Christian-Albrechts-Universität zu Kiel

# Advanced Diagnostics for Electric Space Propulsion

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*International Online Plasma Seminar (IOPS)*

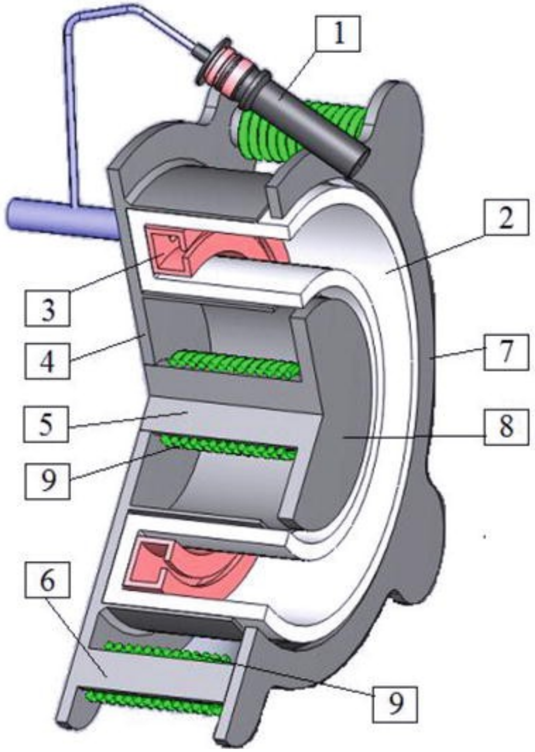
# Outline

1. Standard Diagnostics in EP Development and Testing
2. Force probes as a novel Diagnostic
3. The EPDP for the Heinrich Hertz Satellite
4. Data from the Plasma Sensor
5. Unexpected Features of the Retarding Potential Analyzer
6. Conclusion

# Standard Diagnostics in EP Development and Testing

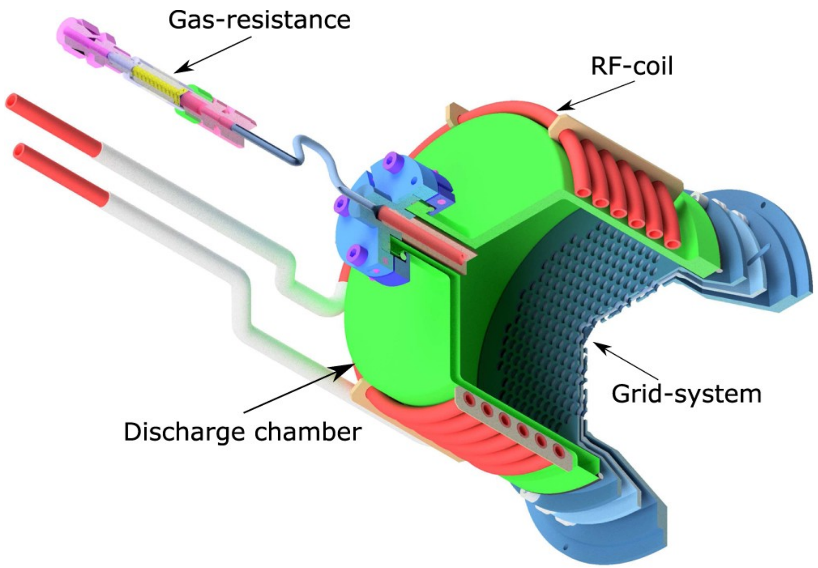
# Some Important Thruster Types

Hall Thruster



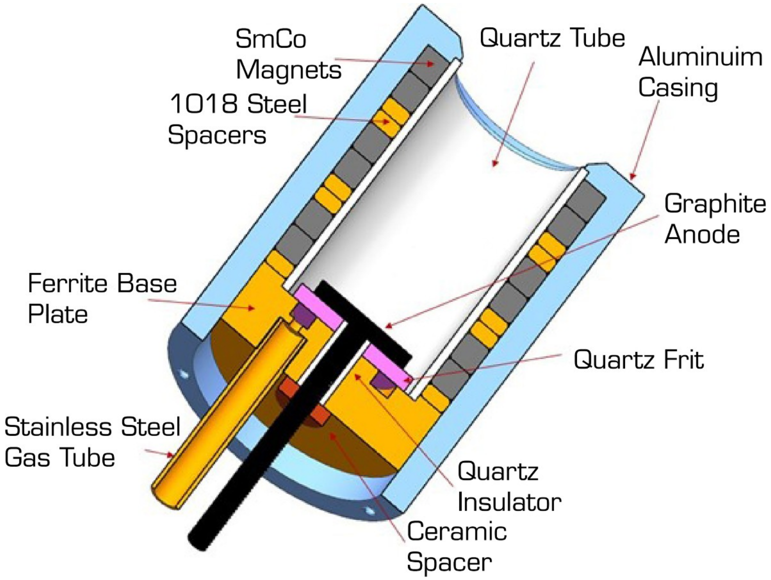

A. V. Loyan and A. N. Khaustova,Hall Thruster Erosion. IntechOpen (2019).https://doi.org/10.5772/intechopen.82654

Gridded Ion Thruster




P. Dietz et al., Plasma Sources Sci. Technol. 28, 084001 (2019)

High-Efficiency Multistage Plasma Thruster (HEMPT)

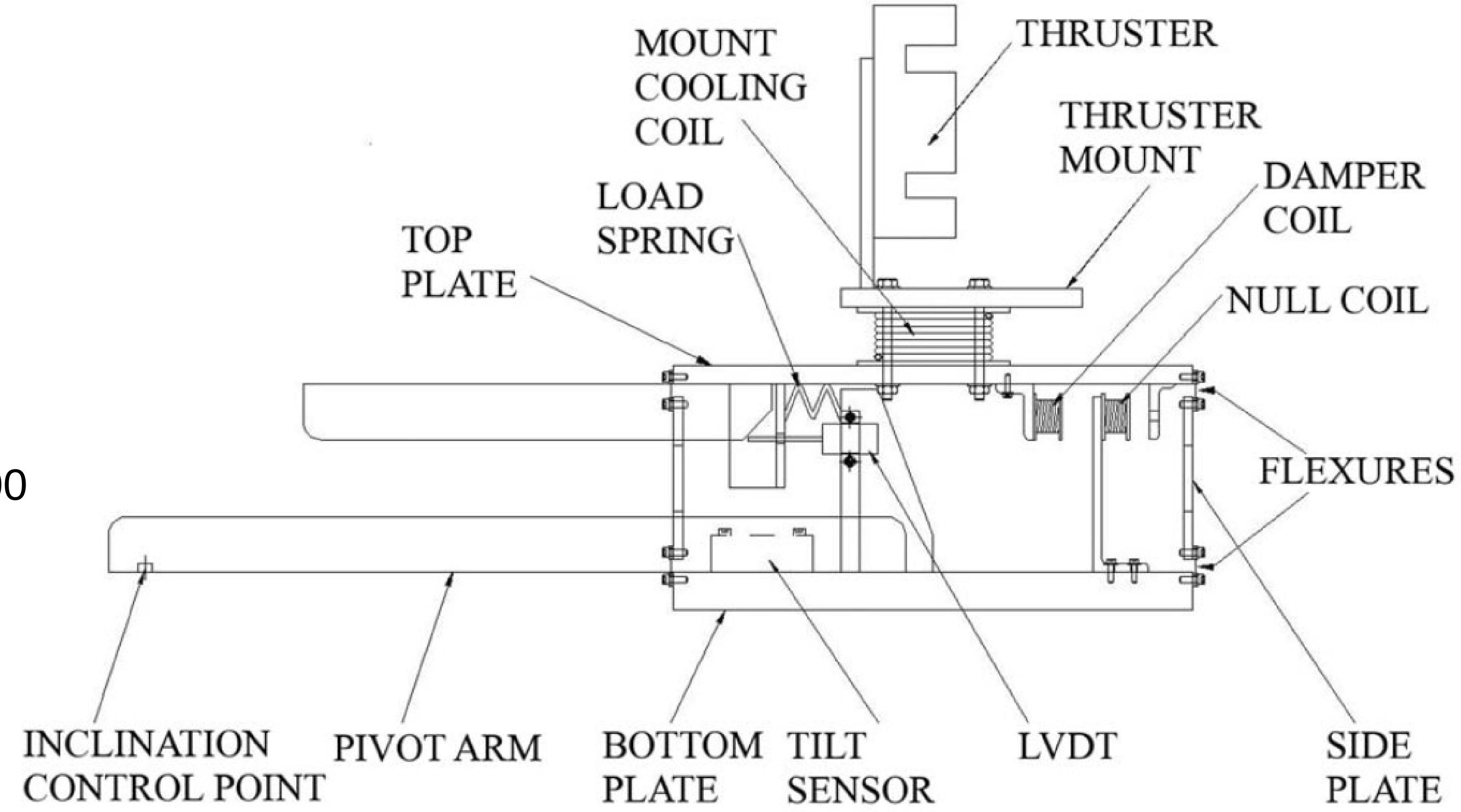



Saridede, Yediyildiz, and Celik, J. Aerosp. Technol. Manag. 15 (2023)https://doi.org/10.1590/jatm.v15.1294

# Direct Thrust Measurements

Example of a thrust balance:

<u>Inverted Pendulum Thrust Balance</u>



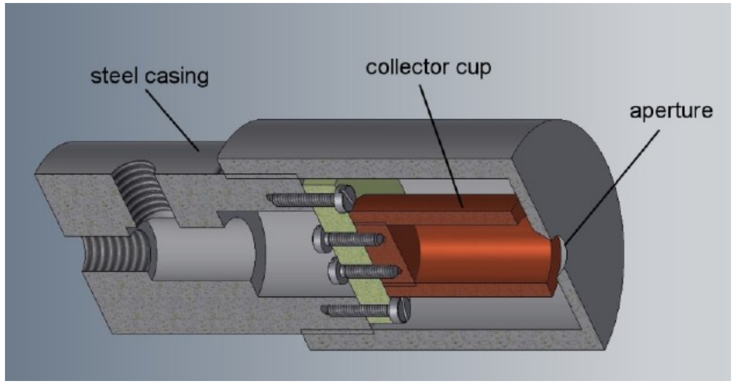

Challenges:

- Thrust-to-weight ratio often < 1:500
- Cables, gas feeds act like springs

Xu and Walker, Rev. Sci. Instrum. 80, 055103 (2009)

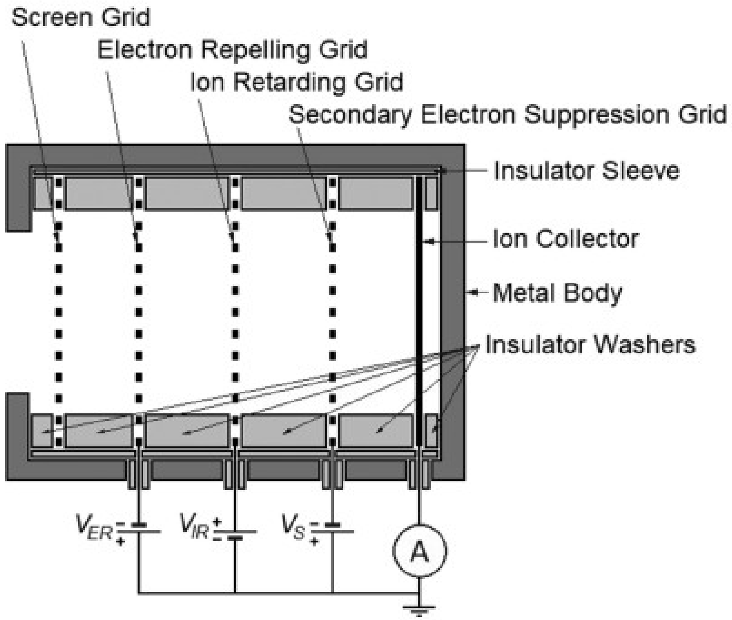
# Standard Diagnostics mostly measure Currents

## Faraday Cup




A. Spethmann et al., Rev. Sci. Instrum. 86,015107 (2015)

## Retarding Potential Analyzer




Maystrenko et al., Rev. Sci. Instrum. 93,073504 (2022)

## Others

- Langmuir probes
- „Faraday probes“

Less common in test facilities, more common in research laboratories:

- Emission spectroscopy
- Laser induced fluorescence
- Quadrupole mass spectrometry
- ExB probe (Wien or velocity filter)
- Electrostatic filters

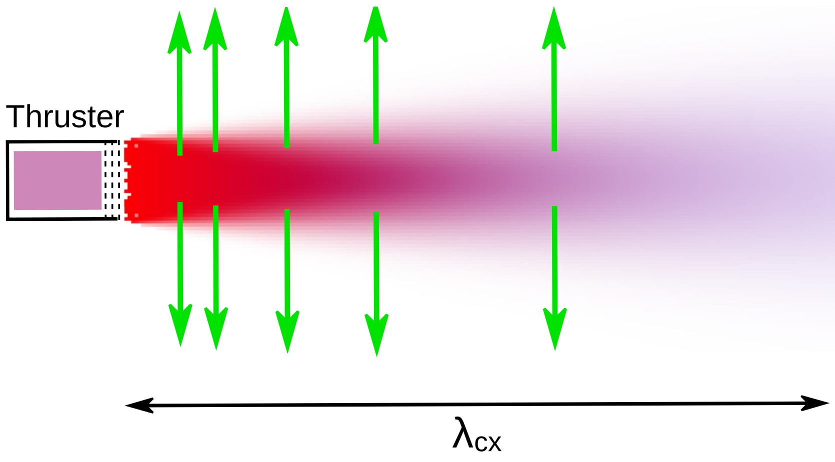
# The Challenge of Charge-Exchange Collisions

## CEX collision reactions:

$$Xe^{+} + Xe \rightarrow Xe + Xe^{+}$$

$$Xe^{2+} + Xe \rightarrow Xe^{+} + Xe^{+}$$

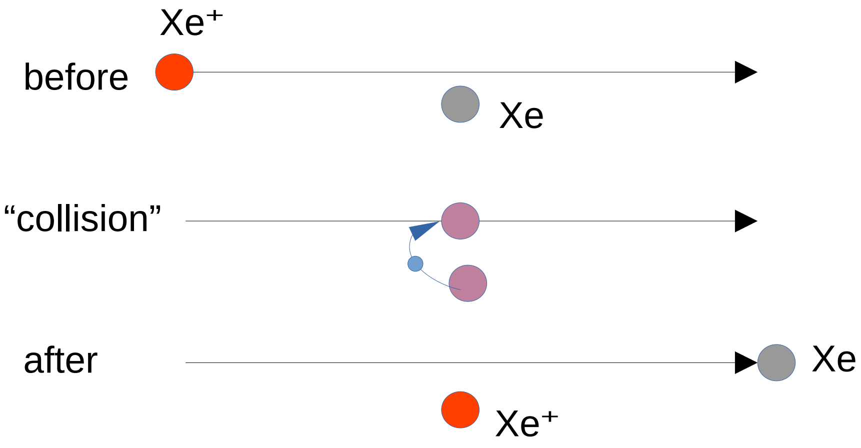
$$Xe^{2+} + Xe \rightarrow Xe + Xe^{2+}$$

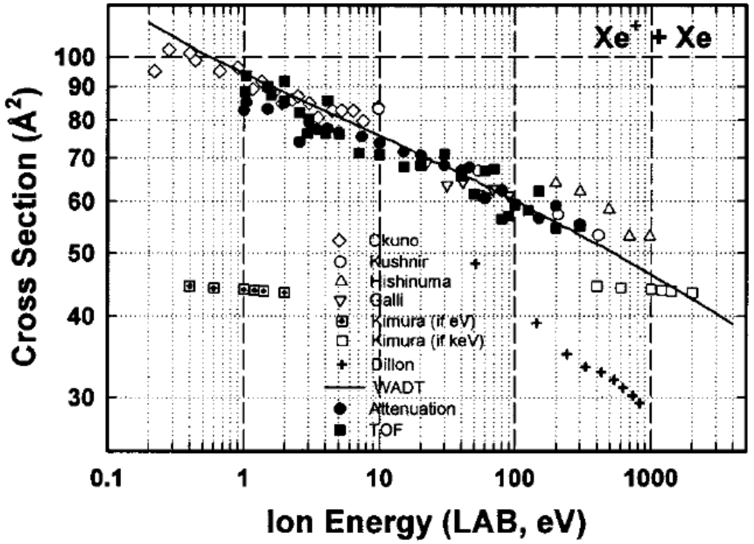



Example:

$p$ = 10 mPa
$E_{kin}$ = 1200 eV

→ $\lambda_{cx}$ = 0.92 m




Miller and Pullins, J. Appl. Phys. 91, 984 (2002)

Why are CEX collisions important?

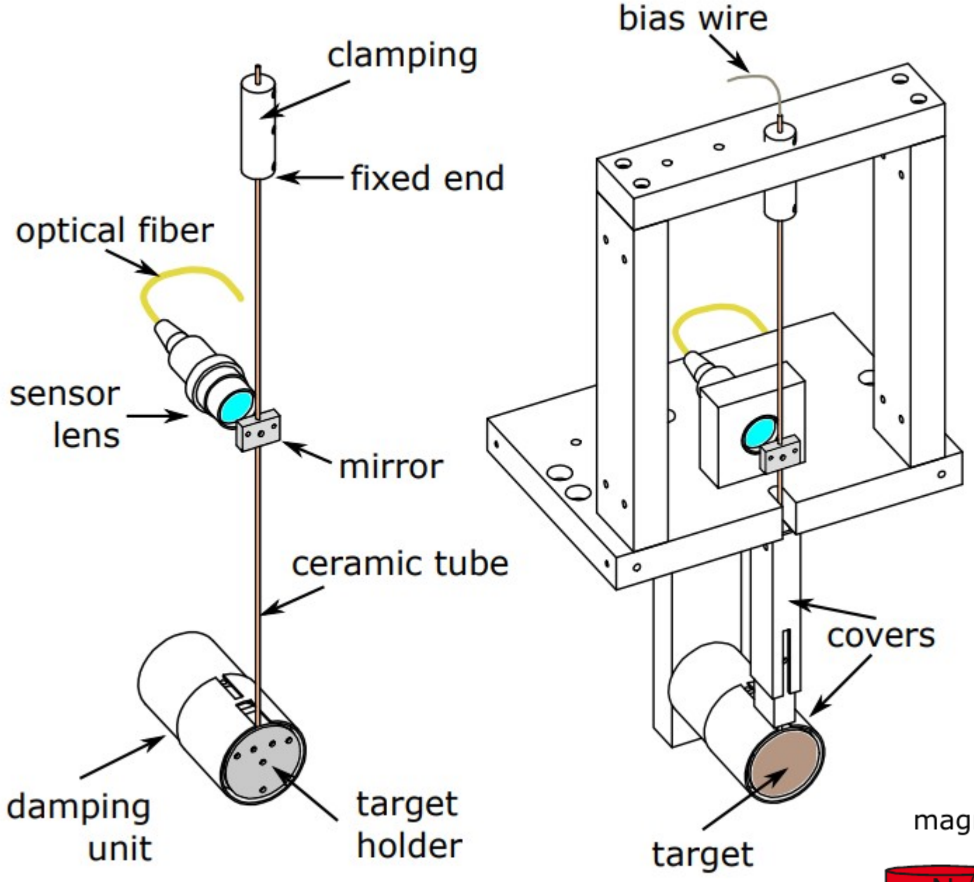
Electrostatic diagnostics
can only measure currents

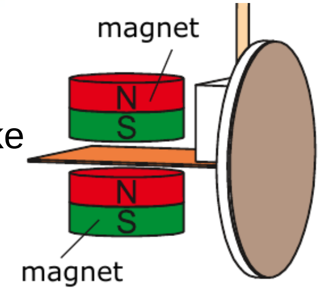
Thermal (slow) ions are released
at elevated potentials
and return to the spacecraft
with high kinetic energies
(sputtering)

