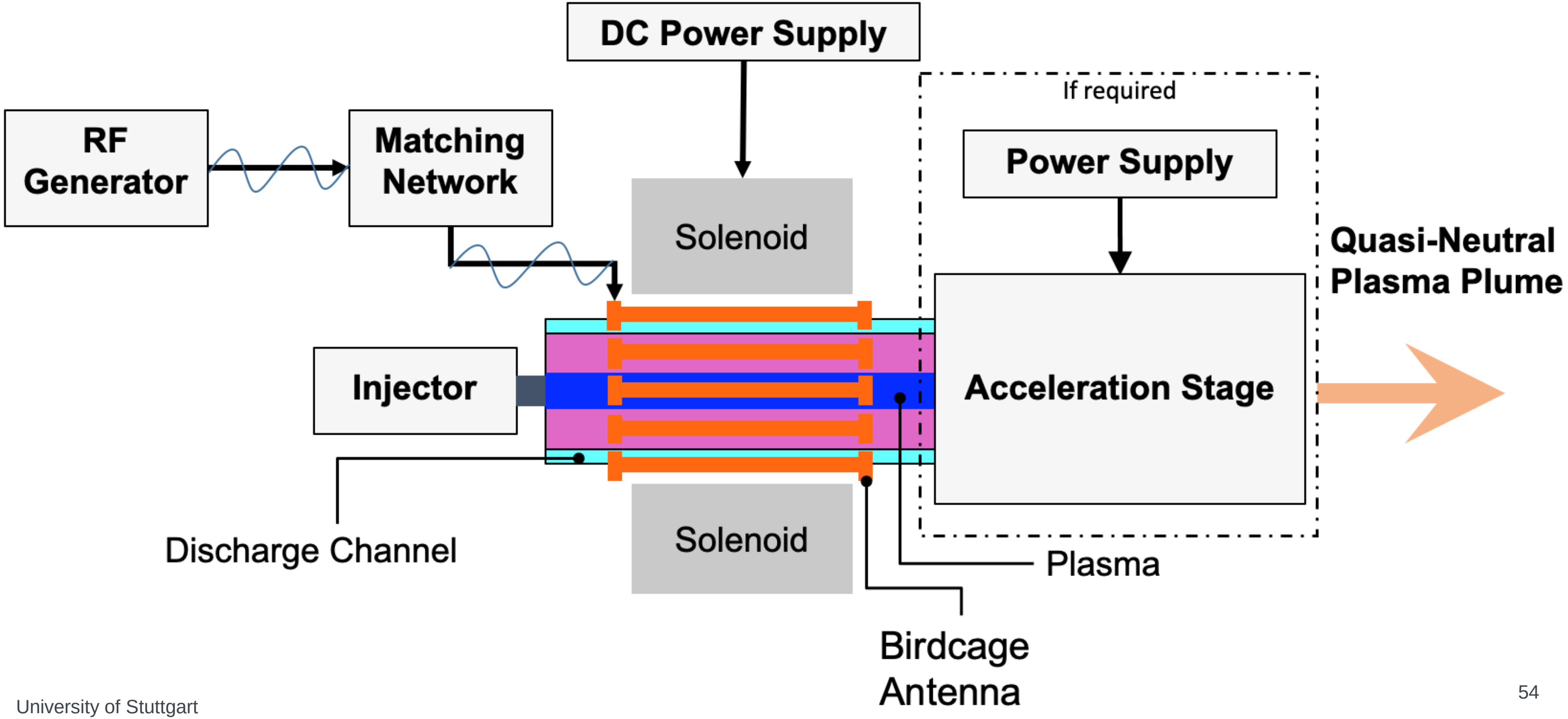




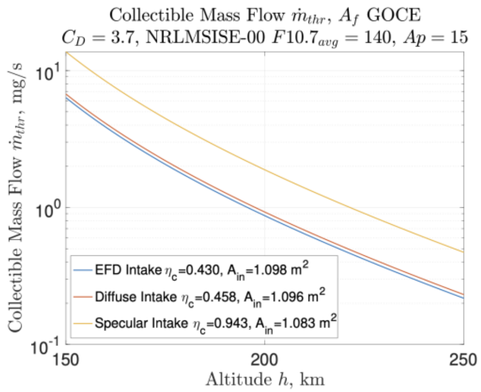
Magnetic Nozzle

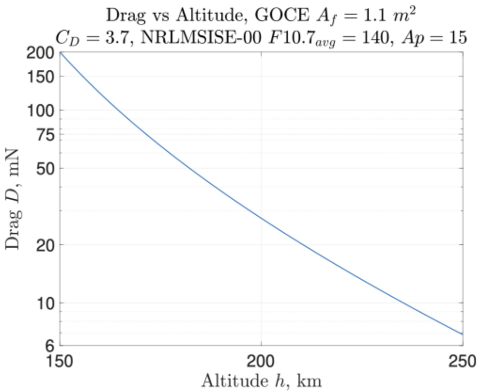


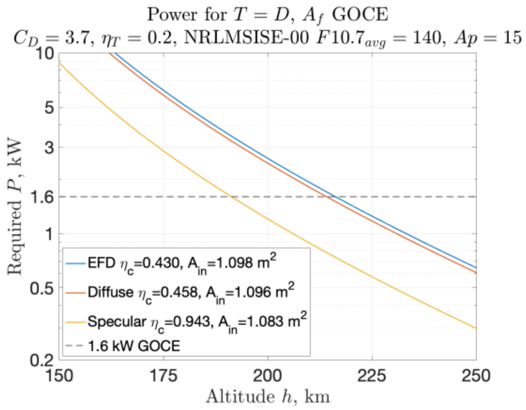
RF Helicon-based Plasma Thruster Concept

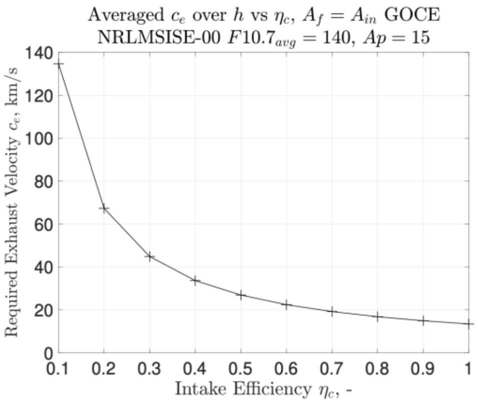


System Analysis for a GOCE-like Satellite









GOCE Satellite Main Properties

$A_f = 1.1\ \mathrm{m}^2$

$C_D = 3.7$

$P = 1.6\ \mathrm{kW}$

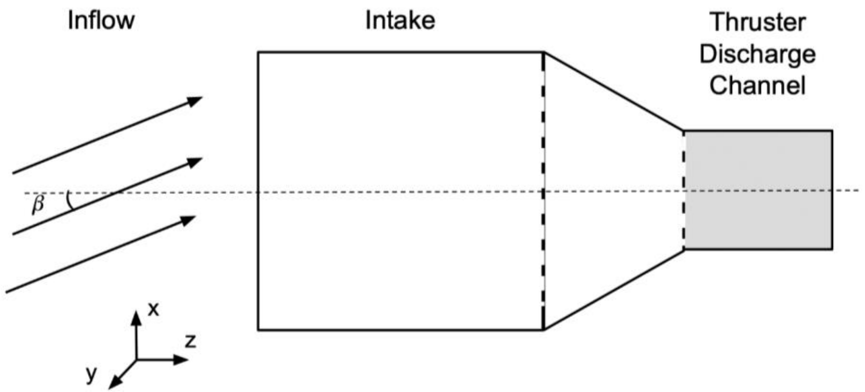
GOCE-like ABEP-based in VLMO

P_{ABEP} kW	h km	T/P mN/kW	I_{sp} $\times 10^3$s	C_D –
1.6 – 0.02	120 – 160	30 – 65	0.5 – 1.1	3