# Force Probes as a Novel Diagnostic

# Force Probes as a Novel Thruster Diagnostic

## Essential parts

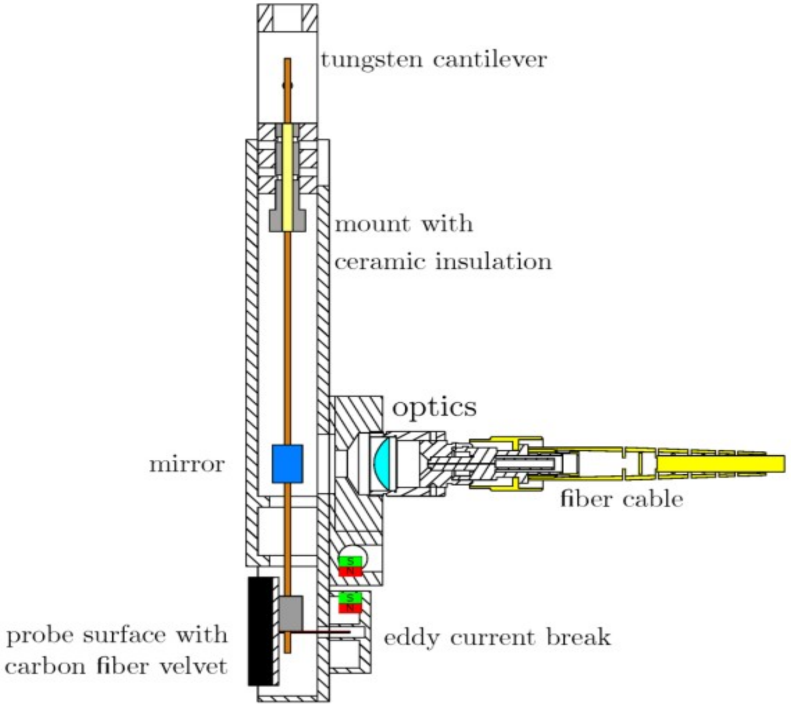


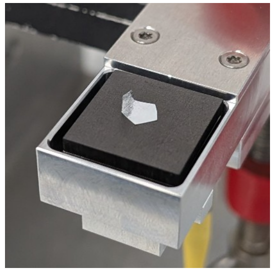

eddy current brake

T. Trottenberg et al., 35th Int. Electric Prop. Conf.,Georgia, Atlanta, USA, IEPC-2017-096 (2017)

## Compact version of the force probe



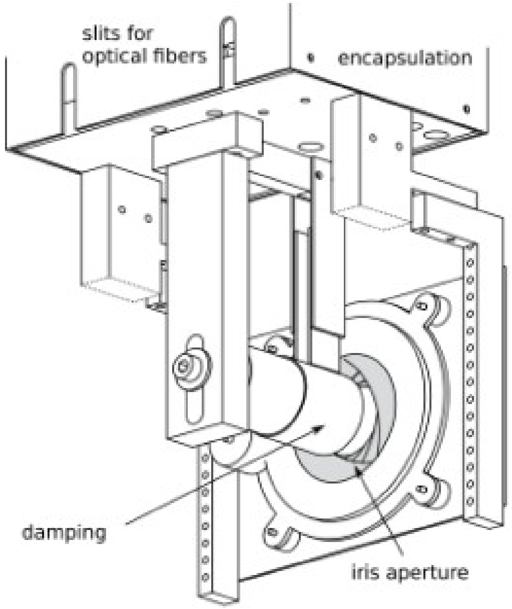

Klette et al., J. Vac. Sci. Technol. A 38, 033013 (2020)



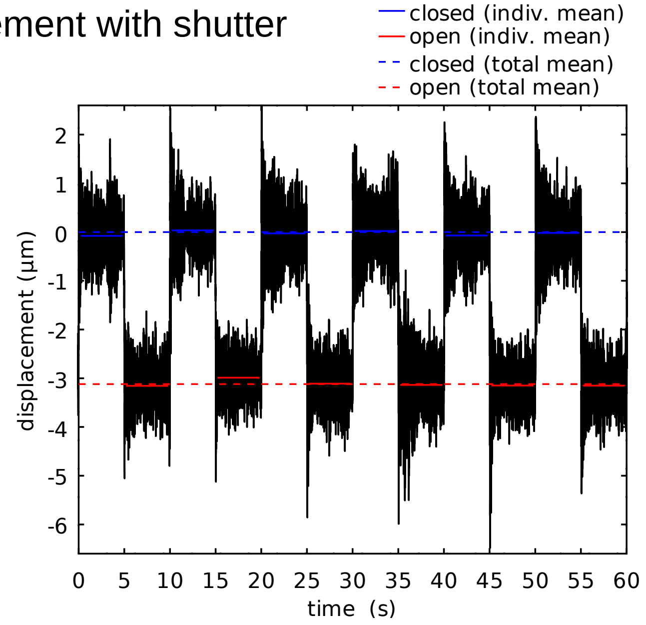
Calibration with mg weights

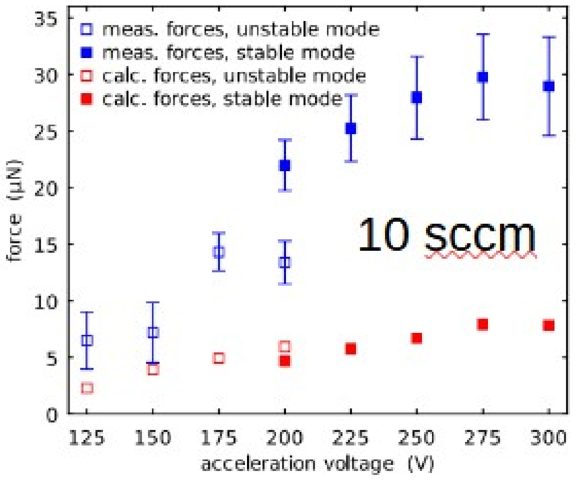
# Force Probes as a Novel Thruster Diagnostic

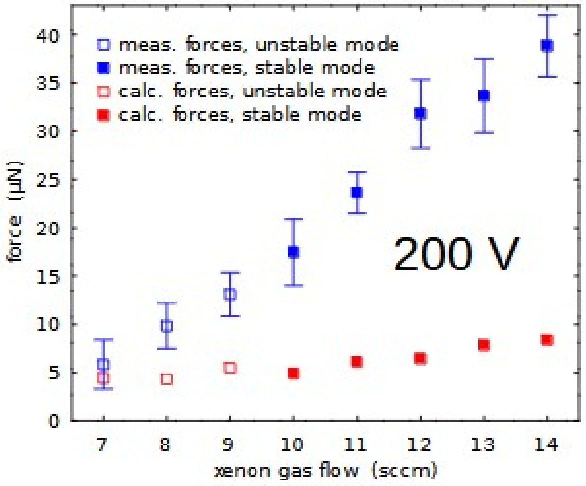
ISCT200-MS Hall thruster




Measurement with shutter



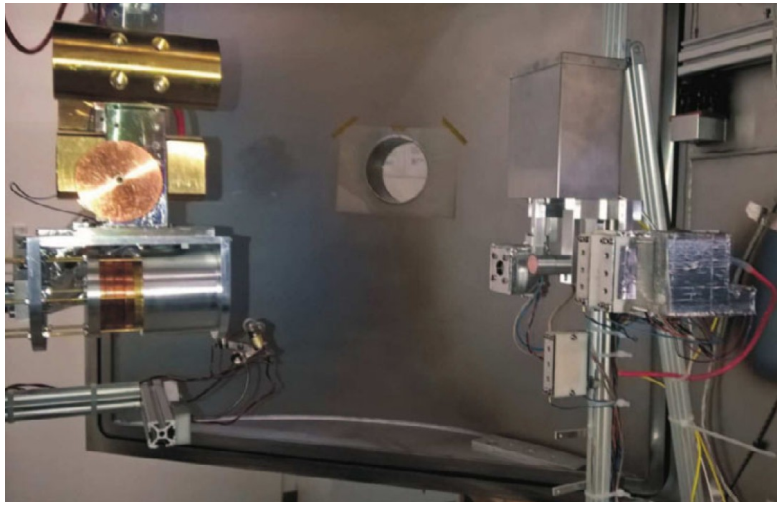




Measurement in der “NexET” chamber at ICARE in Orléans.

- Simultaneous current measurement with the grounded target
- Currents include electrons
- Calculation of the force from the measured electric currents underestimates the real forces

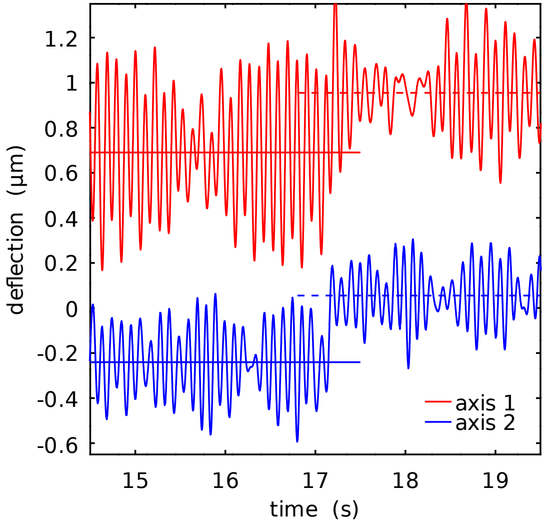
Spethmann et al., EPJ Techn.Instrum. 9, 4 (2022)

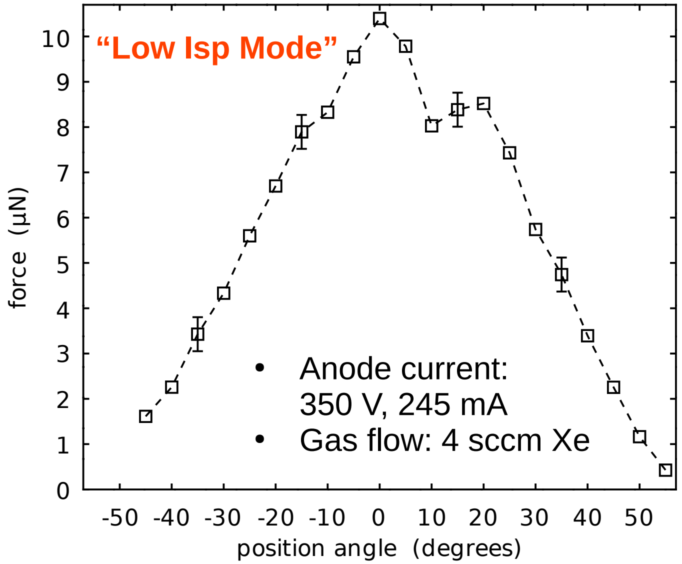
# Force Probes as a Novel Thruster Diagnostic

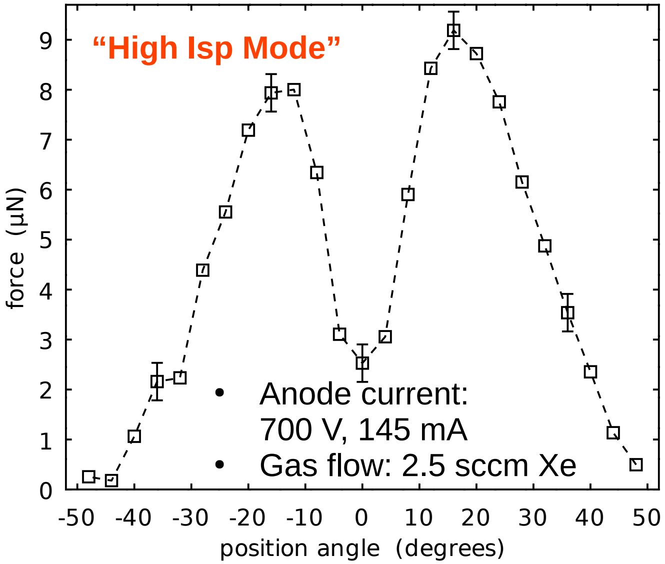


Measurement at the *Laboratory for Enabling Technologies*, Airbus, Friedrichshafen, Germany.

- Swivel arm (constant distance)
- Integration of the momentum flux density agrees with direct thrust measurement (thrust balance)
- Forces calculated from currents underestimate the real forces (charge-exchange collisions)



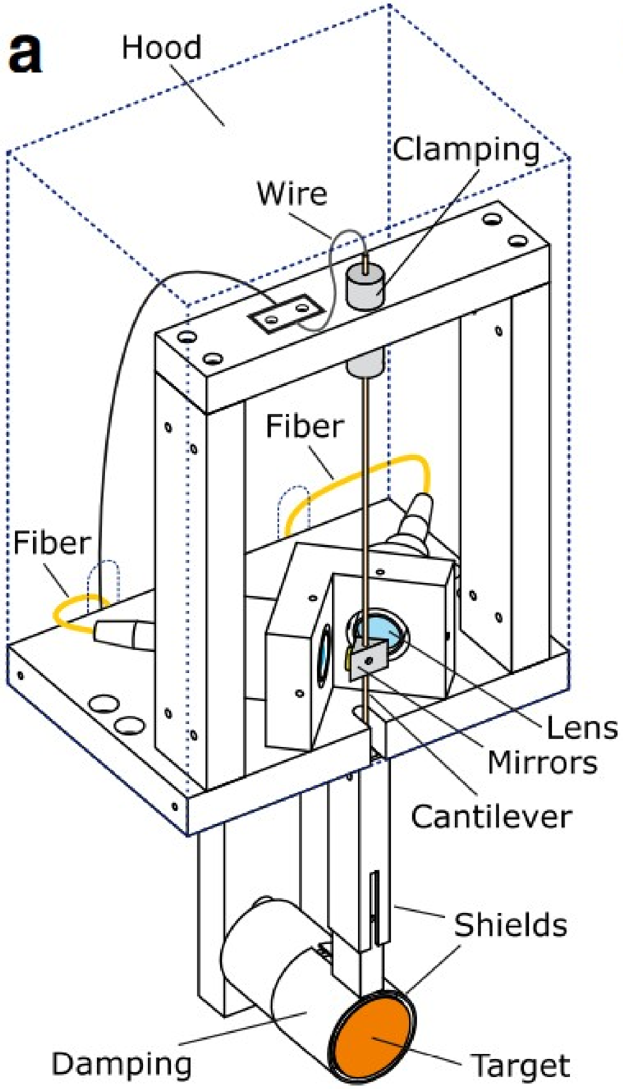




Comparison with thrust balance

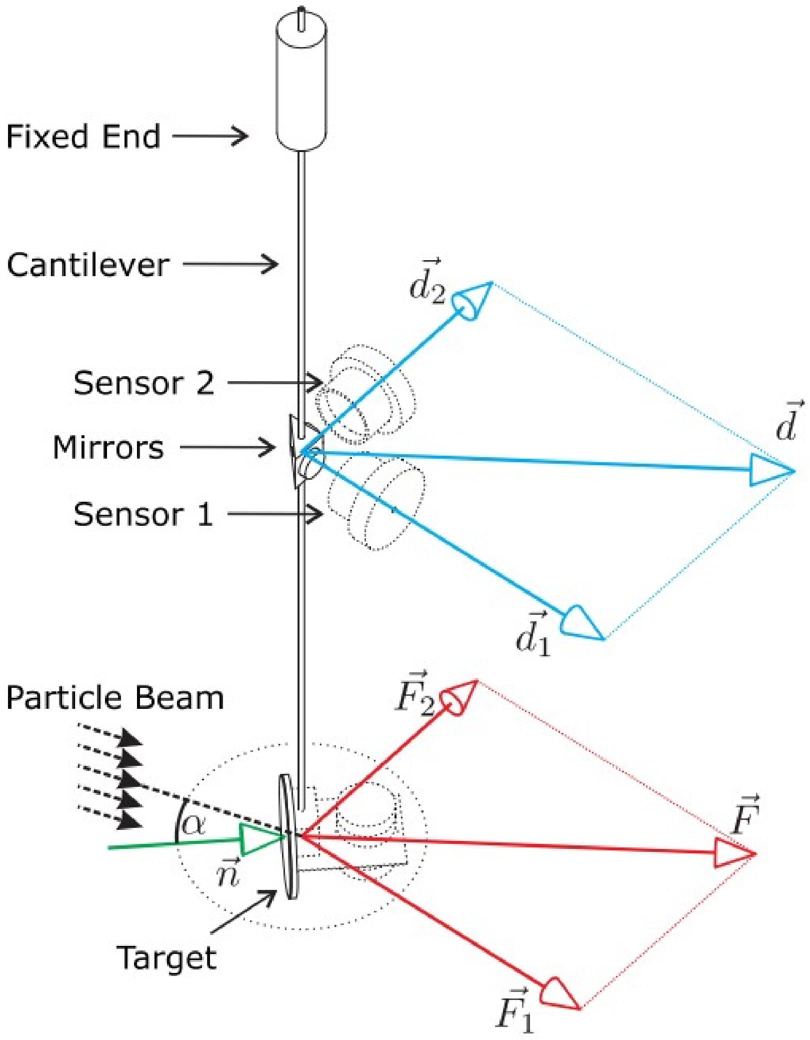
- "High Isp Mode": Integration: 2.9 mN, Balance: 3236 µN
- "Low Isp Mode": Integration: 3.6 mN, Balance: 3200 µN

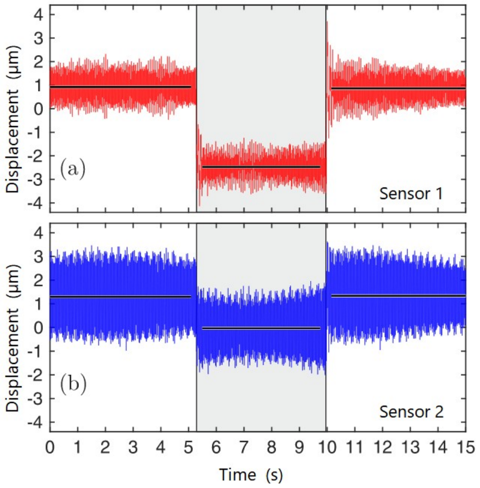
Spethmann et al., EPJ Techn.Instrum. 9, 4 (2022)

# Force Probes for the Study of Sputtering





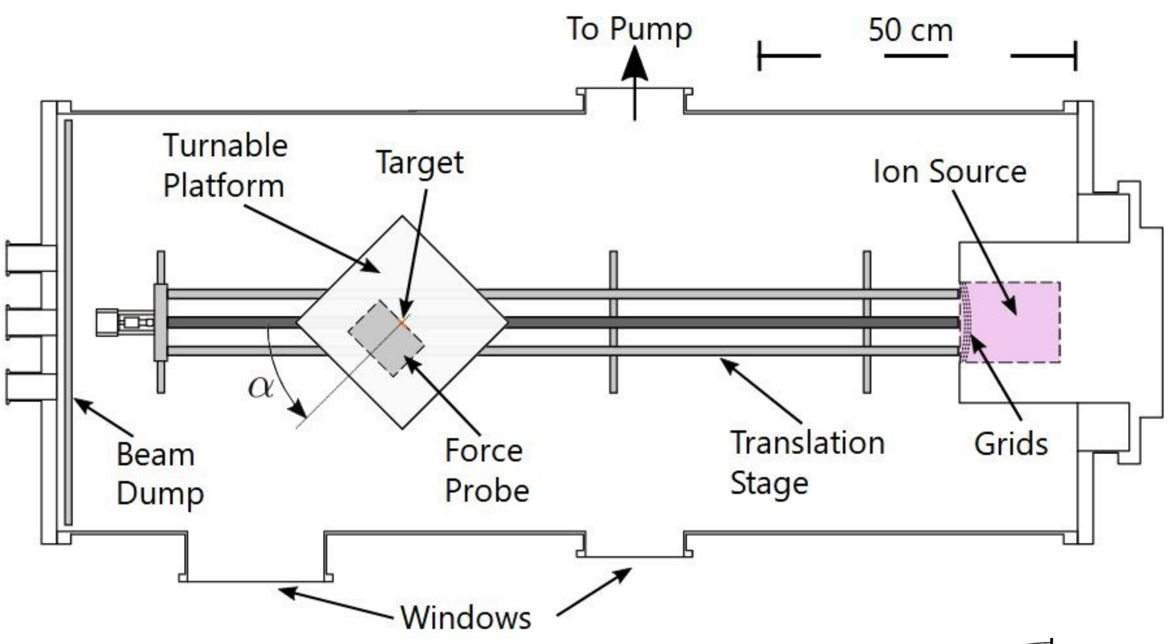


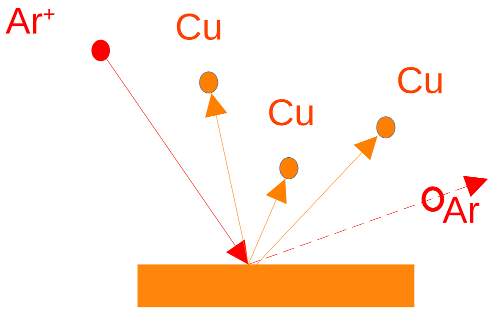



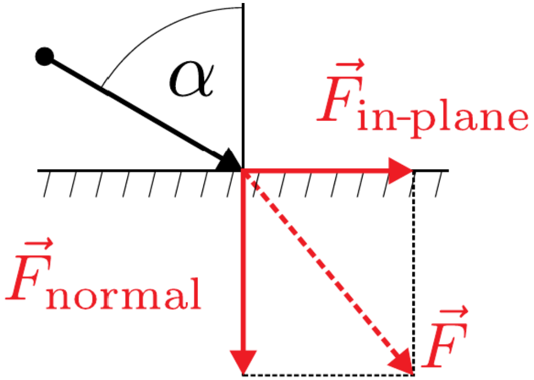

The two-axis probe measures force as a 2d vector

Trottenberg et al., EPJ Techn. Instrum. 5, 3 (2018)