For the ABEP Performance

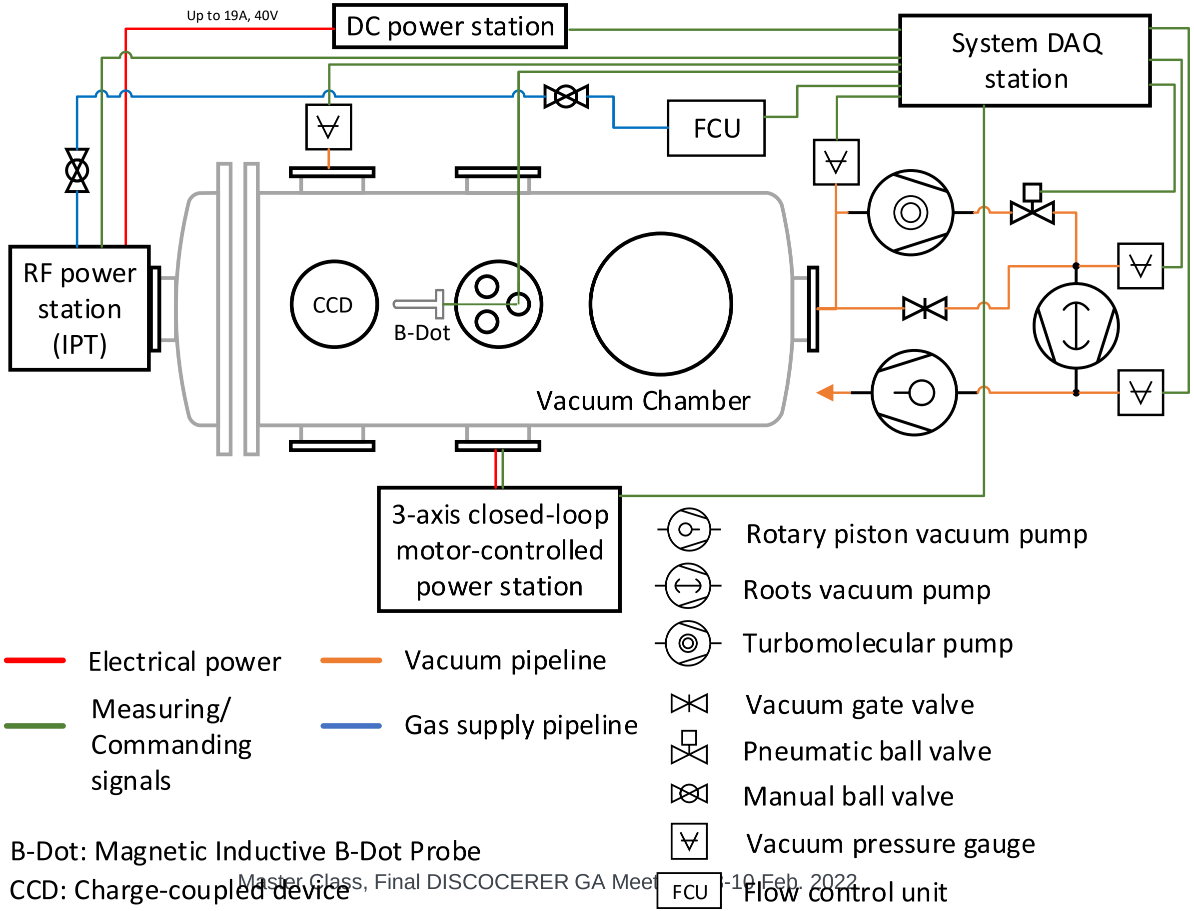
η_c –	η_T –
0.43, 0.46, 0.94	0.2

Effect of Misalignment on Intake Performance



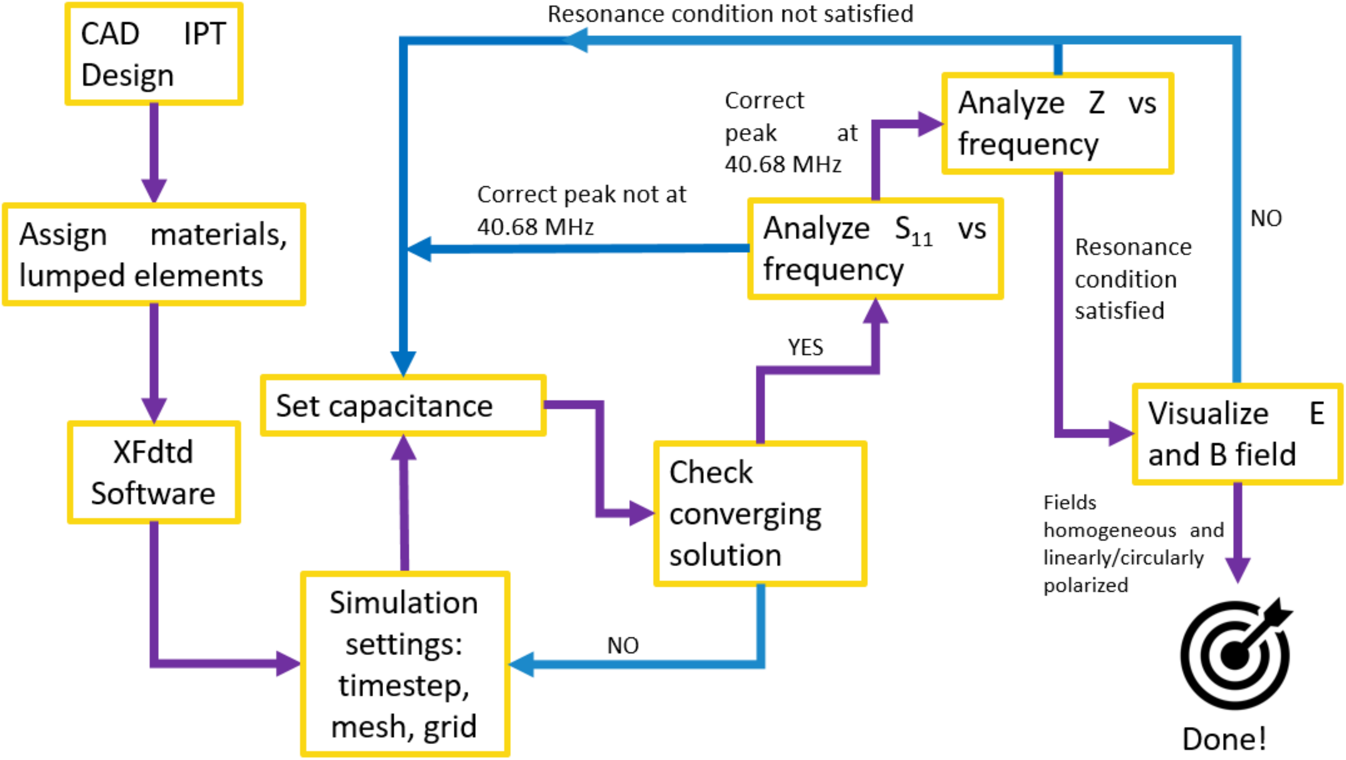
Intake	η_c %	$\Delta\eta_{c,\beta=5^o}$ %	$\Delta\eta_{c,\beta=10^o}$ %	$\Delta\eta_{c,\beta=15^o}$ %
Diffuse	45.8	-17	-41	-67
Specular	94.3	~ 0	-5	-8

The Facility

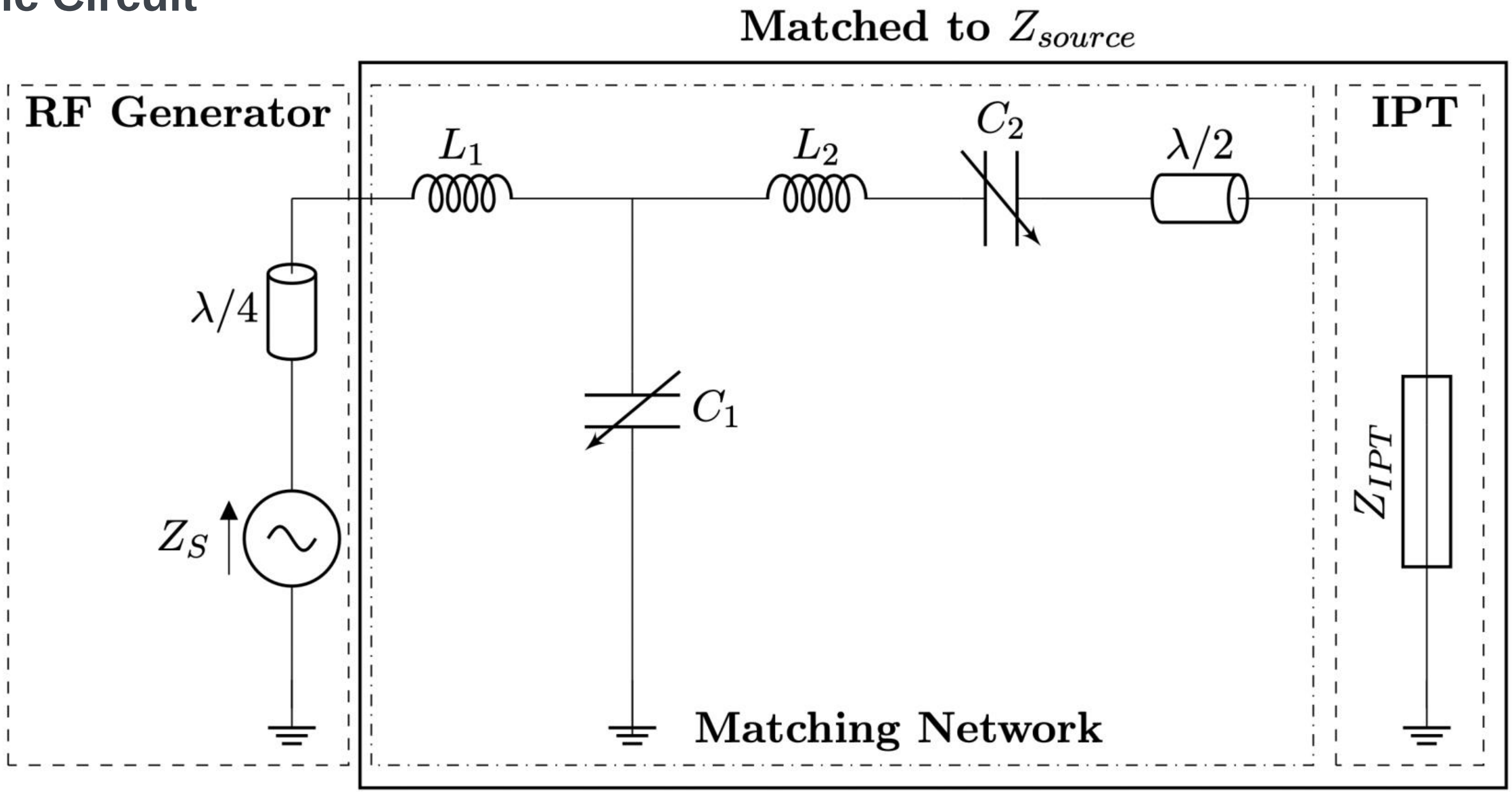


B-Dot: Magnetic Inductive B-Dot Probe
CCD: Charge-coupled device

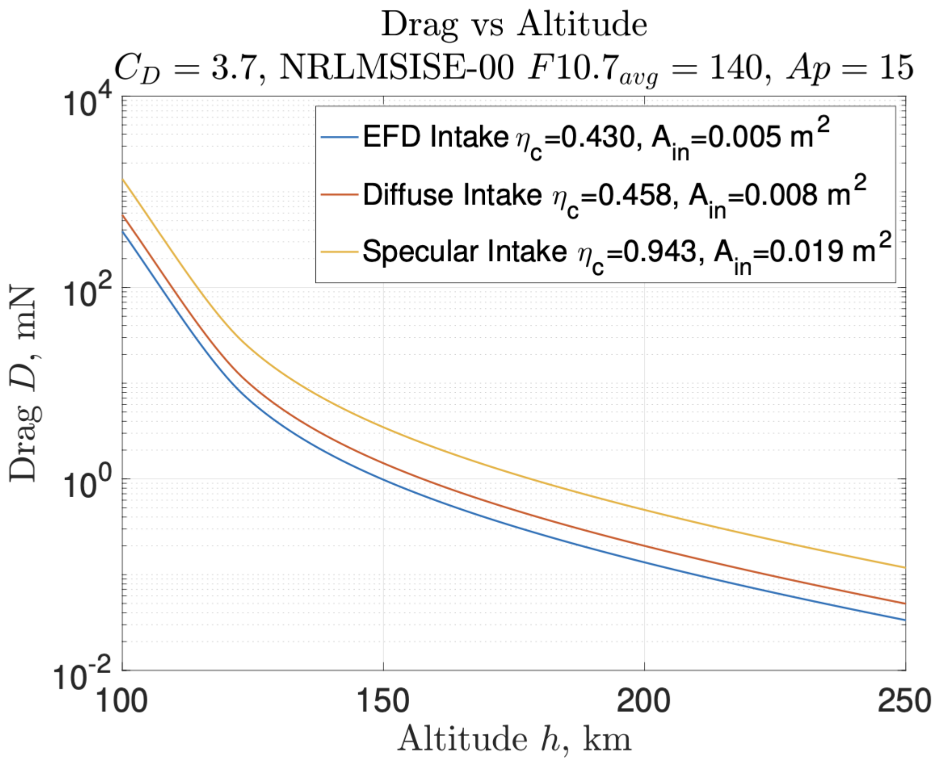