# Force Probes for the Study of Sputtering

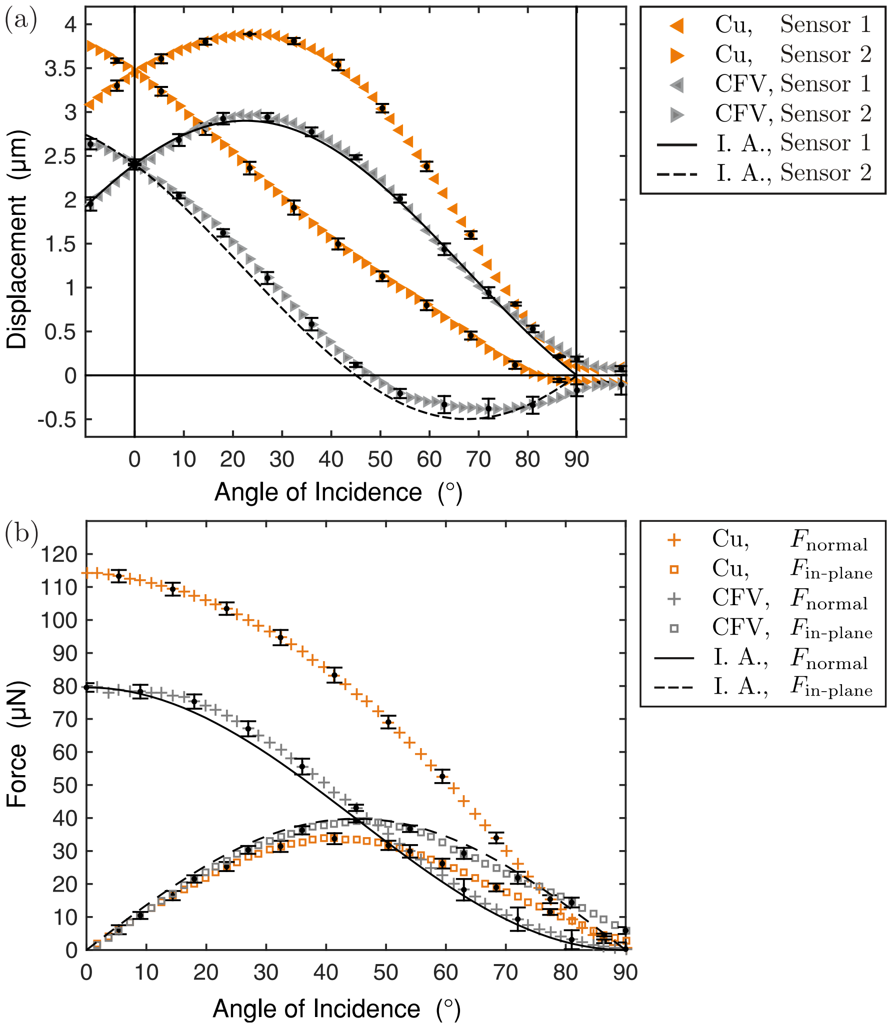



$$F_{\text{normal}} = \sqrt{\tfrac{1}{2}}(F_1 + F_2)$$

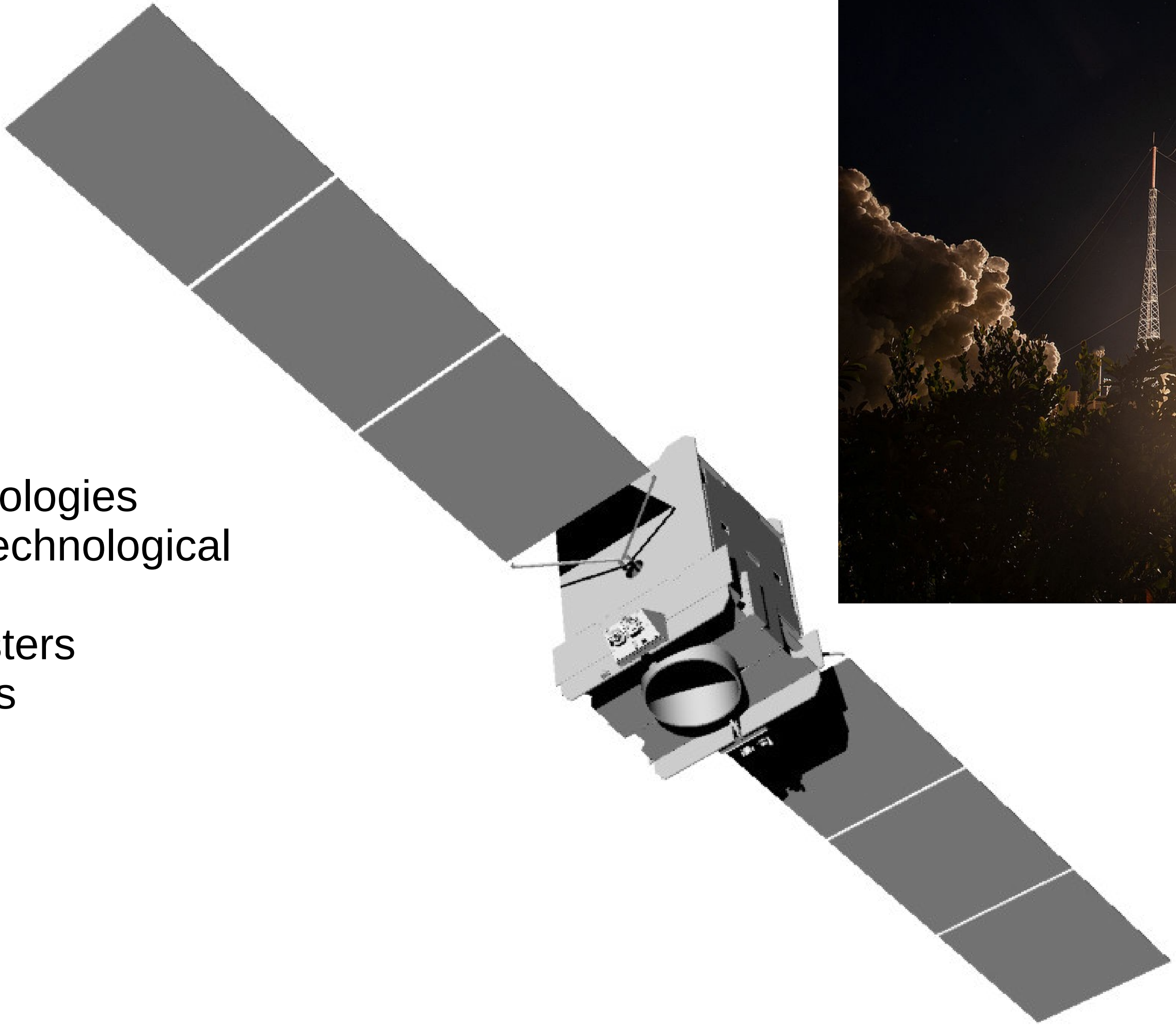
$$F_{\text{in-plane}} = \sqrt{\tfrac{1}{2}}(F_1 - F_2)$$




A 1.2 keV Ar/Ar$^+$ beam impacts on a copper (Cu) surface and a *carbon fiber velvet* (CFV) suface. The solid and dashed lines indicate the theoretical case of ideal absorption (I.A.).

Trottenberg et al., EPJ Techn. Instrum. 5, 3 (2018)

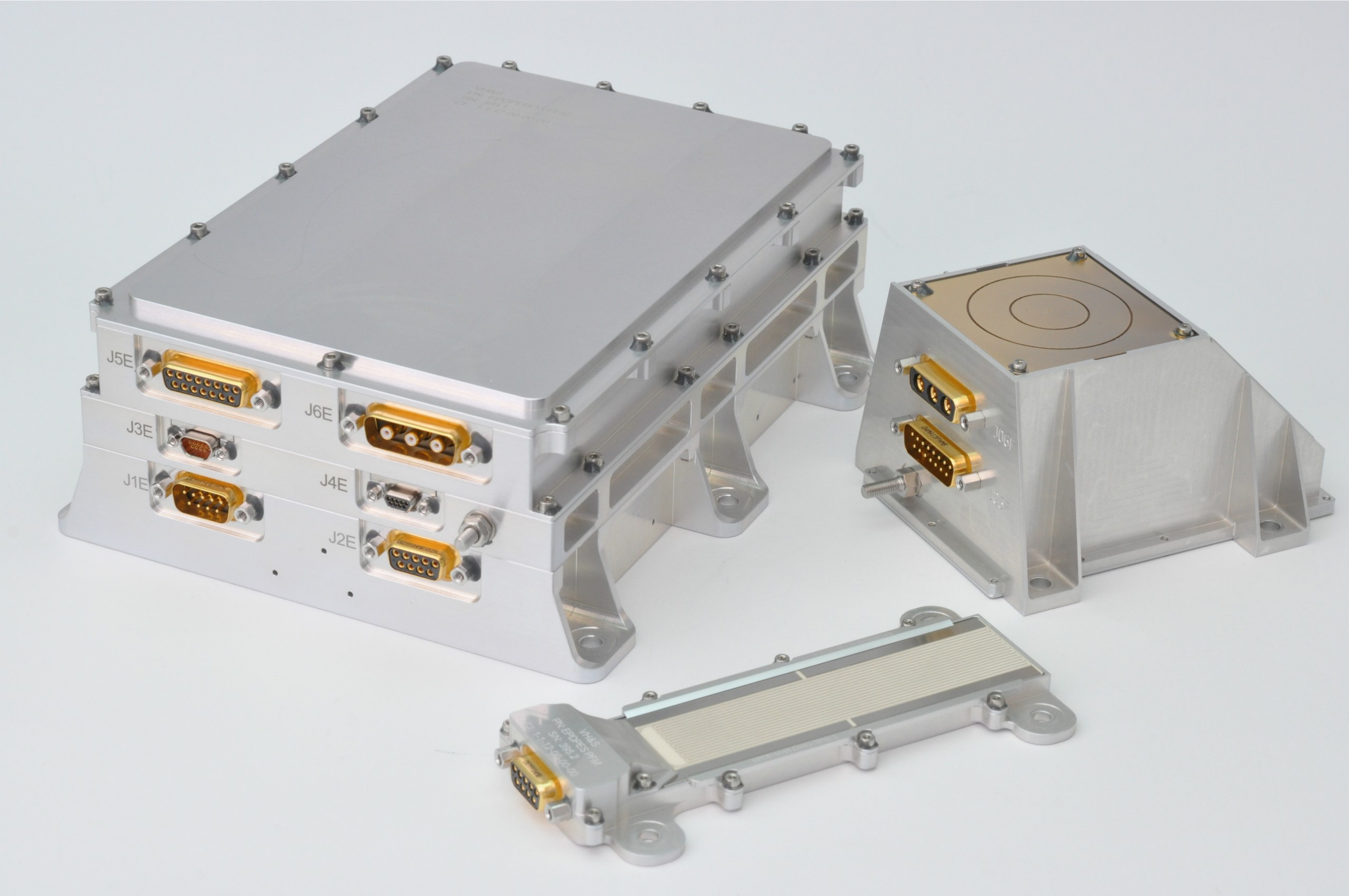
# The EPDP for the Heinrich Hertz Satellite



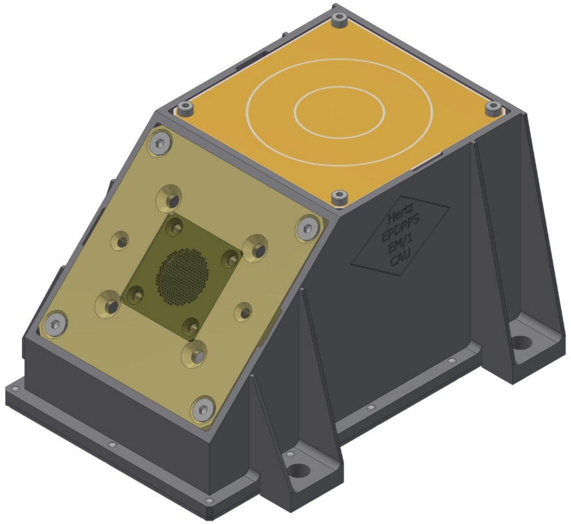
## Heinrich Hertz Satellite

- Explore and test new telecommunications technologies
- Platform for sientific and technological experiments
- Pair of HEMPT 3050 thrusters
  + pair of SPT-100 thrusters
- launched July 6th, 2023
- Financed by DLR
- Integrated by OHB

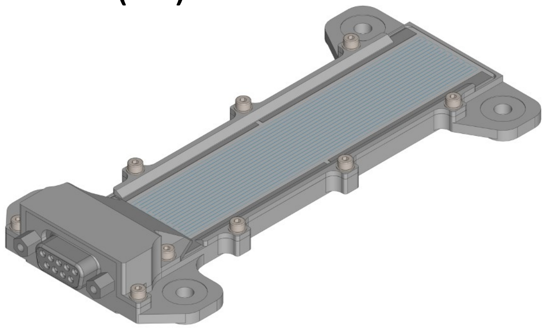
# Electric Propulsion Diagnostic Package



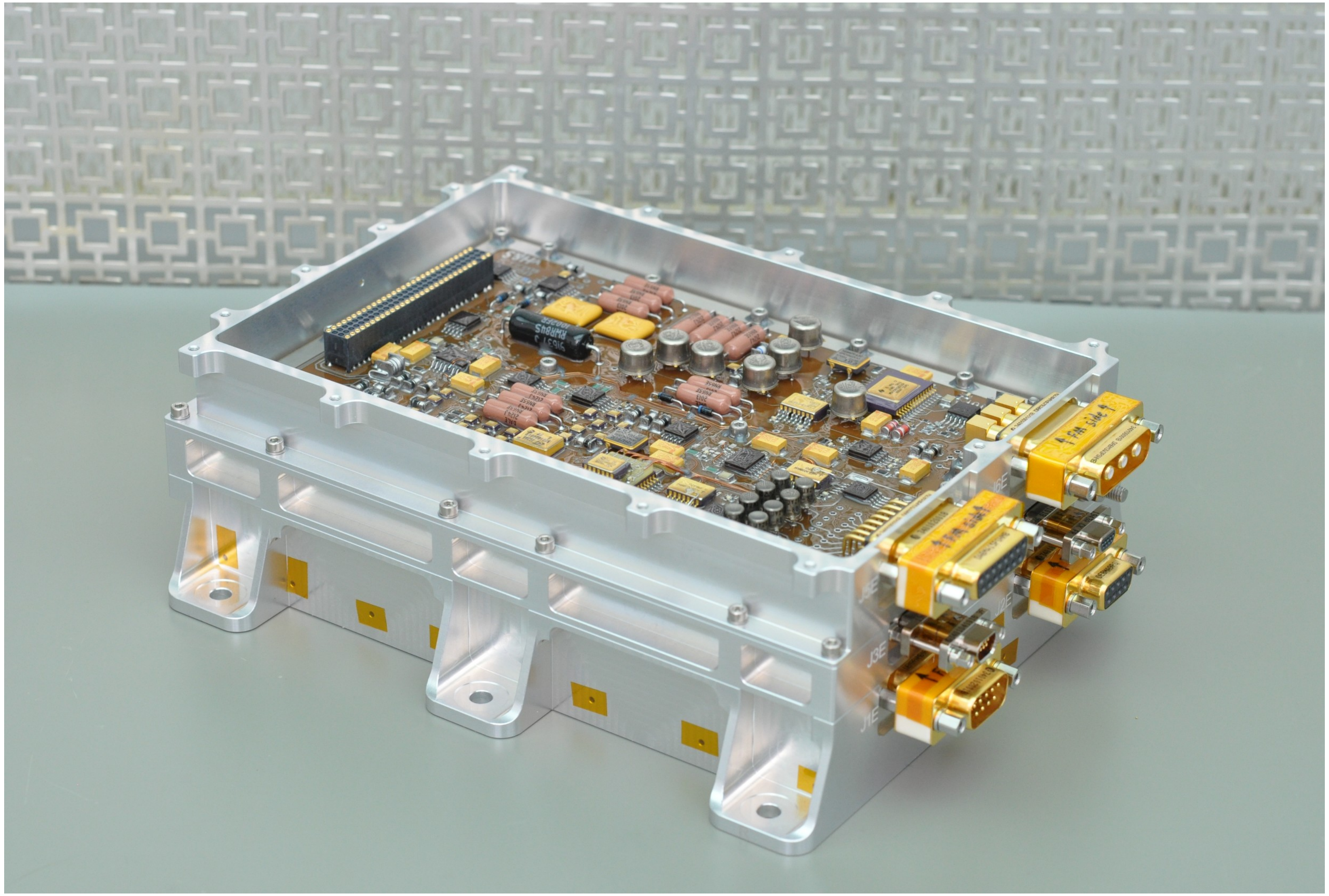

Plasma Sensor (PS)

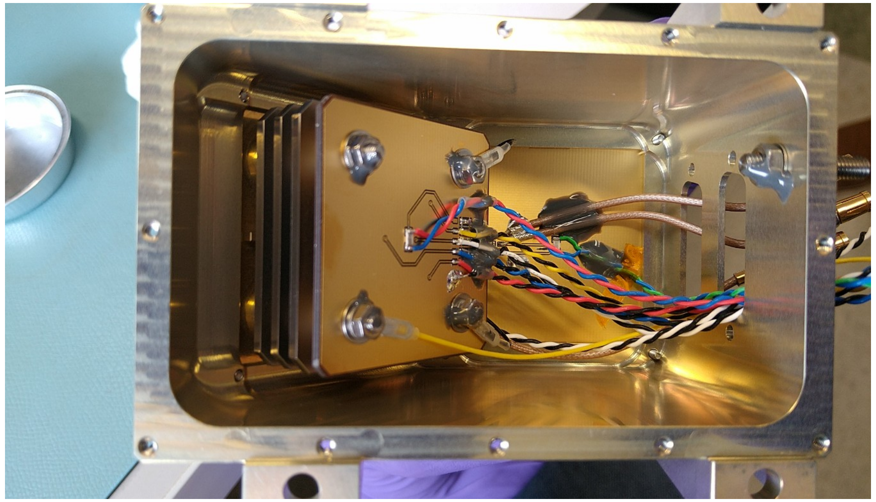


Erosion Sensor (ES)

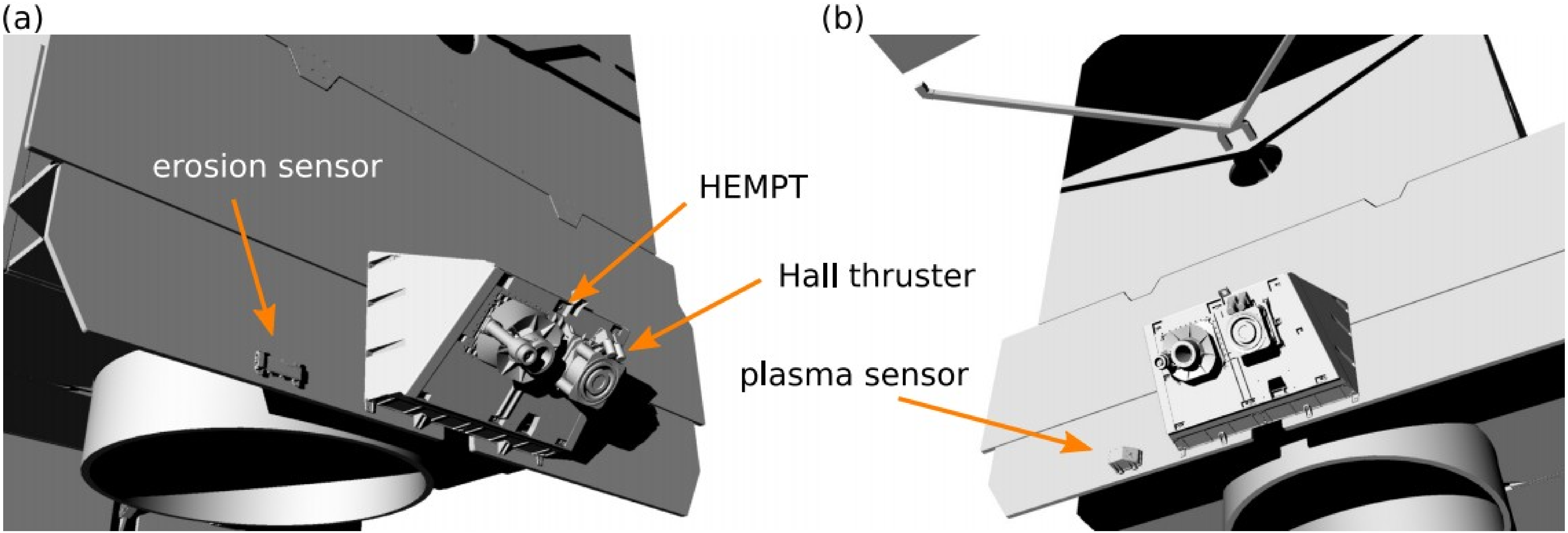


# Electric Propulsion Diagnostic Package

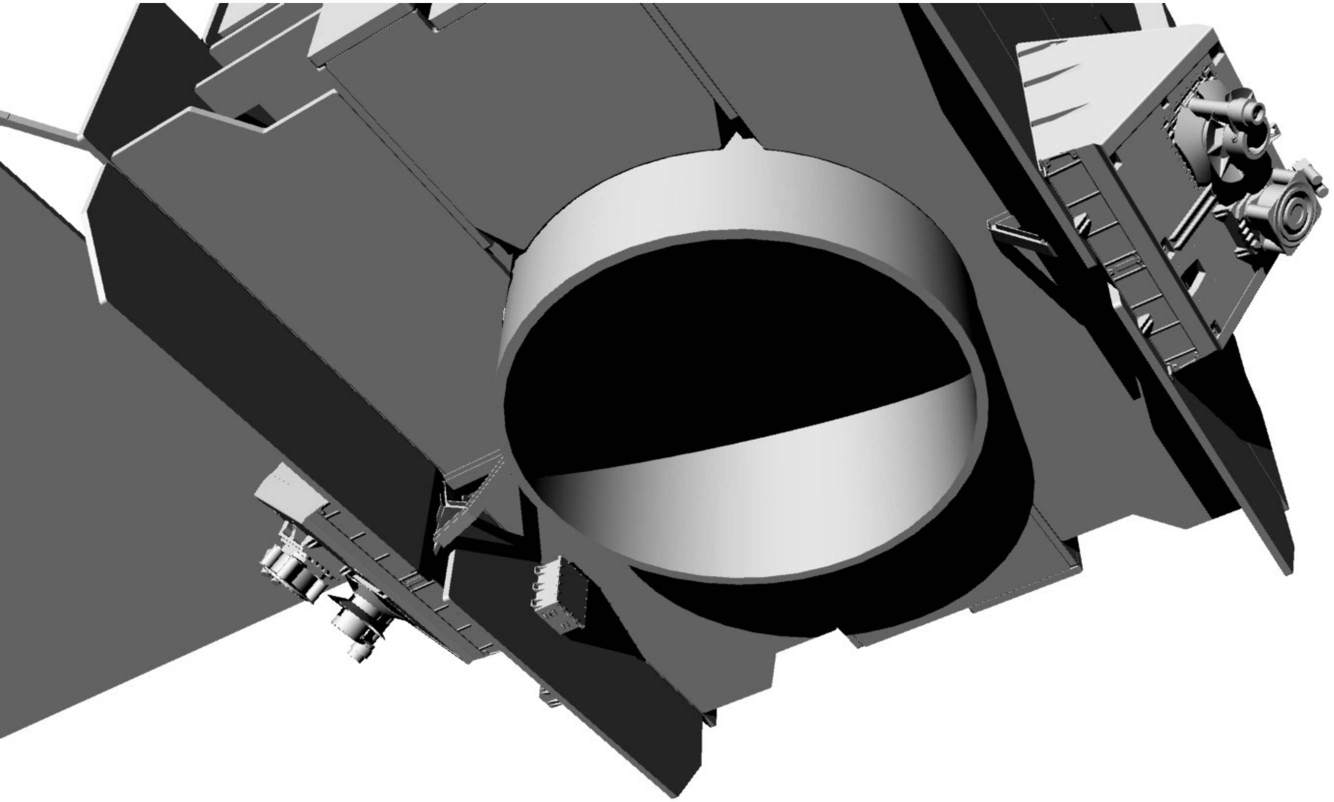


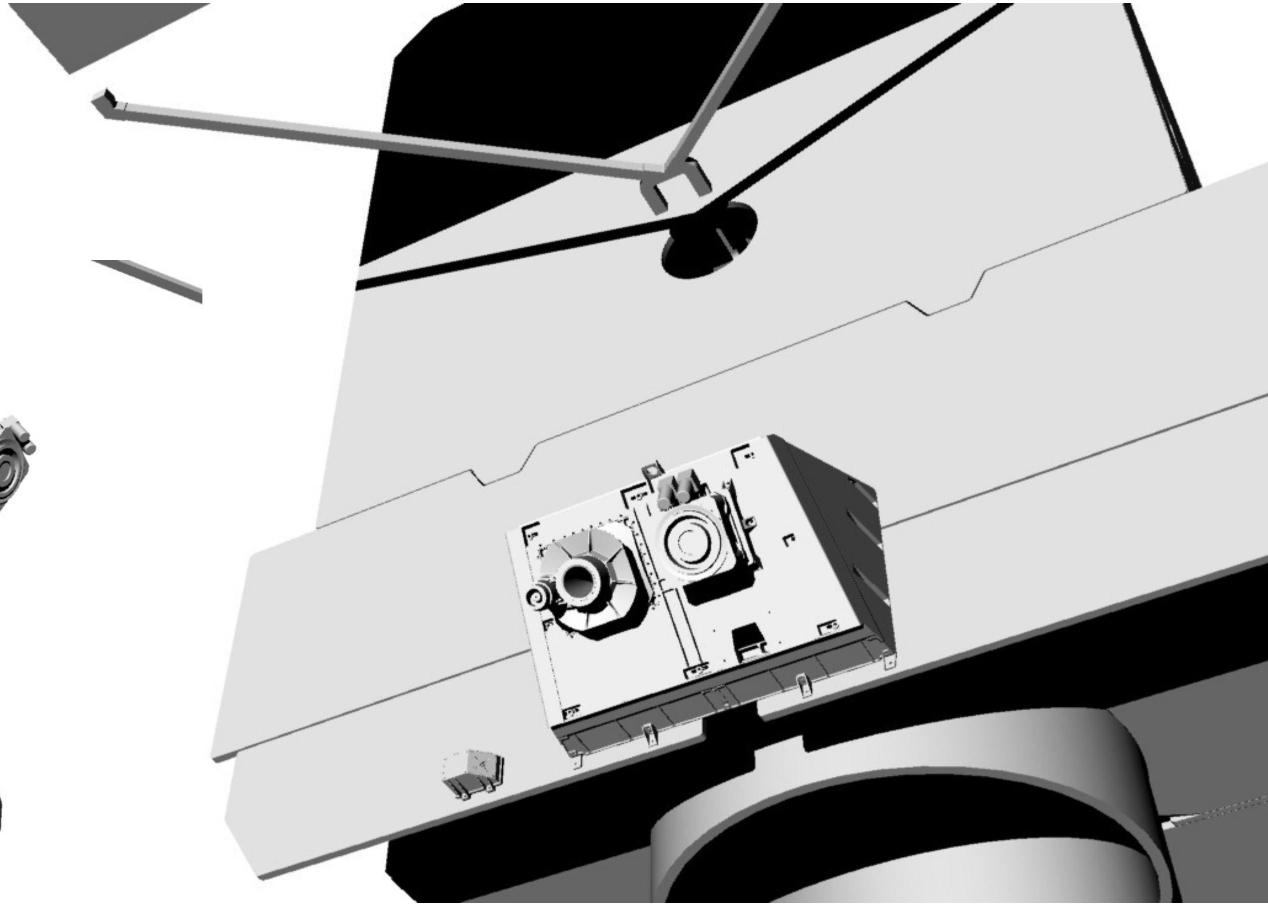


# EPDP Mounting Positions on the Satellite

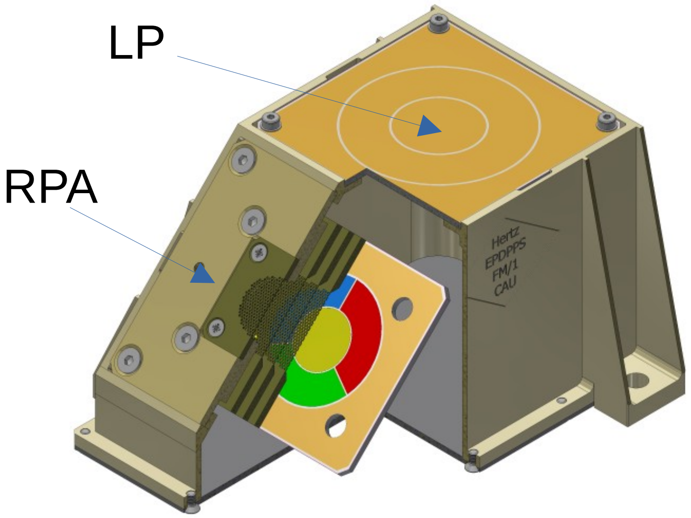


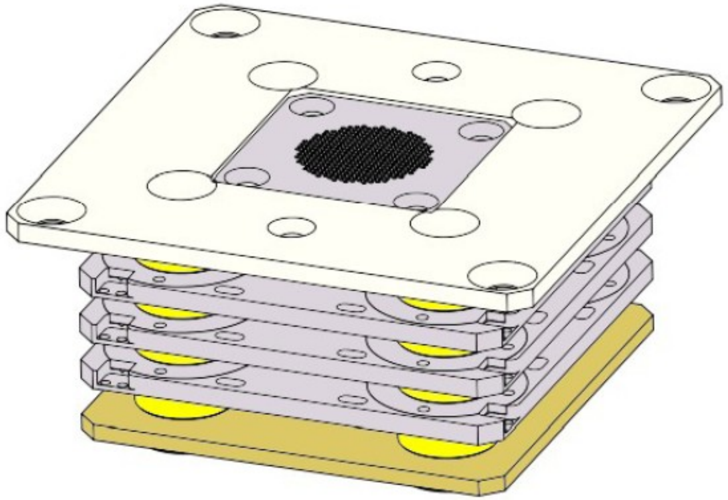
# EPDP Mounting Positions on the Satellite

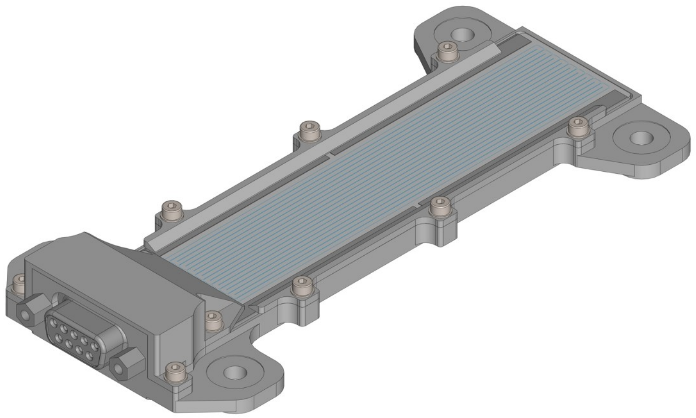




# The EPDP Sensors





Langmuir Probe (LP):

- Probe area 3.1 cm²
- Ion saturation currents
  2 nA … 0.5 µA

Retarding Potential Analyzer (RPA):

- Four grids
- 0.5 mm holes
- Hexagonal pattern
- 0.7 mm "grid constant"
- Segmented collector
- 23 mm entrance to collector

Erosion Sensor:

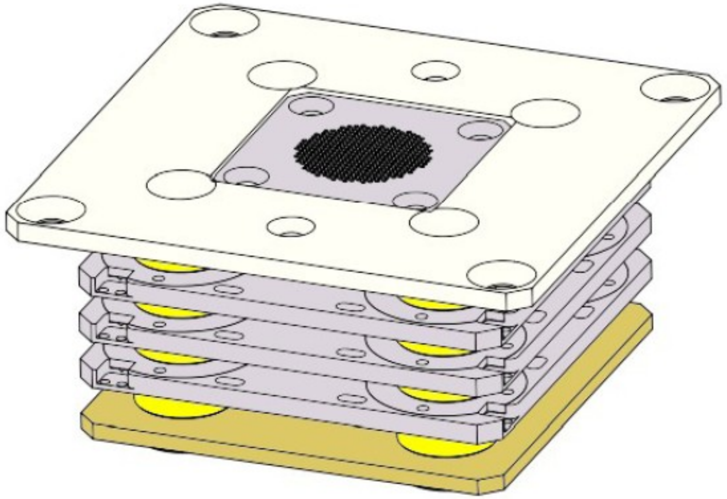
Resistance measurement

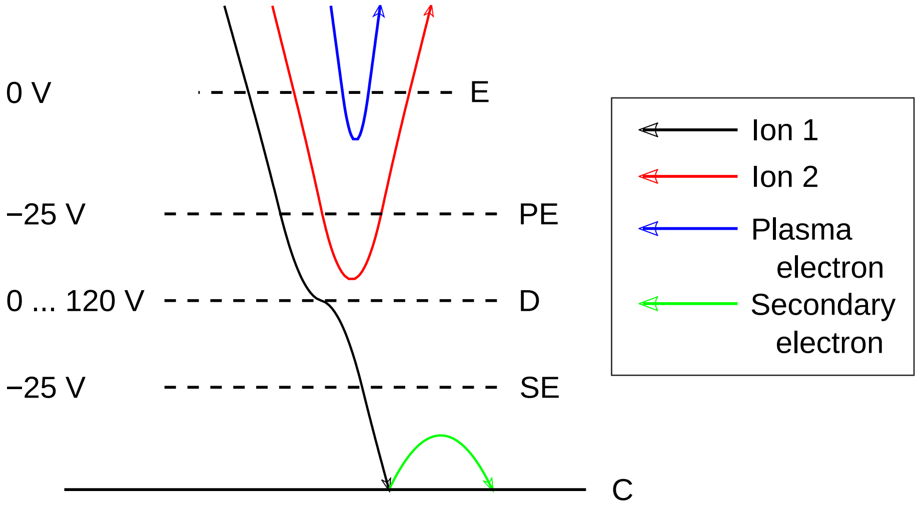
Silver meander on ceramic originally 15 Ω:

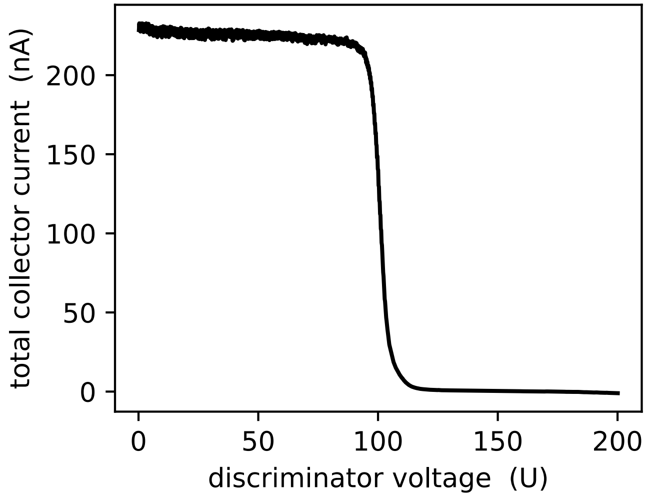
- 180 cm long
- 2 µm thick
- 1 mm wide

Trottenberg et al., EPJ Techn. Instrum. 8, 16 (2021)

# Quick Recap: What is a Retarding Potential Analyzer (RPA)?






<u>Four-grid RPA</u>

E: Entrance grid
PE: Plasma electron repeller grid
D: Discriminator grid
SE: Secondary electron repeller grid
C: Collector

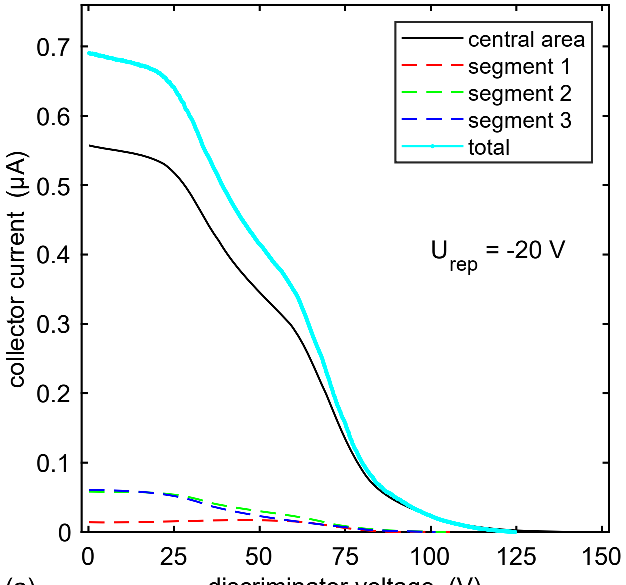
The trajectories illustrate…

- an ion (black) that overcomes the retarding potential,
- one that does not (red),
- electrons originating from the plasma (blue),
- electrons from the collector (green).

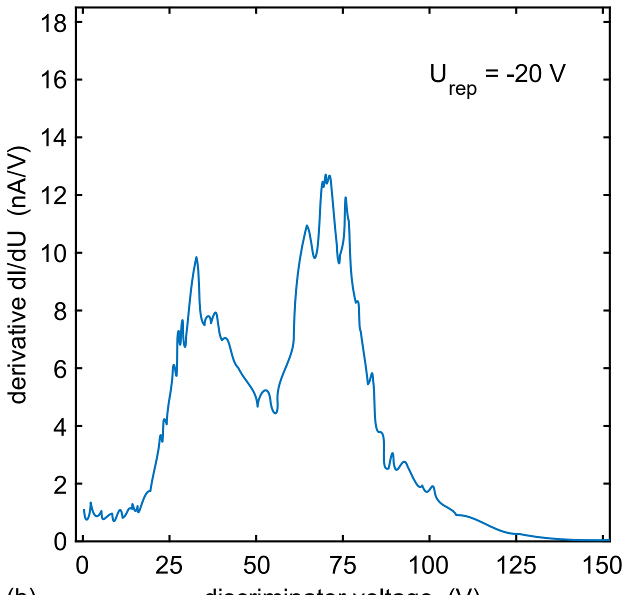
- Characeristics are monotonically decreasing
- Derivatives yield distribution functions

# Data from Measurements with a HEMPT: Chamber & Space

## Data from Tests in ULAN chamber (Thales)

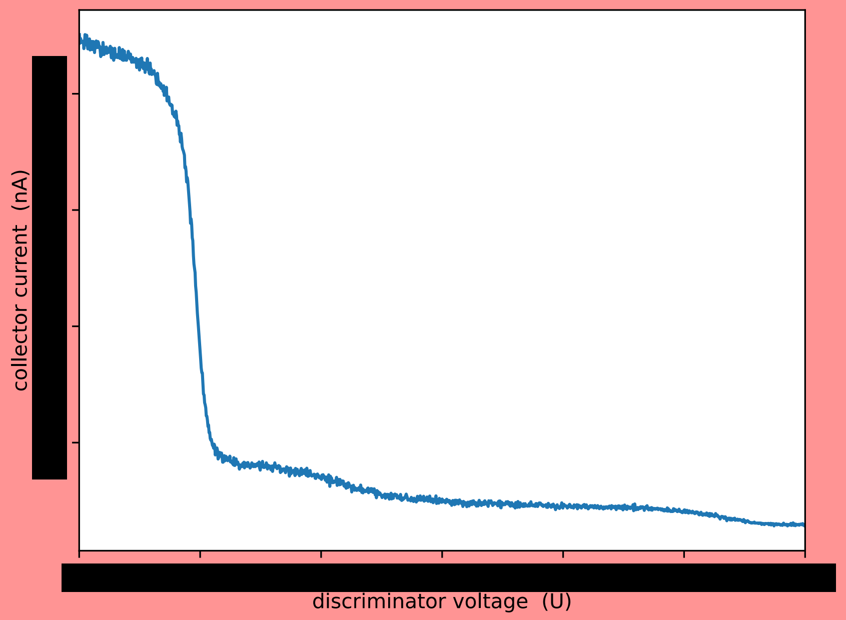



(a)



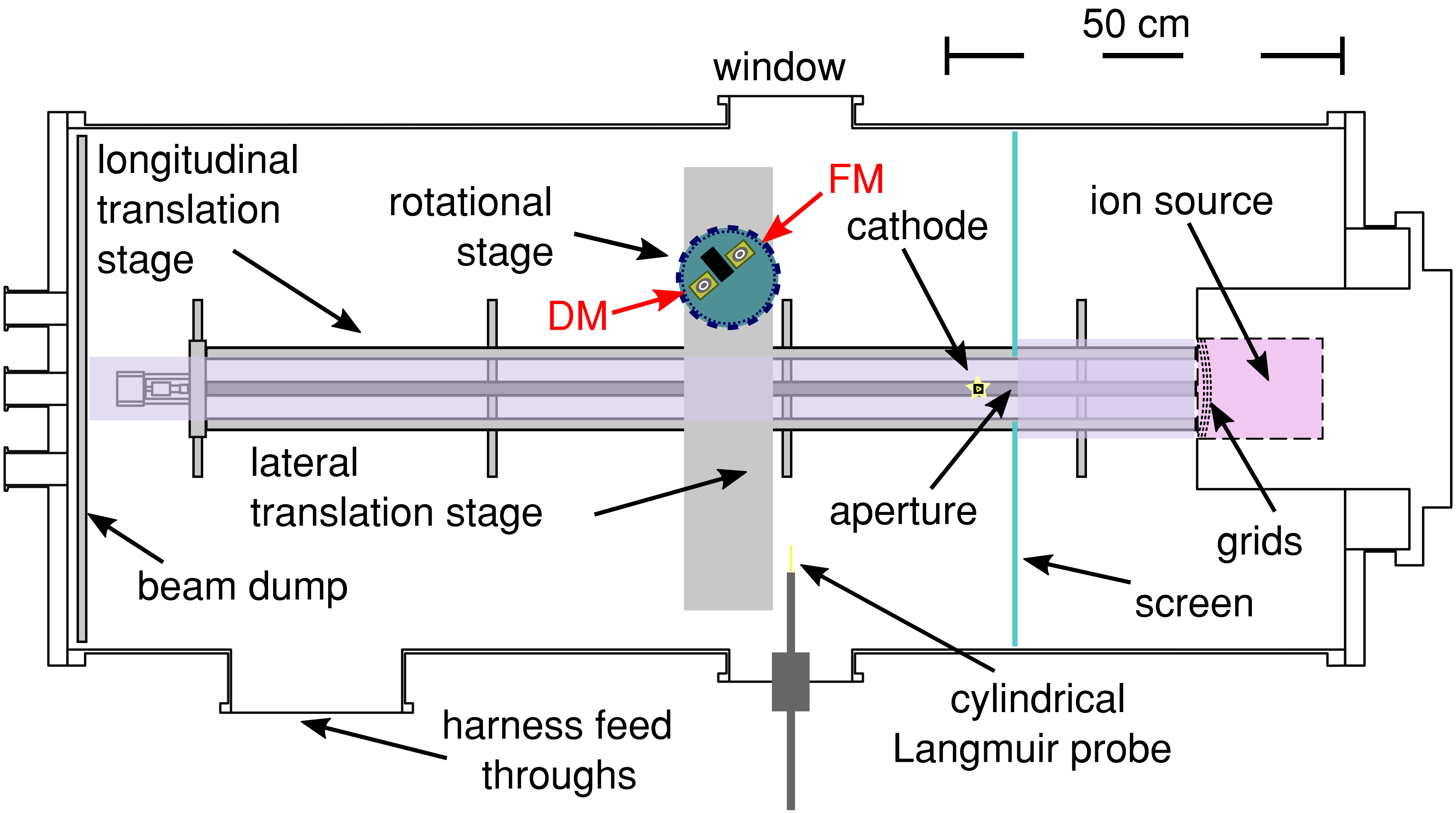

(b)