Design Procedure

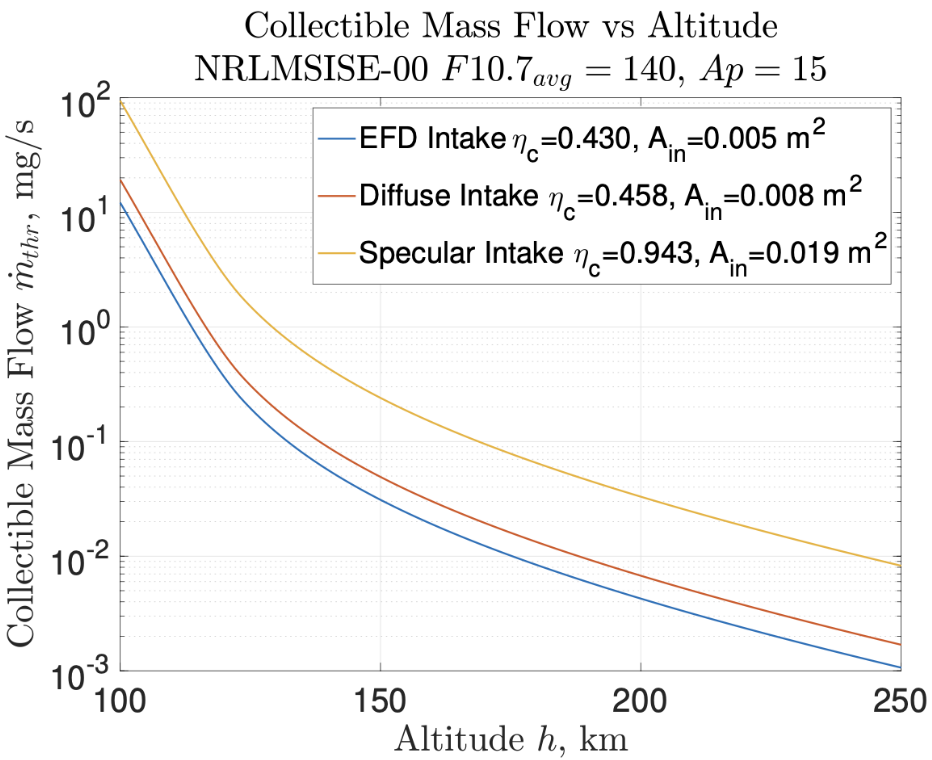


Electric Circuit



System Analysis

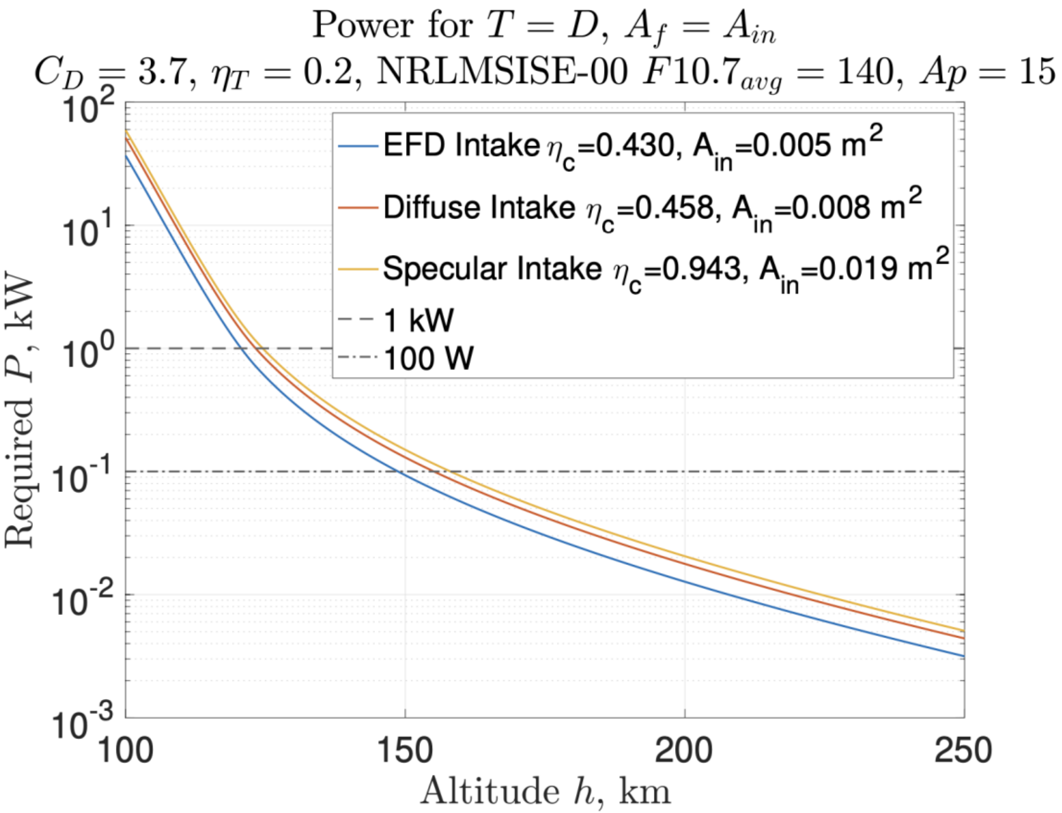




System Analysis

Literature max. helicon thruster efficiency

$\eta_T = 20\%$ [1]



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