## Data from EPDP in Space (absolute values not disclosed)

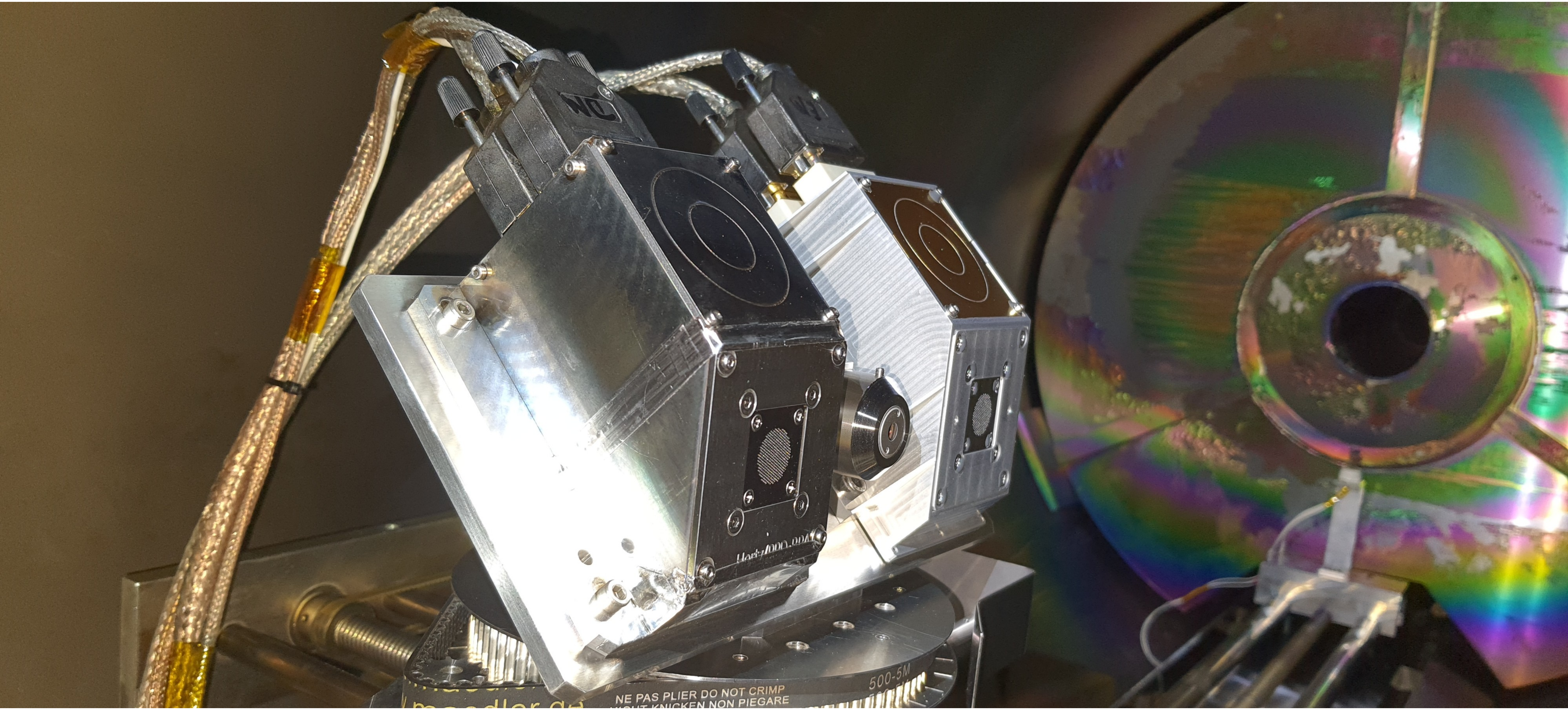


# Data from the Plasma Sensor

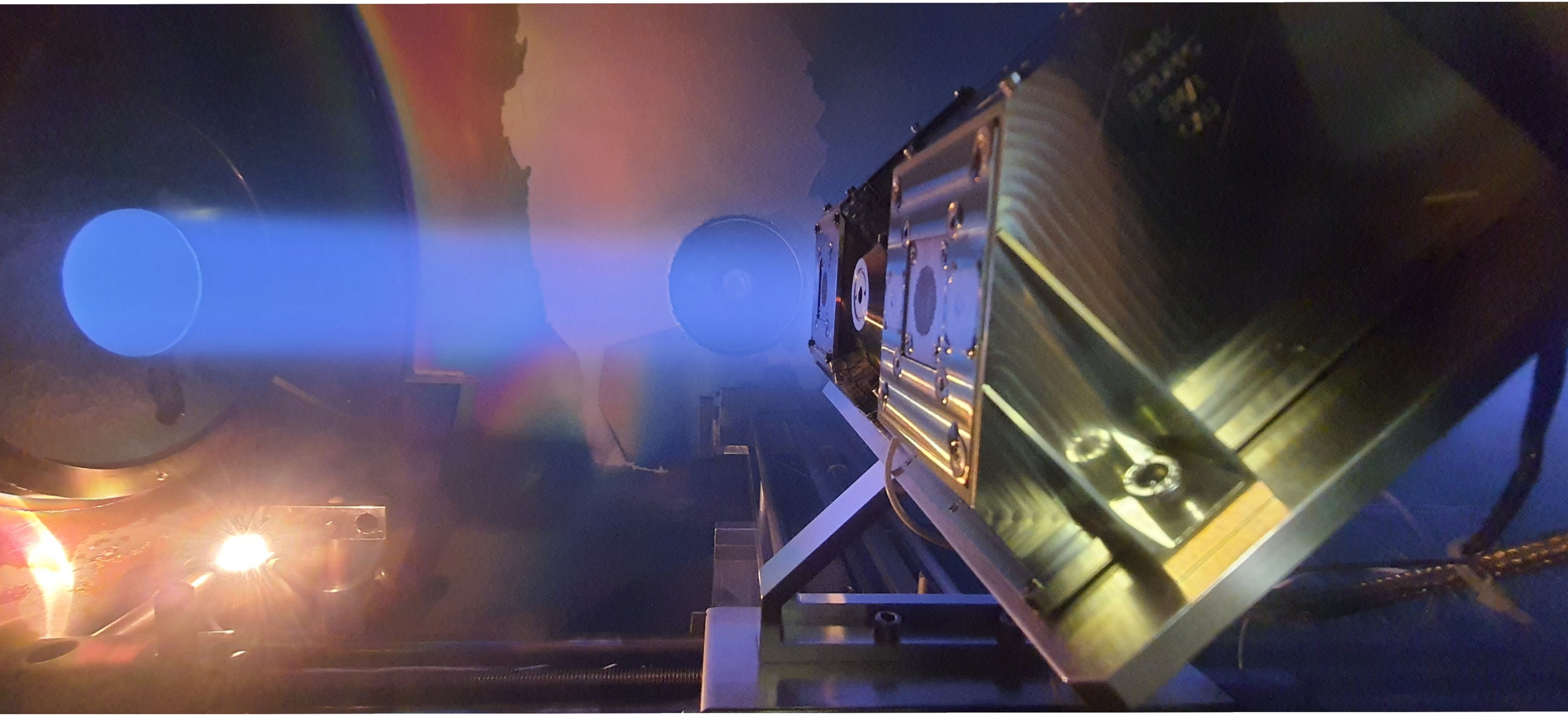
# Test Setup for Mimicking the Secondary Plasma from the Thruster



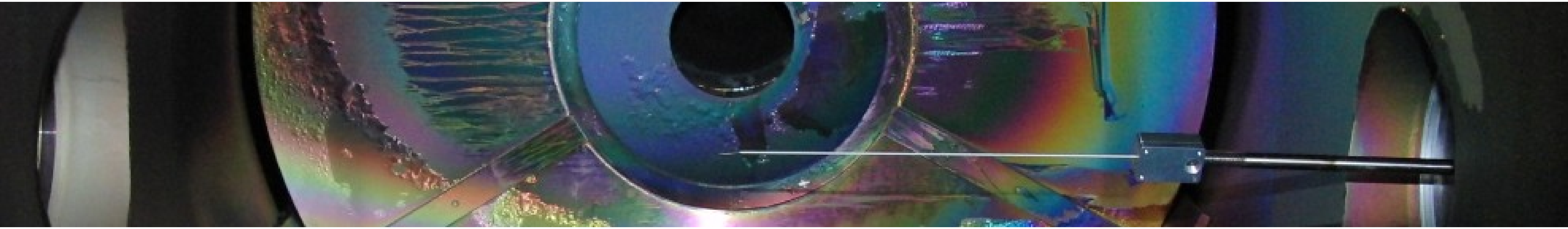
# Test Setup with two Prototypes of the Plasma Sensor

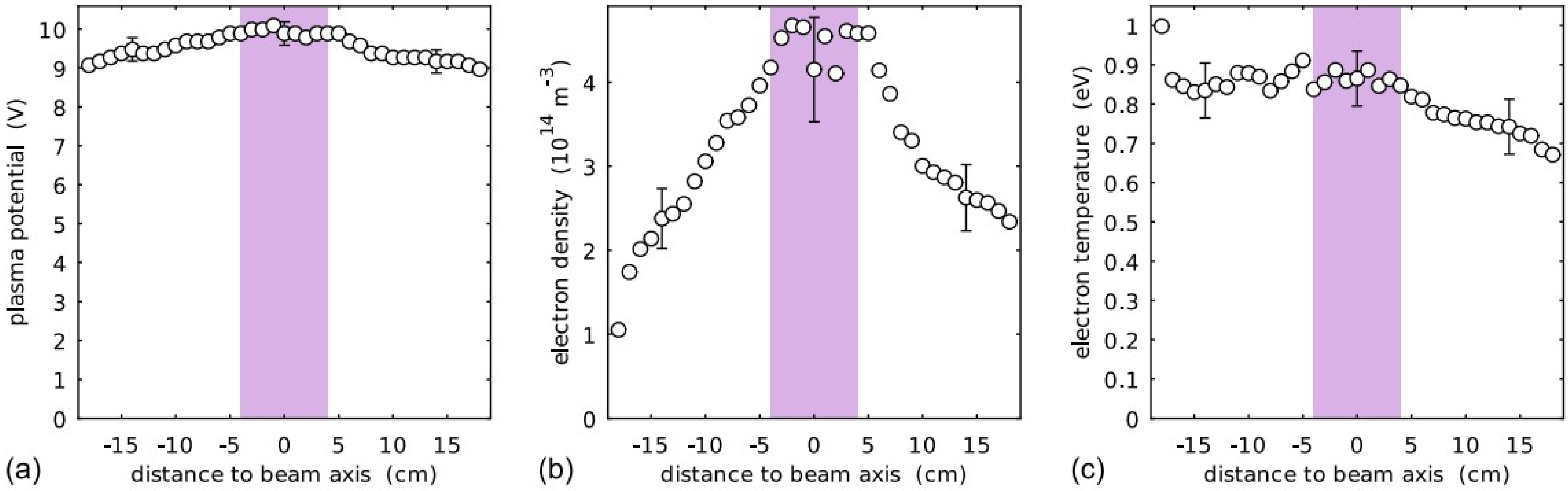


# Test Setup with Xenon Ion Beam



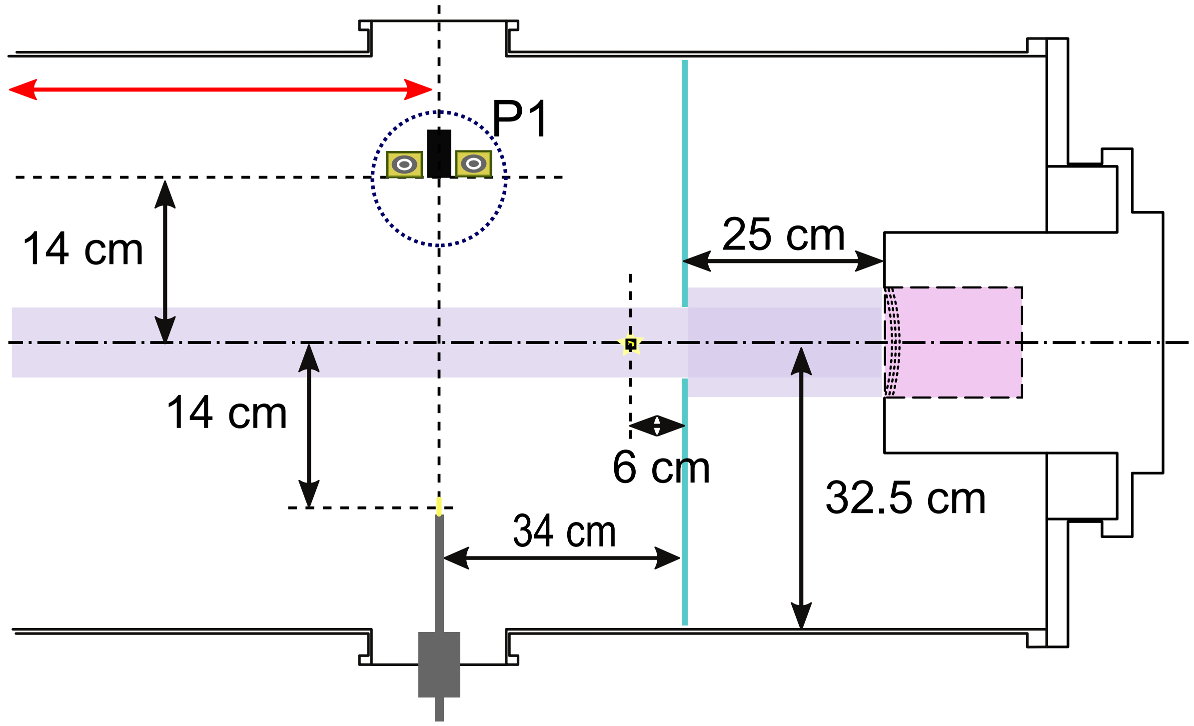
# Test Setup: Plasma Diagnostics in the Chamber with Xenon Ion Beam





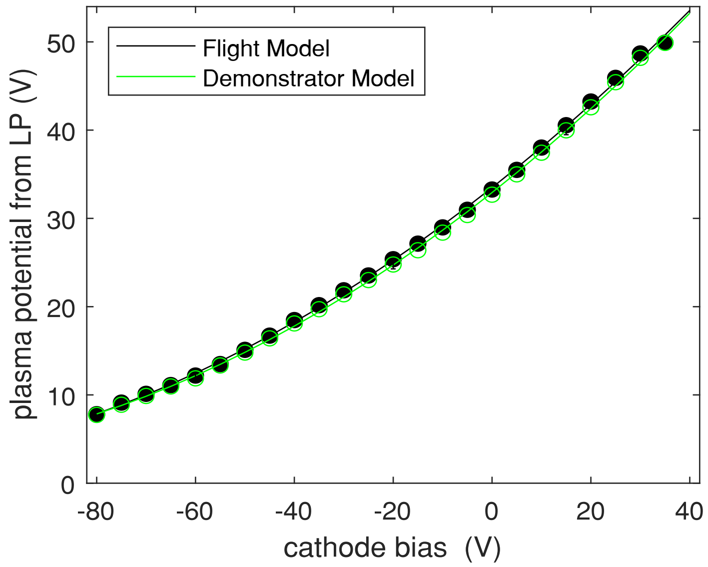

Trottenberg et al., EPJ Techn. Instrum. 8, 16 (2021)

# Test Setup: Controlled Generation of CEX Ions with Different Energies




The cathode is biased in the range -80 V … +20 V.

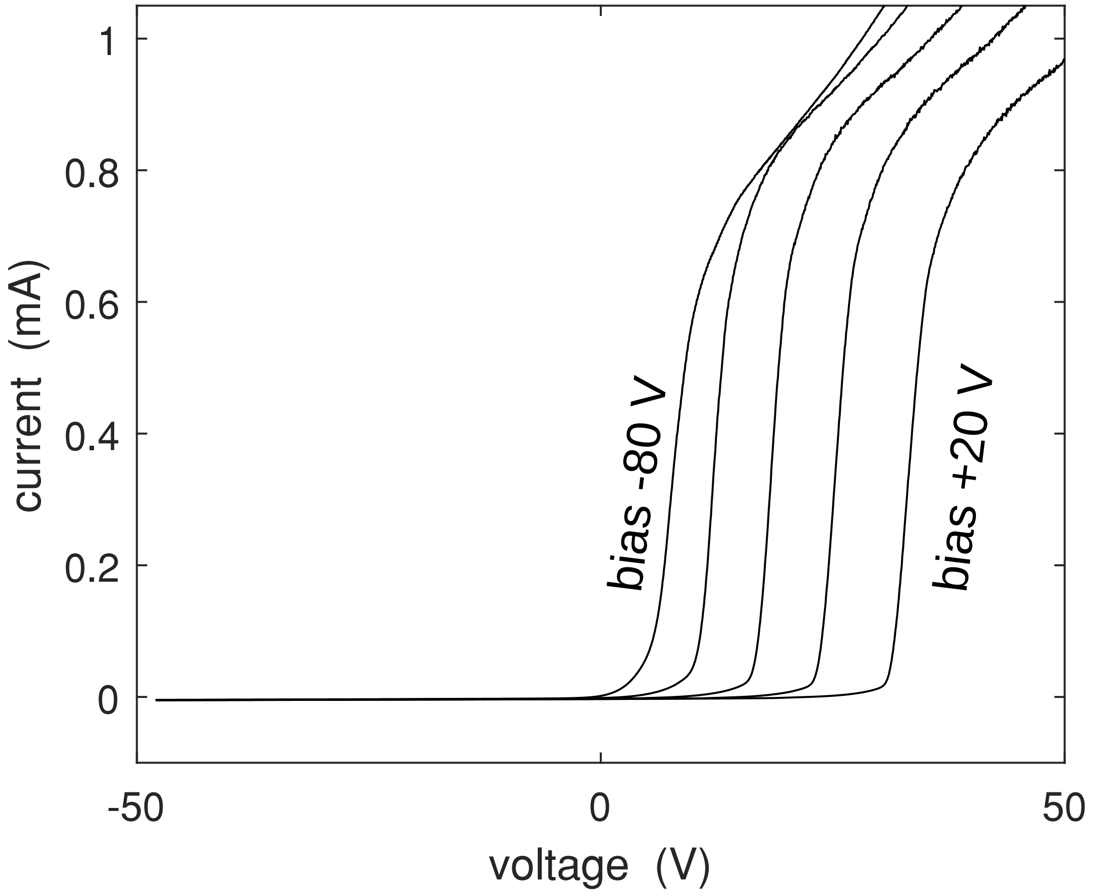
The plasma potential varies from ~10 V to ~50 V.



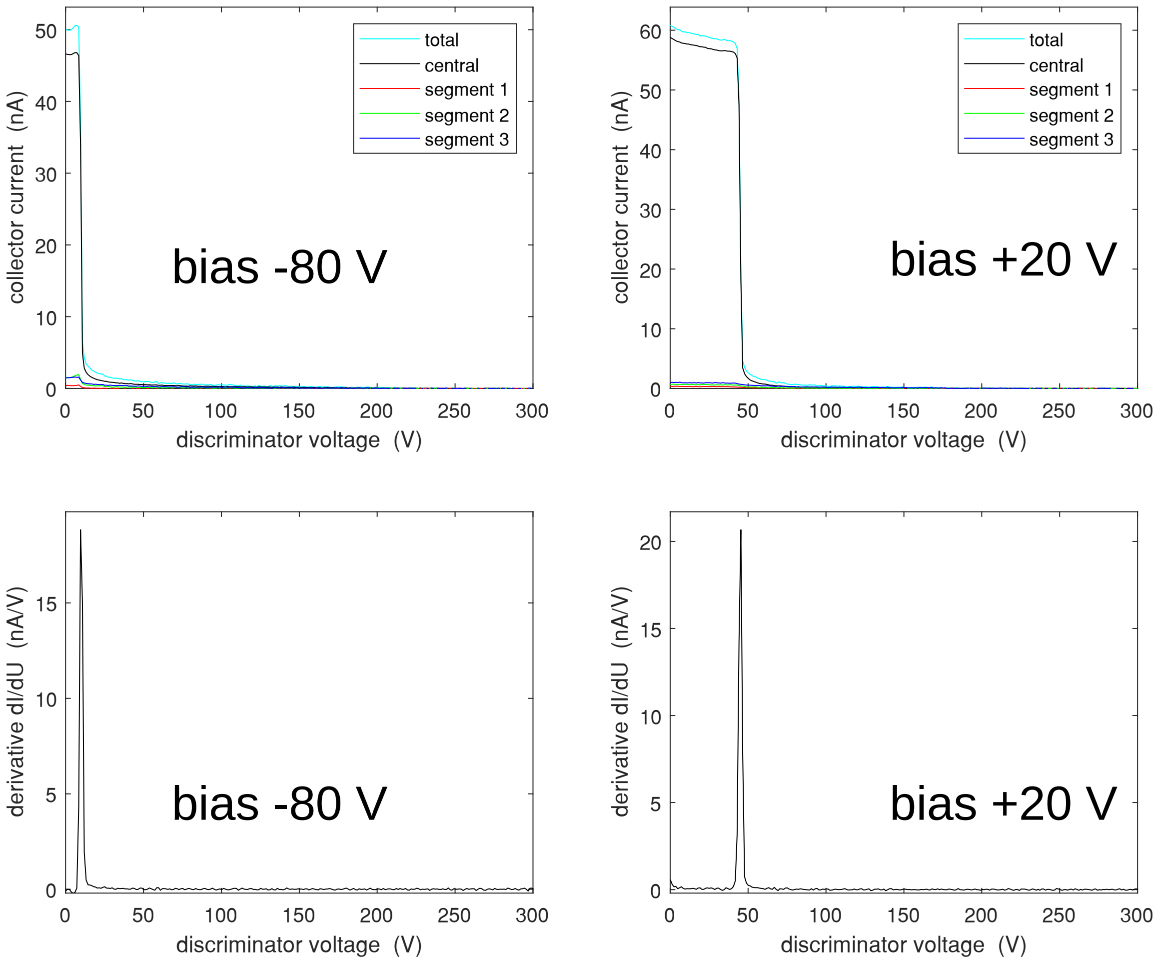

- Position of the sensors: outside the 1.2-keV beam
- Biasing the cathode shifts the plasma potential
- Purpose: Different energies can be given to the CEX ions.

# Test Setup: Controlled Generation of CEX Ions with Different Energies

LP: measured 14 cm away from the beam
for $U_{cath}$ = -80 V, -60 V, -40 V, -20 V, 0 V




RPA: measured 14 cm away from the beam
for $U_{cath}$ = -80 V, +20 V.



# Test Setup with “Idling” Ion Beam Source: Ion energies ~100 eV

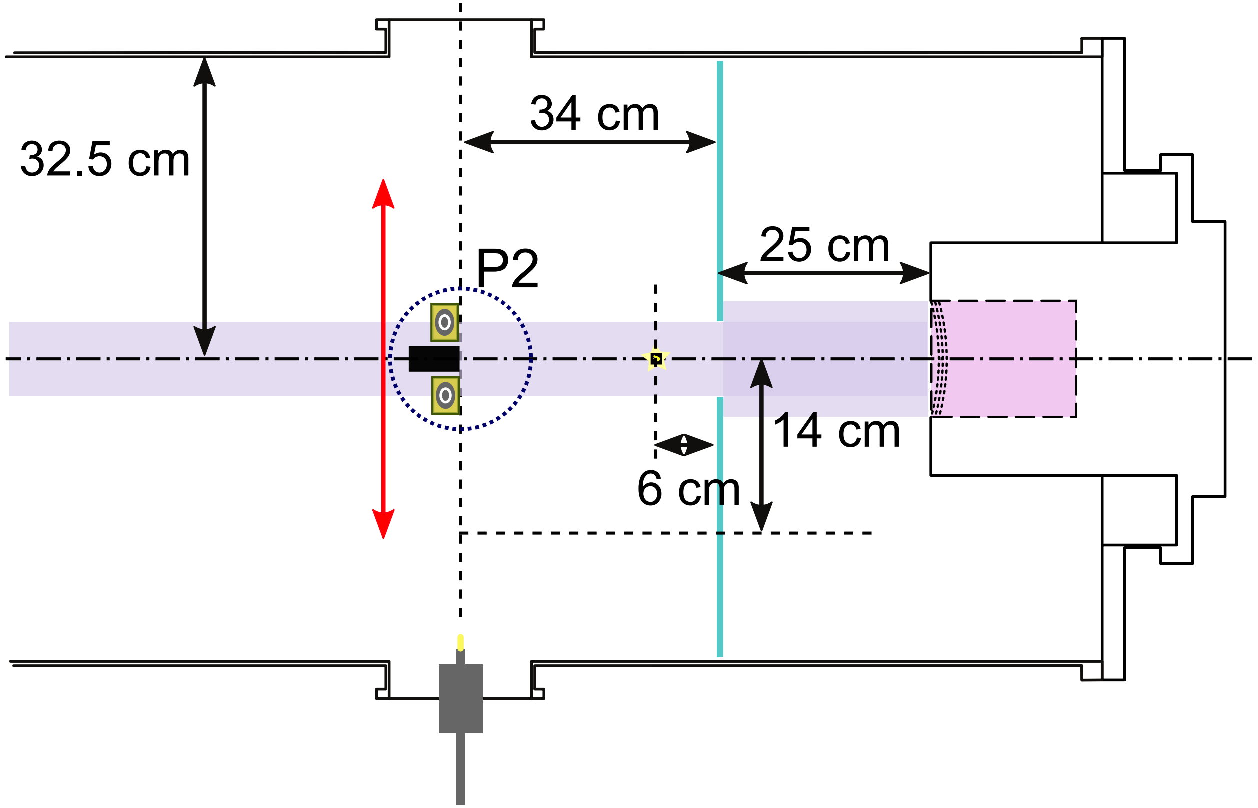
Ranges of the Plasma Sensor:

Energy: 0 – 300 eV
Collector currents: < 1 µA

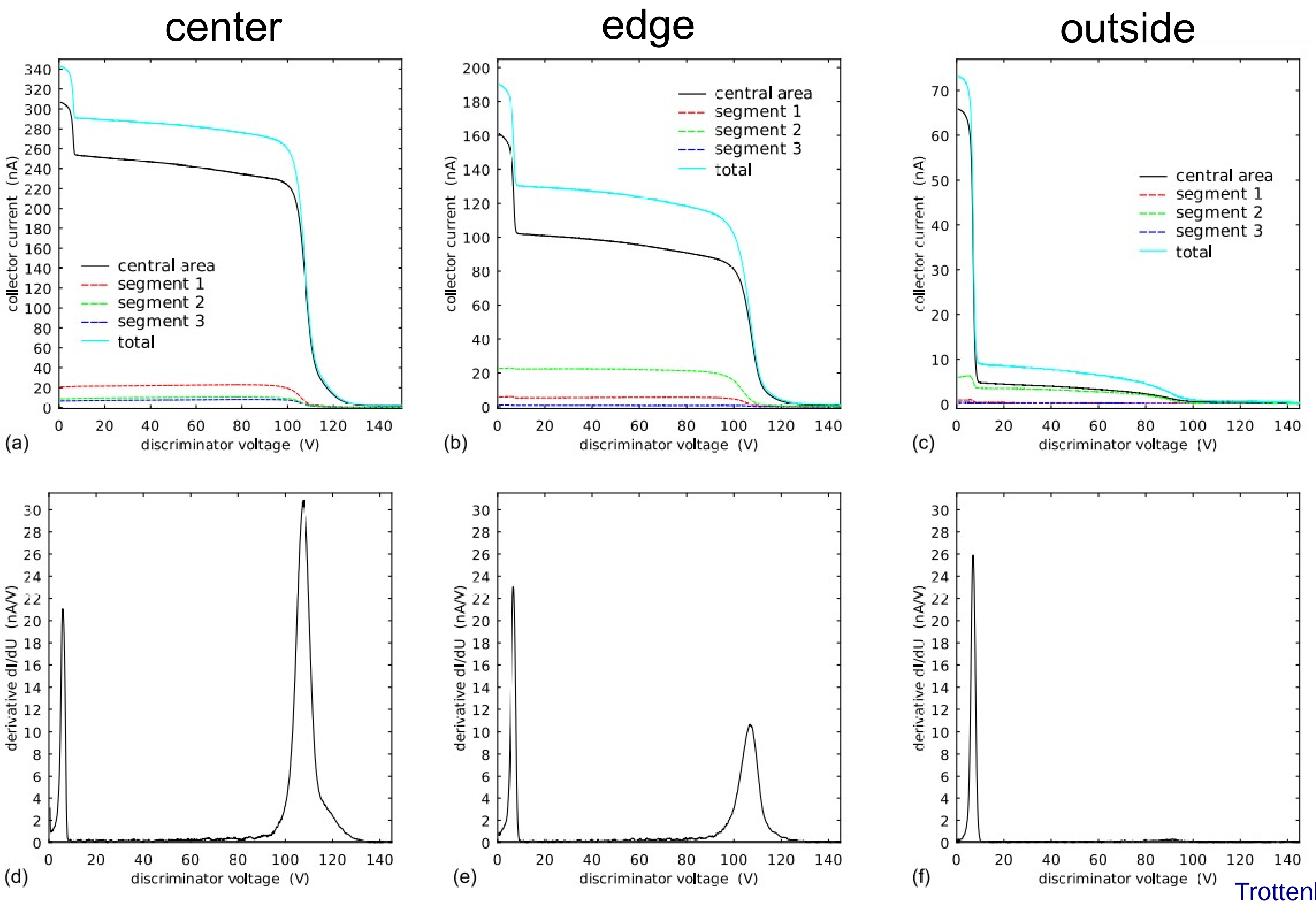
Cannot be exposed to 1,2-keV beam

Operating the ion source without acceleration (anode) voltage:

Ion energy: ~ 100 eV
Ion current density: 17.3 mA/m²



# Test Setup with “Idling” Ion Beam Source: Ion energies ~100 eV



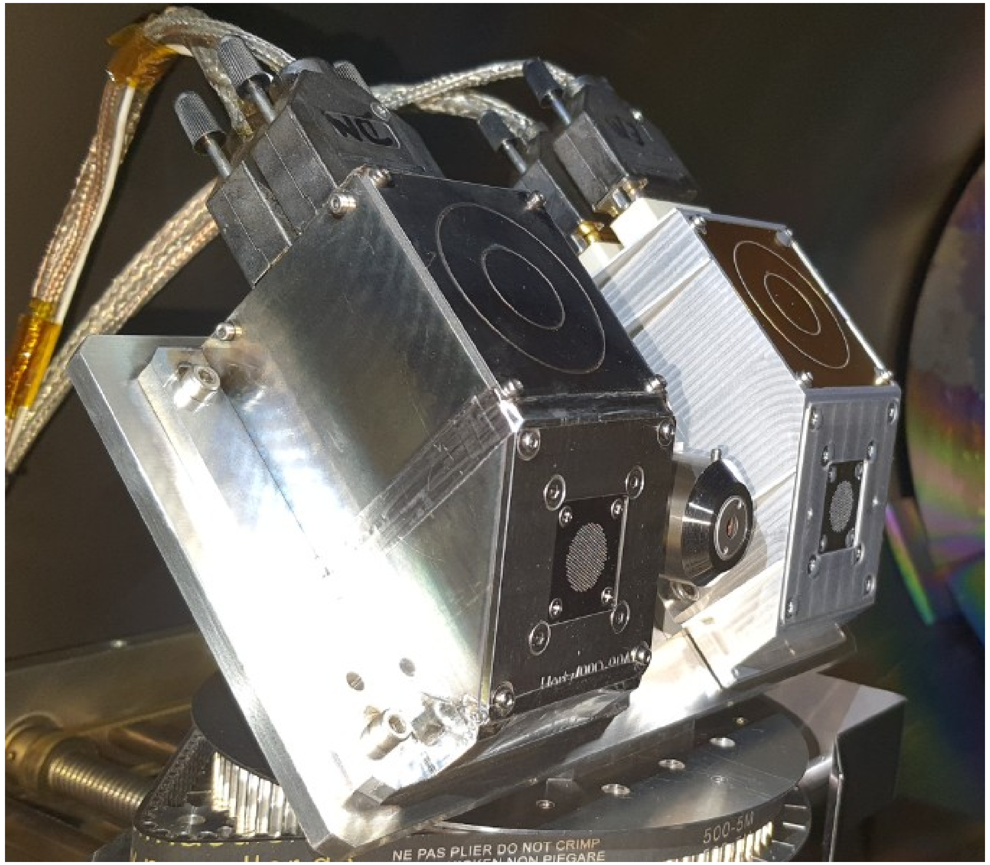

RPA characteristics and derived energy distributions at three positions relative to the beam.

Two populations:
- Primary ions
- Charge-exchange Ions

Trottenberg et al., EPJ Techn. Instrum. 8, 16 (2021)

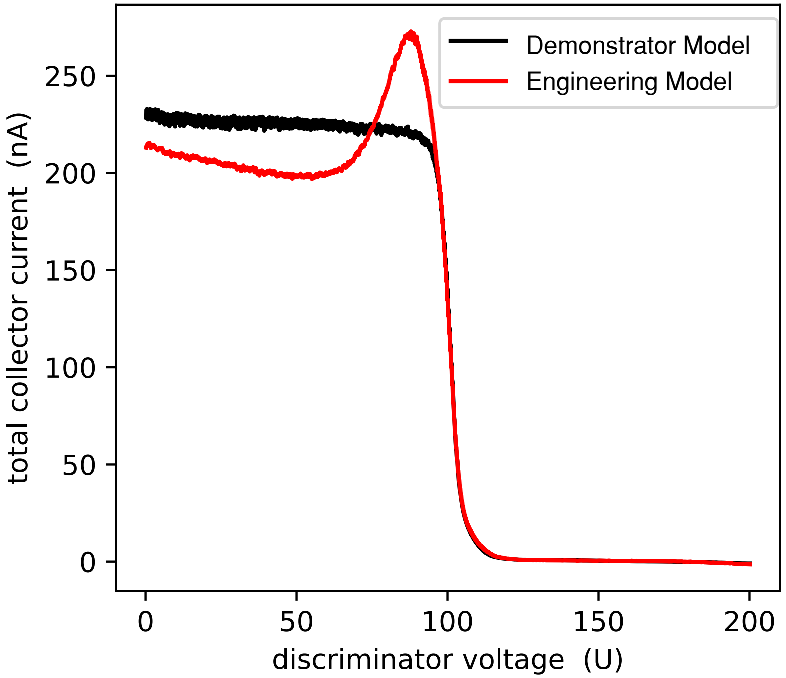
# Unexpected Features of the Retarding Potential Analyzer

# A Surprising Anomalie in the Characteristic of the EM

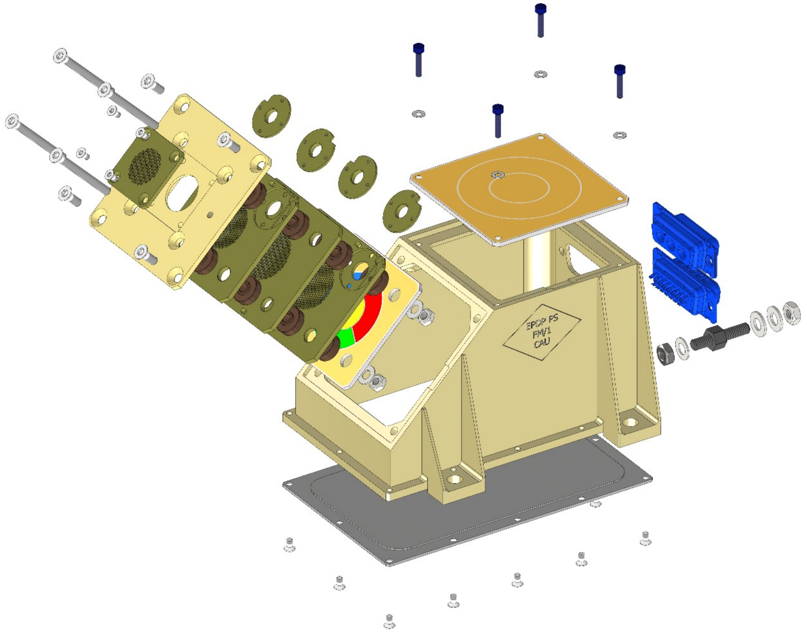



The ‚Demonstrator Model‘ and the later built Engineering Model‘ produced significantly different trajectories – What happened?

A “good” characteristic should be monotonically decreasing!

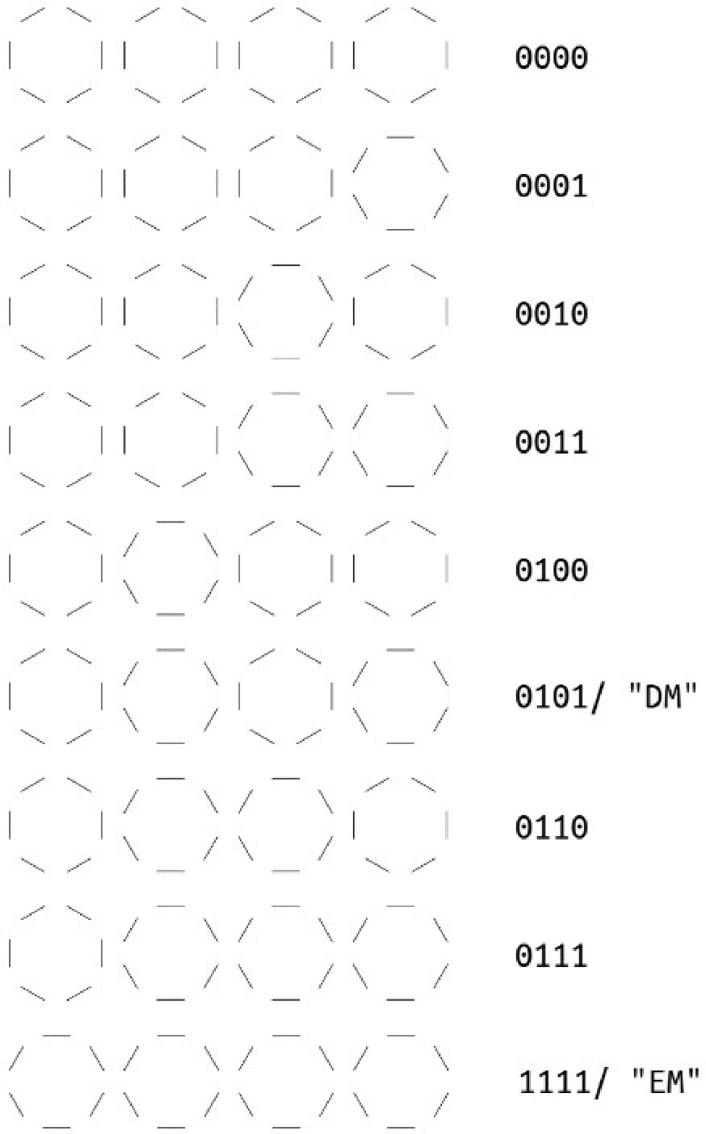


# Grid Orientations



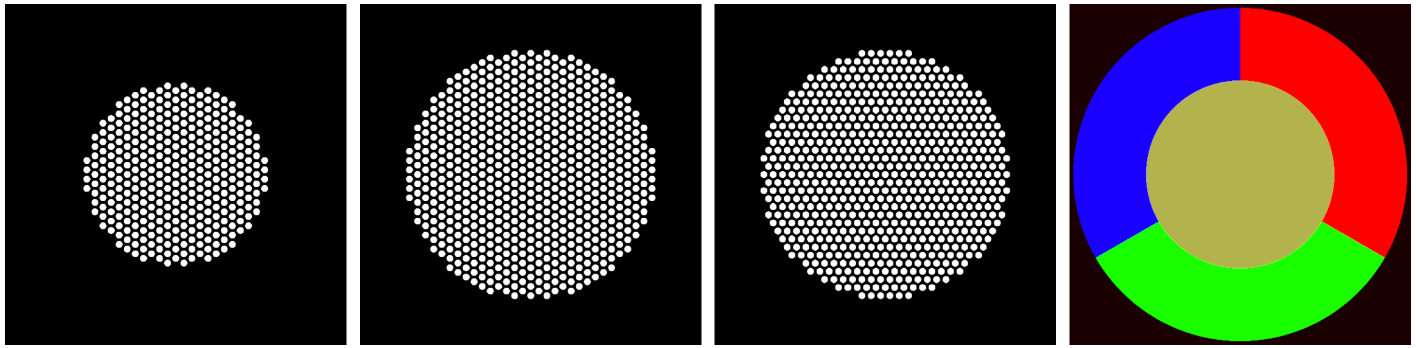

The hexagonal pattern and the square frames allow two different orientations of each grid: *rotated* or *not rotated*.

0: not rotated
1: rotated




„0“ „0“ „1“

(a) (b) (c) (d)



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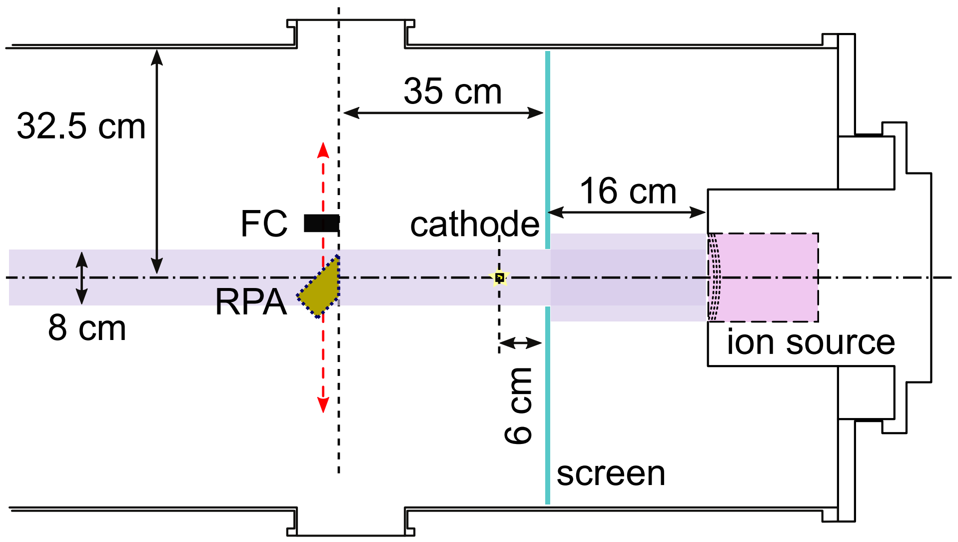


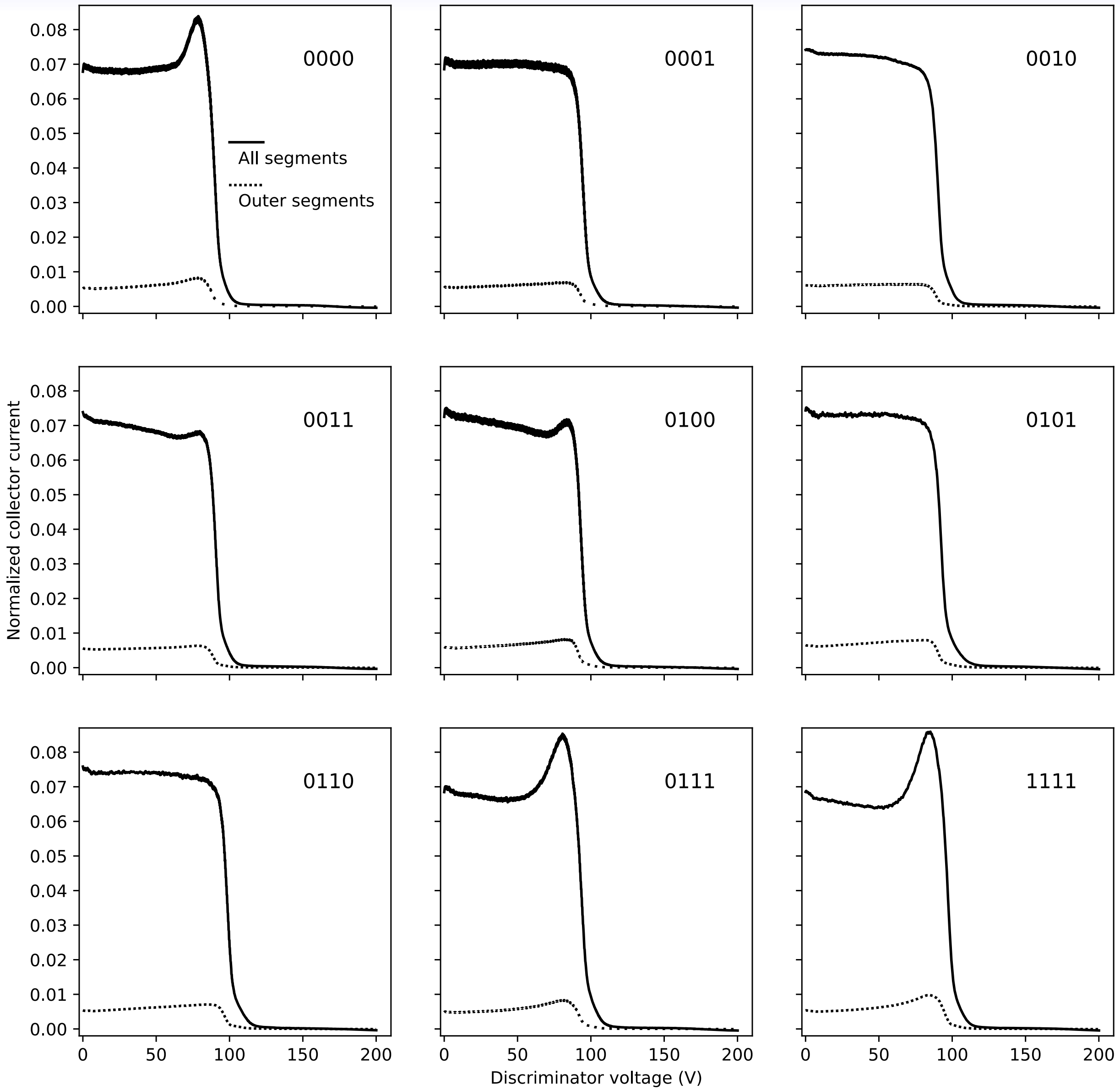

We operated the ion source without applying an acceleration voltage („idling mode“)

–> ion energies: ~100 eV,
low current densities: ~17 mA/m².

The RPA was reconfigured 8 times.

Trottenberg et al., AIP Advances 15, 035030 (2025)

## RPA characteristics (I vs V)



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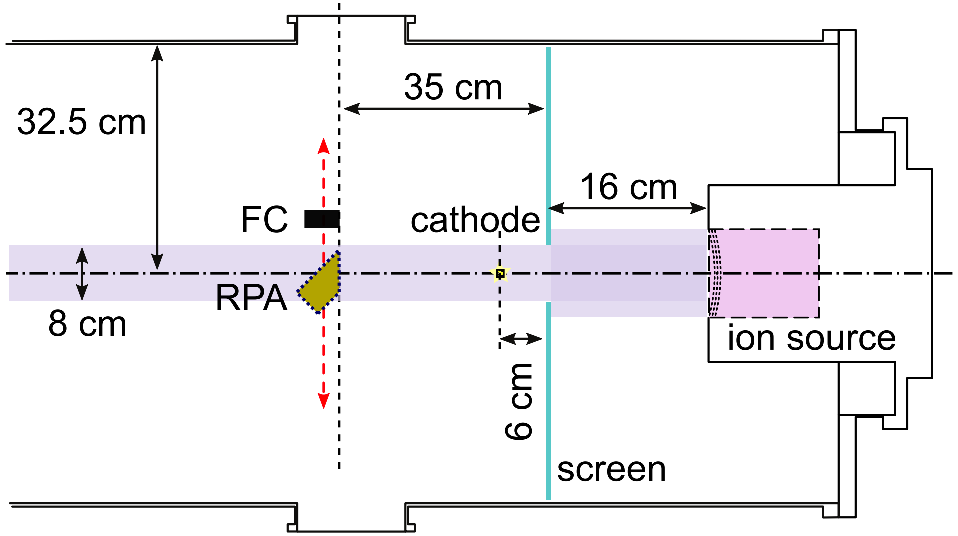


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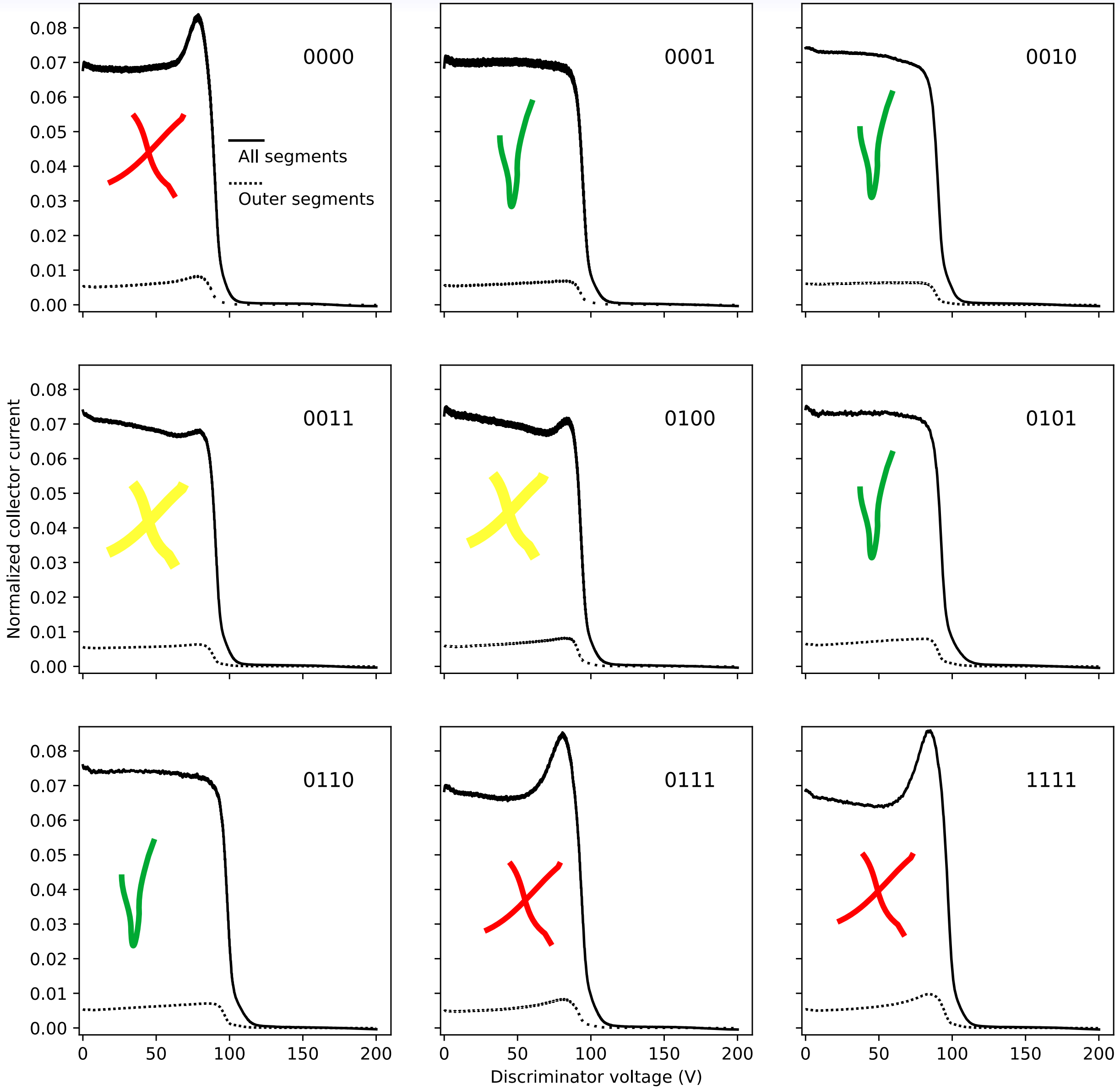
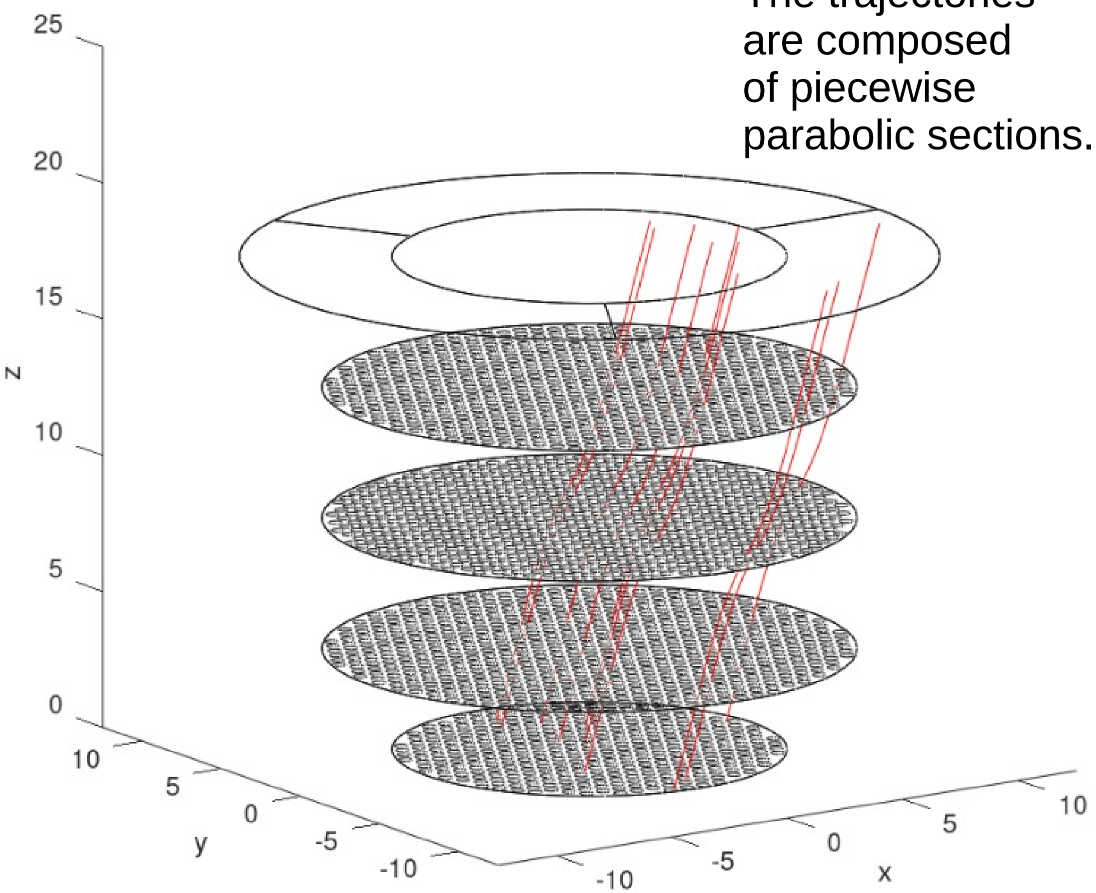


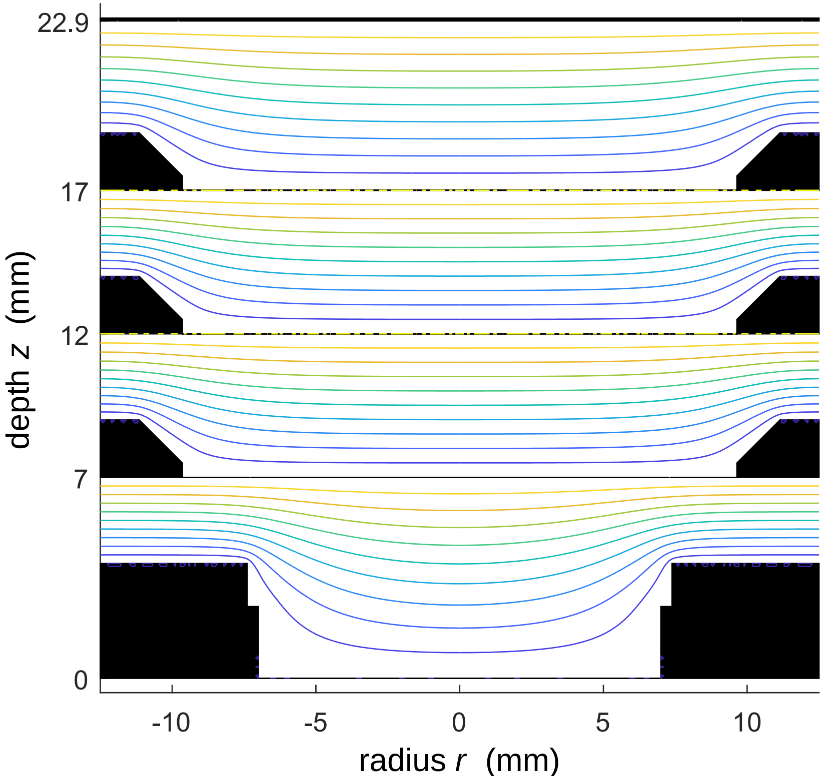
# Modeling of the Retarding Potential Analyzer

The simplest model assumes homogeneous electric fields between the grids

An improved model accounts for field distortions due to the 3d structure of the grid frames

The trajectories are composed of piecewise parabolic sections.



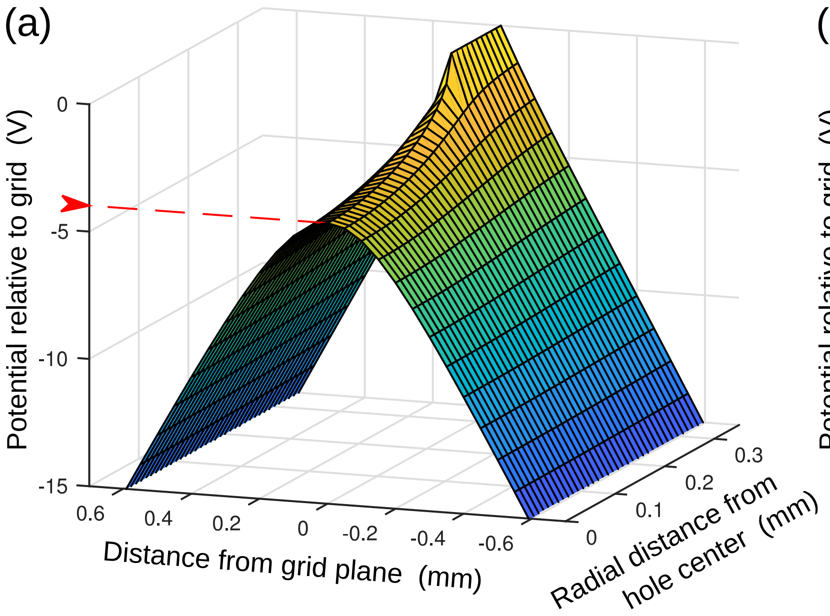

Generic potential map (lines for ΔU/10 steps in gaps).

Trottenberg et al., AIP Advances 15, 035030 (2025)

# Modeling of the Retarding Potential Analyzer

Further refinements: Near-field effects in the holes.
The grid with holes may be either thin or of finite thickness.

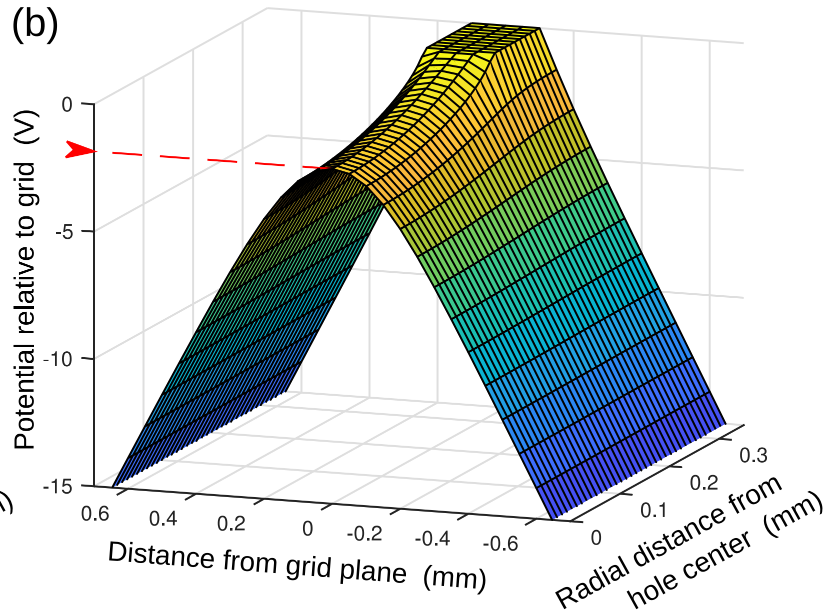
Thin grid




Analytical solution

Jackson, Classical Electrodynamics, 3rd. ed. (1999)

Thick grid (200 µm)




Finite Element Method

Shown Example:
Repeller grids at -25 V,
discriminator grid at +100 V.

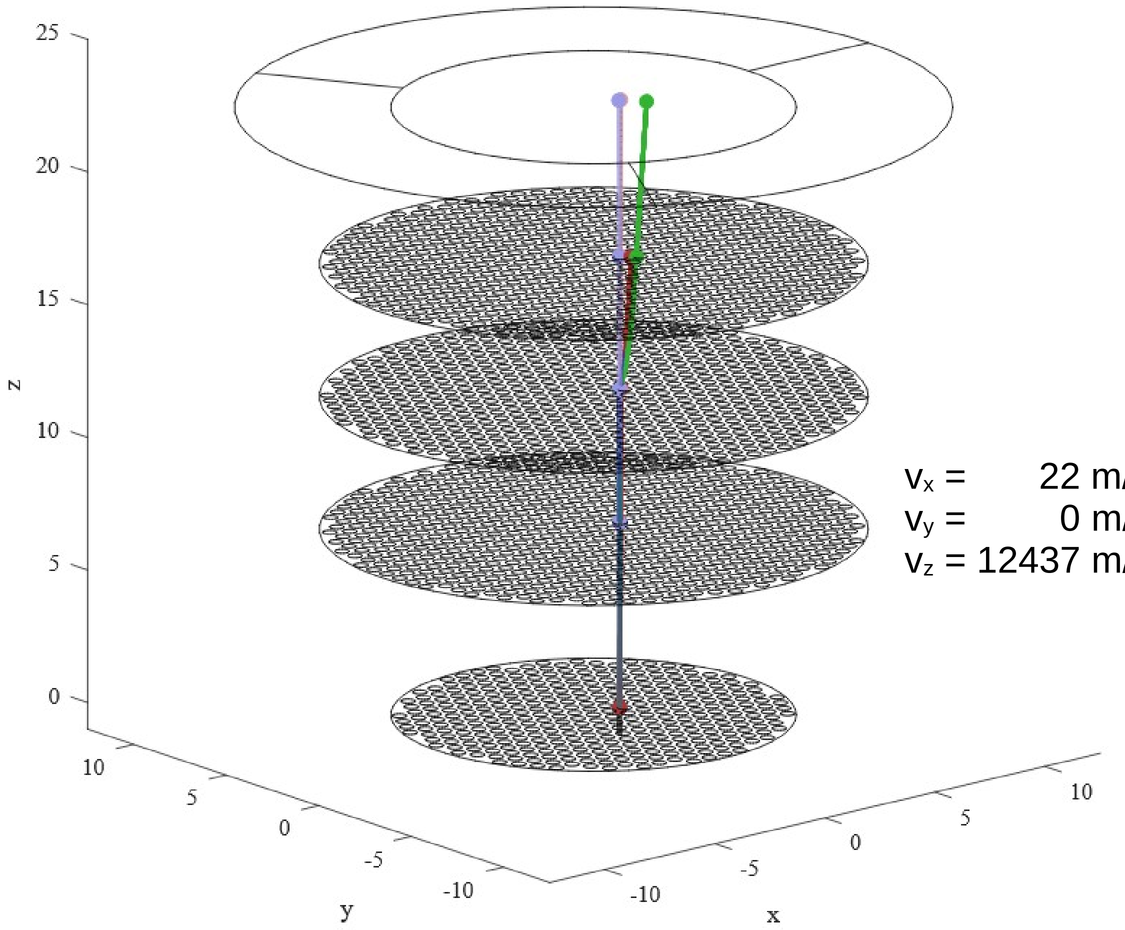
Saddle point potentials:
(a) -3.98 V below grid potential,
(b) -1.85 V below grid potential.

Consequence of the saddle points: „too slow“ ions can pass through the discriminator grid.

Trottenberg et al., AIP Advances 15, 035030 (2025)

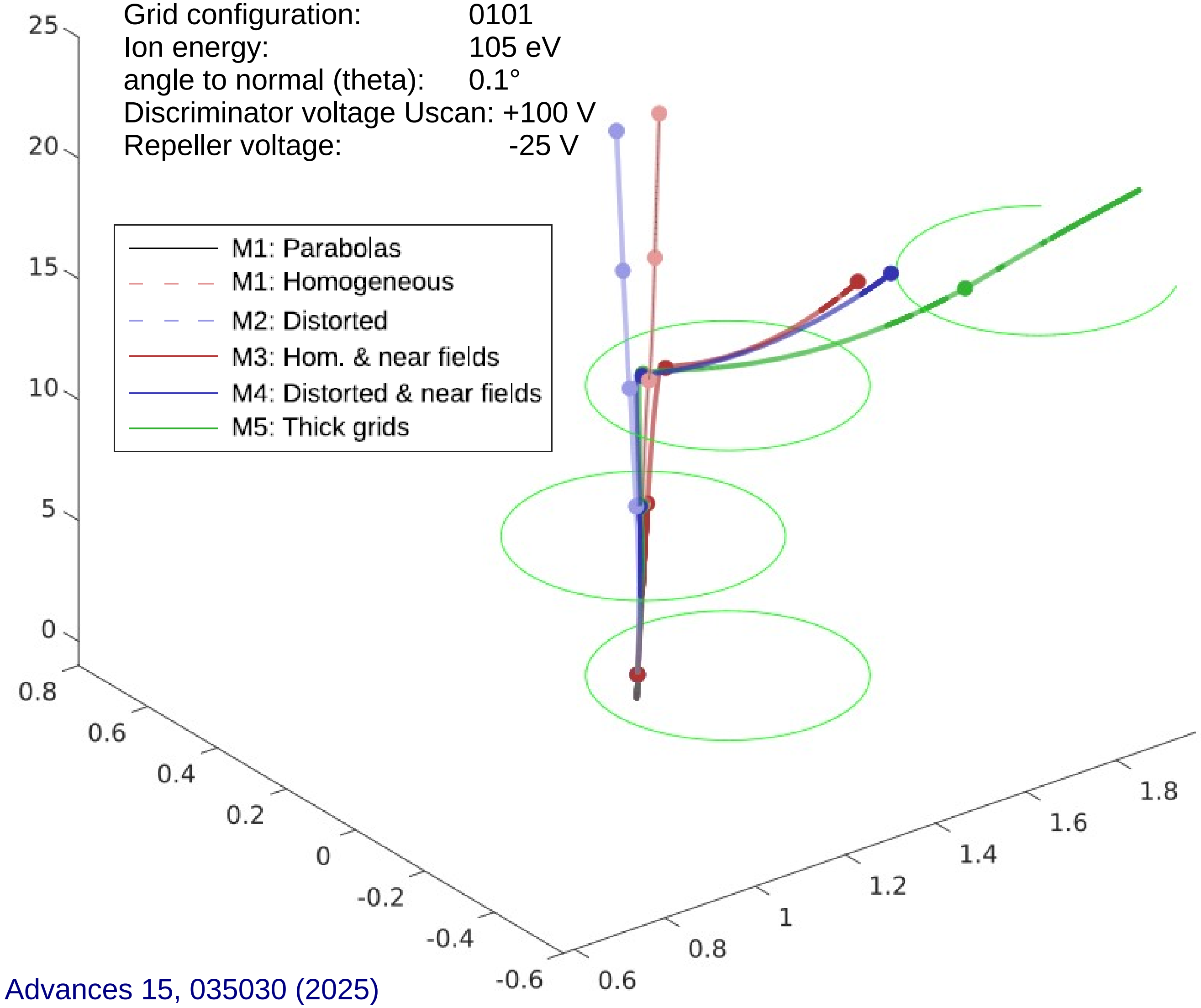
# Modeling of the Retarding Potential Analyzer

Trajectories according to different models




$v_x$ = 22 m/s
$v_y$ = 0 m/s
$v_z$ = 12437 m/s

Grid configuration: 0101
Ion energy: 105 eV
angle to normal (theta): 0.1°
Discriminator voltage Uscan: +100 V
Repeller voltage: -25 V




Trottenberg et al., AIP Advances 15, 035030 (2025)

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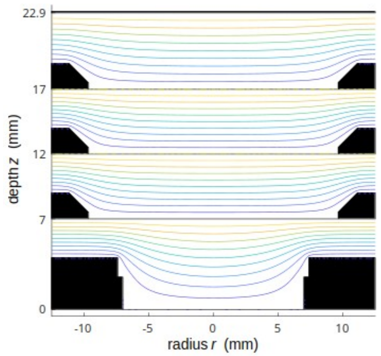


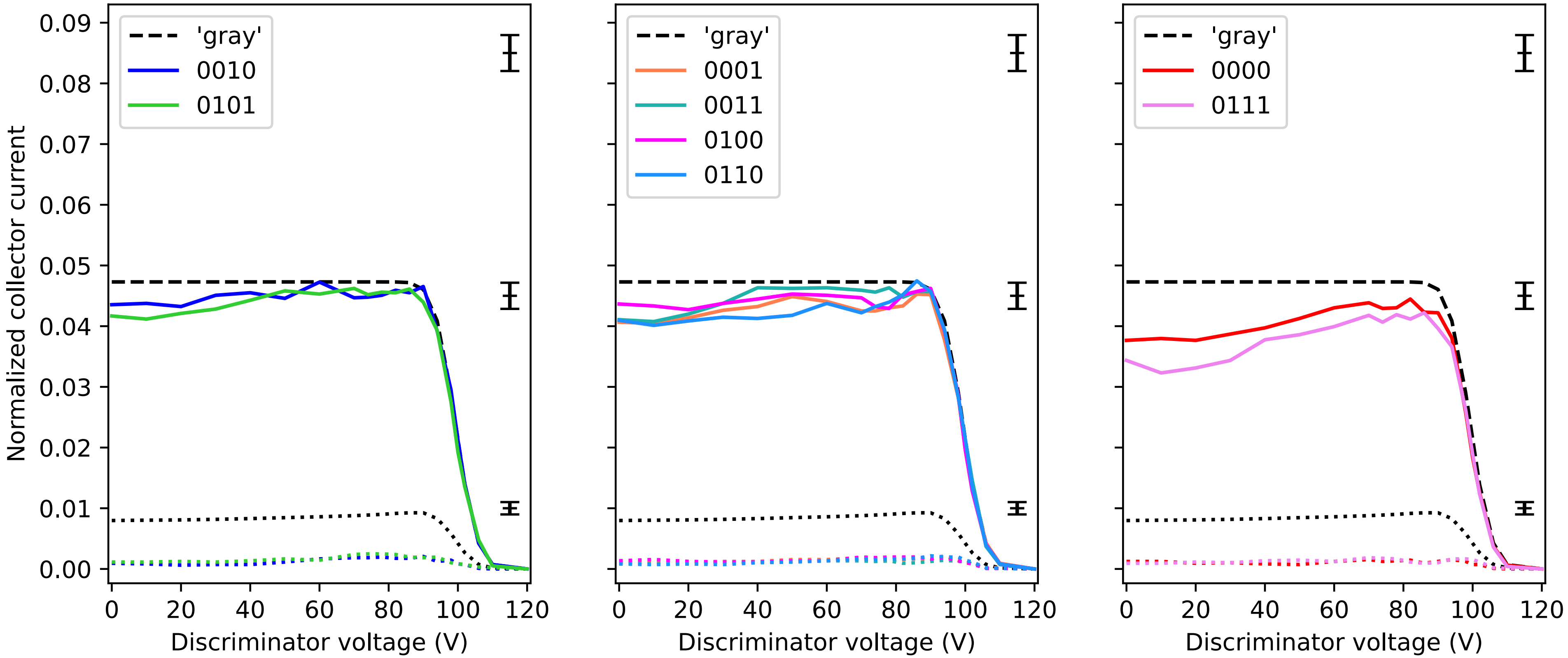


Only radial field distortion, not near fields of the holes

Trottenberg et al., AIP Advances 15, 035030 (2025)

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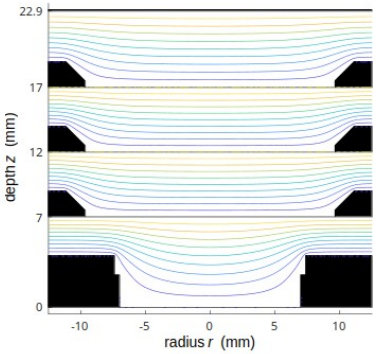


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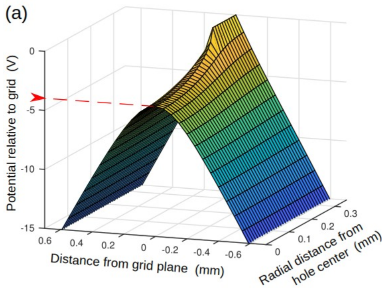
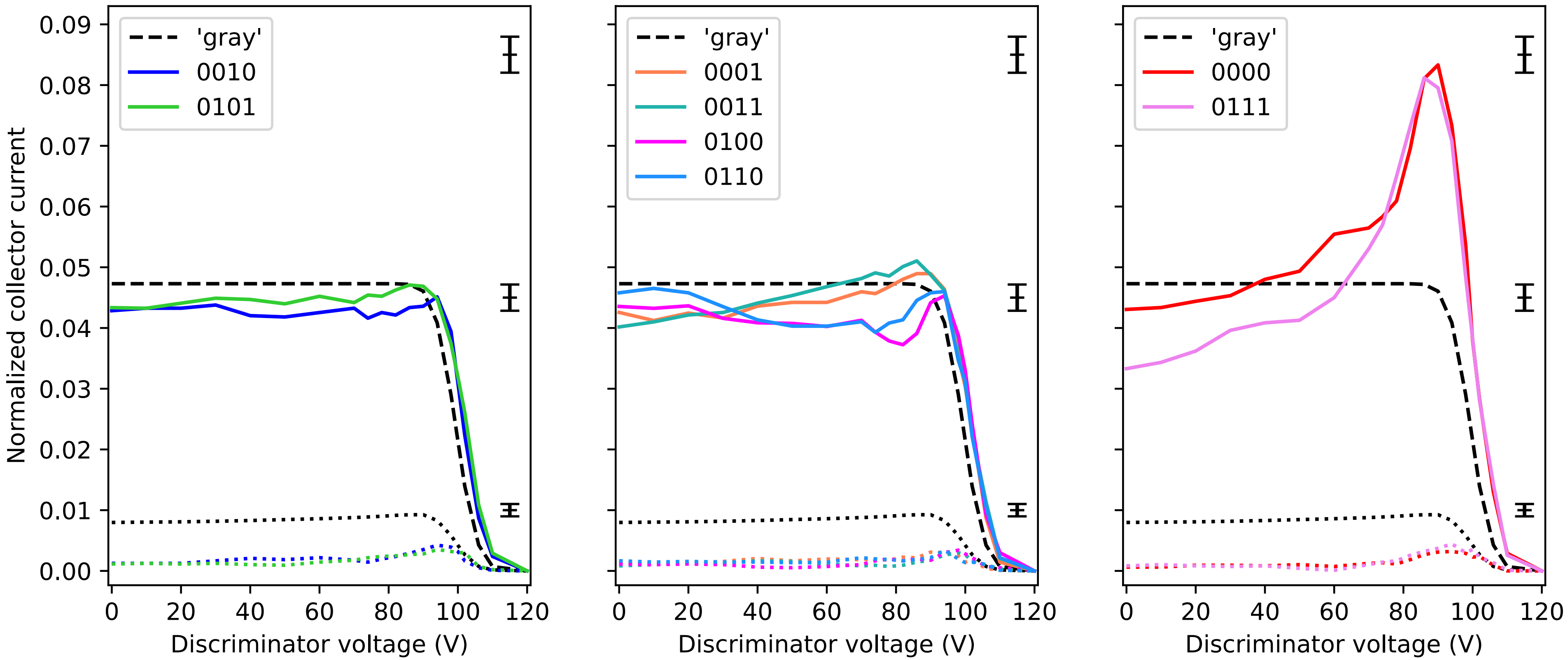
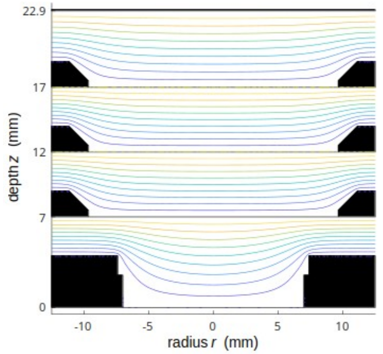



With not near fields of the holes & thin grids

Trottenberg et al., AIP Advances 15, 035030 (2025)

# Modeling of the Retarding Potential Analyzer

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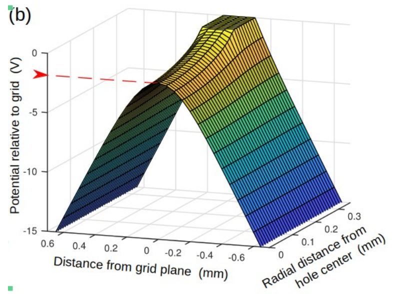


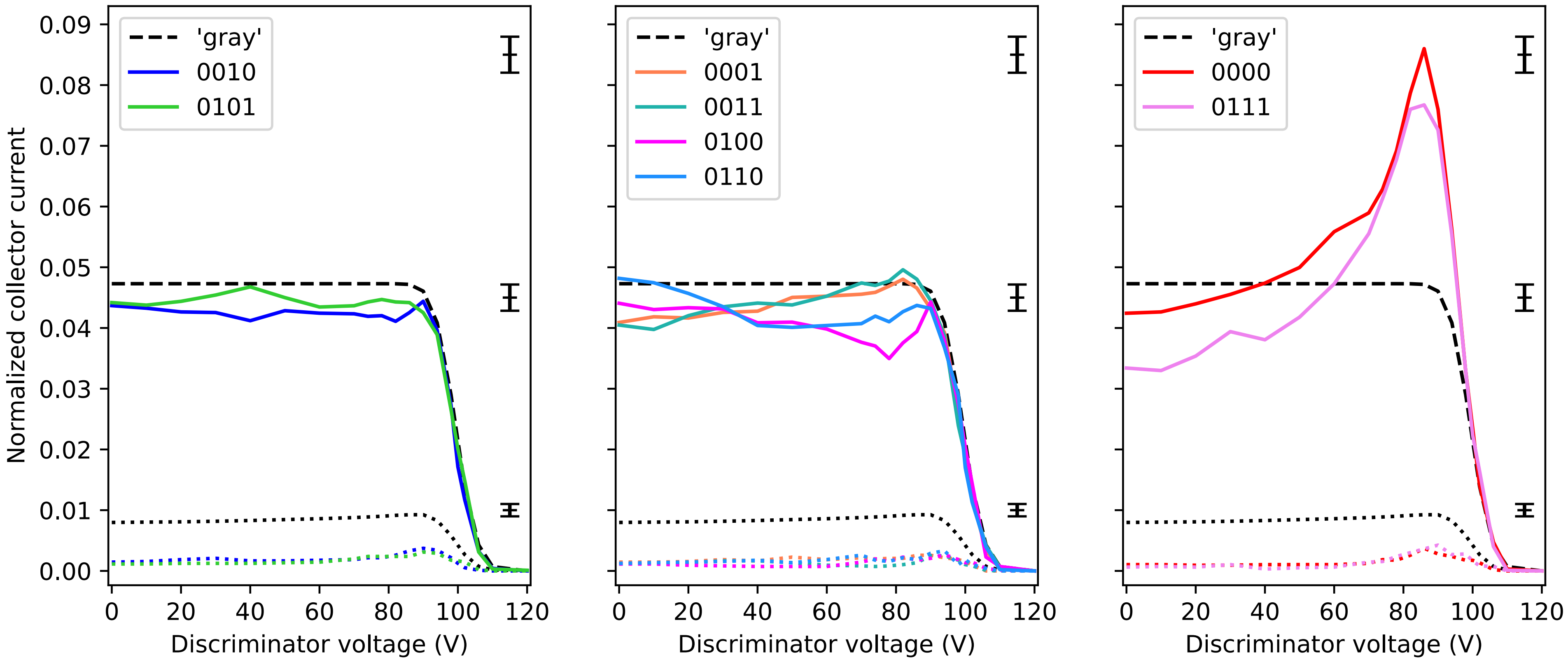


With near fields of the holes & thick grids (2 µm)

Trottenberg et al., AIP Advances 15, 035030 (2025)

# Modeling of the Retarding Potential Analyzer

With regard to the configurations, it can be stated that:

| | |
|---|---|
| "good": | Grids **3 and 4** are **not aligned**, Grid 2 is not relevant. |
| "intermediate": | Grids **3 and 4 are aligned**, Grid 2 is aligned differently. |
| "bad": | Grids **2, 3, and 4 are aligned**. |

- The hole radius should be small compared to the grid spacing.
- The correlations of the hole positions in neighboring grids should be small,
- Irregular hole patterns could be beneficial.

# Summary

# Summary

- Standard diagnostics in EP
- Force probes – a useful charge-independent tool for spatially resolved momentum flux measurements
- Force probes – a tool for investigations of sputtering and validation of simulation codes
- In-flight diagnostics
- Retarding potential analyzer: The role of grid geometry and grid orientations

# Acknowledgements

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