XXIX. Erfahrungsaustausch OTPIP Mühlleithen 2024

Investigation of charge exchange collisions in an ion beam

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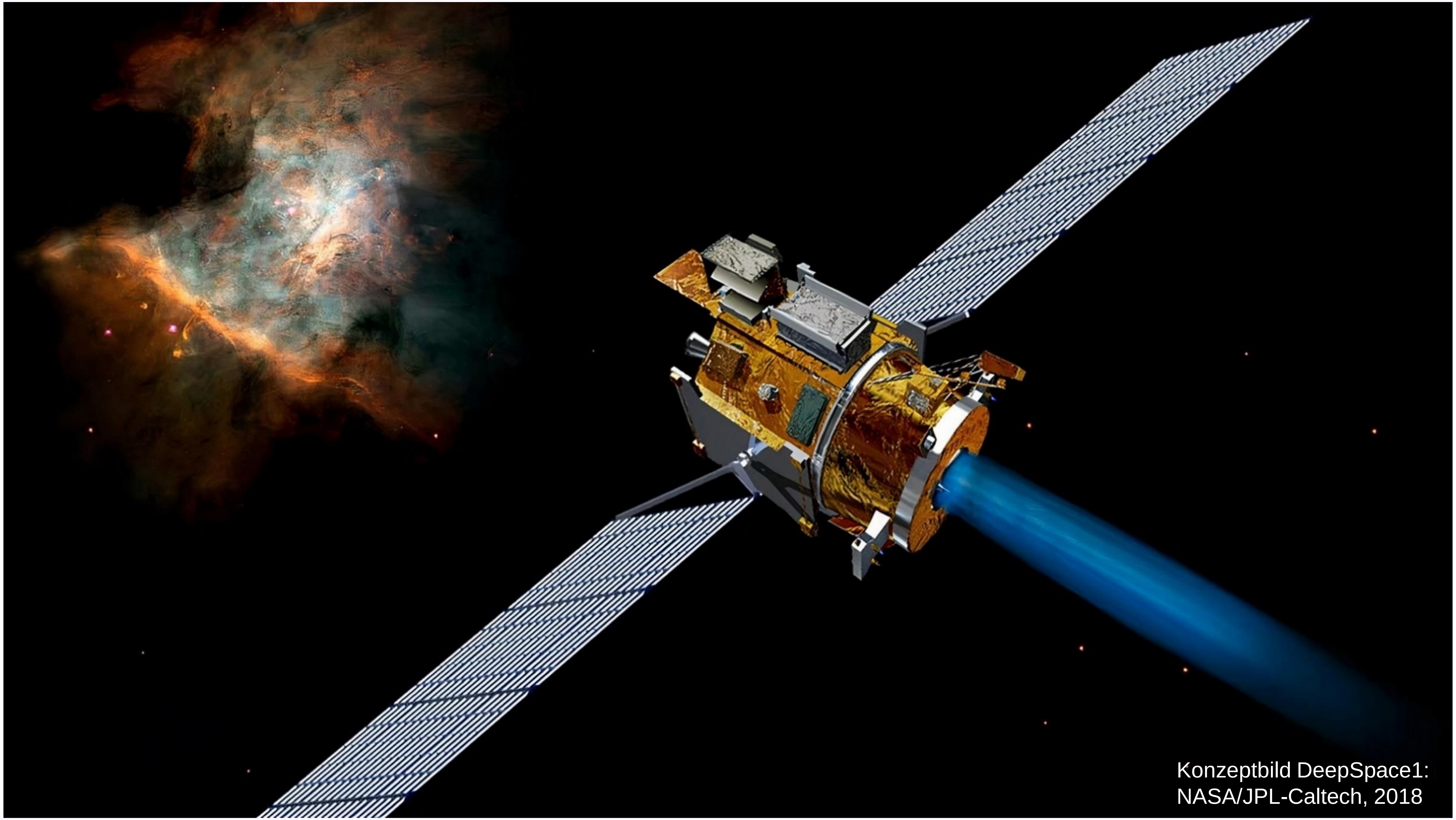
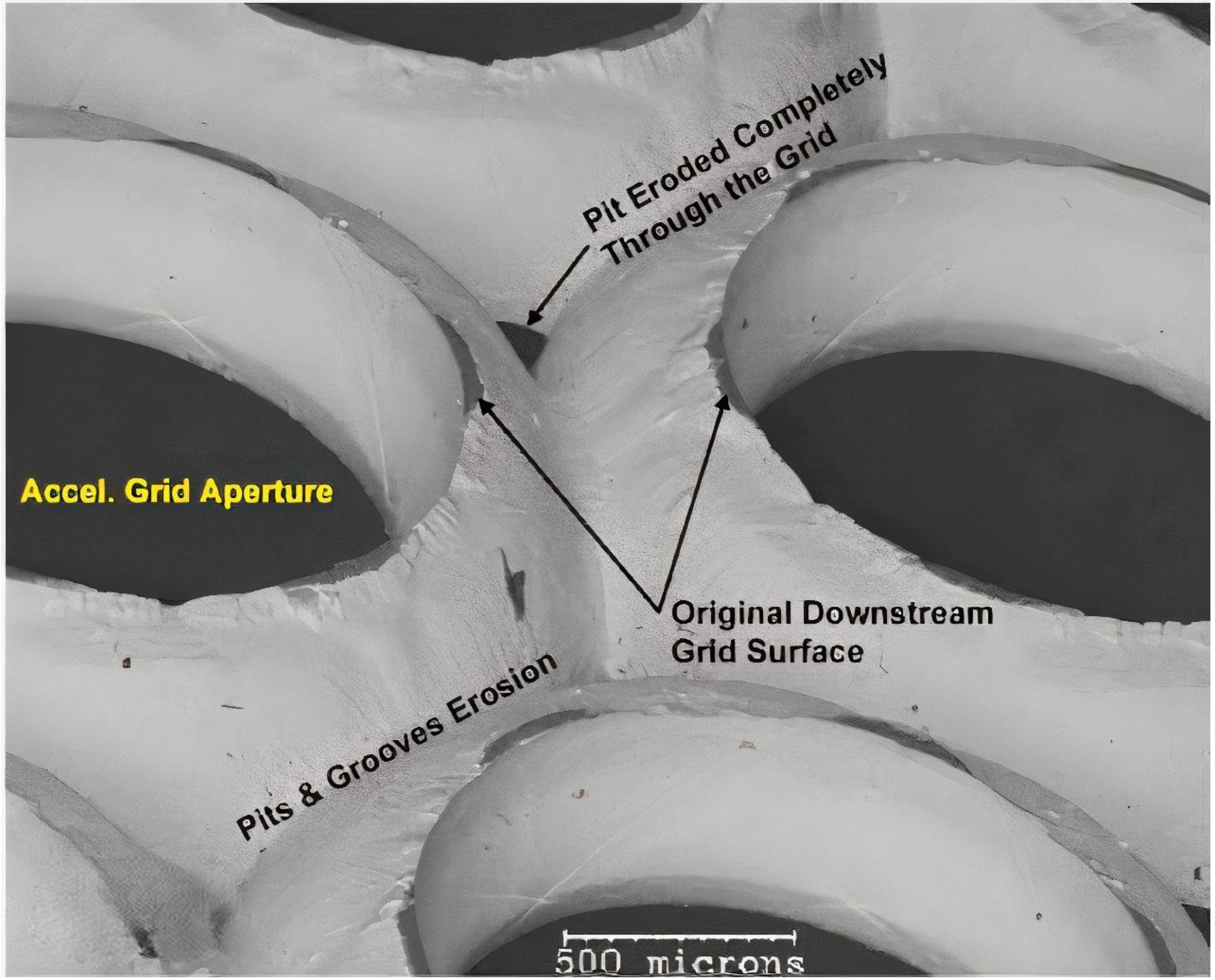
Satellites and electric propulsion



Konzeptbild DeepSpace1:
NASA/JPL-Caltech, 2018

Secondary plasma and charge exchange ions

- Ion beam sources can be used as plasma thrusters
- Secondary plasma is created by charge exchange collisions (CEX) [1]
- Ions with low thermal velocities which can fall back onto the satellite
- These can damage or disrupt the engine and the satellite



[2] Outside of an acceleration grid of an NSTAR thruster after 30000h of operation

[1] Trottenberg, et al., *An in-flight plasma diagnostic package for spacecraft with electric propulsion*, 2021
[2] Yalin, et al., *42nd AIAA/ASME/SAE/ASEE Joint Prop. Conf.*, 2006

Charge exchange collisions and mean free path

1. Charge exchange collisions

- Is a process in which an ion collides with a neutral gas atom
- The ion acquires an electron from the neutral gas atom
- This results in a slow ion and a fast neutral gas atom

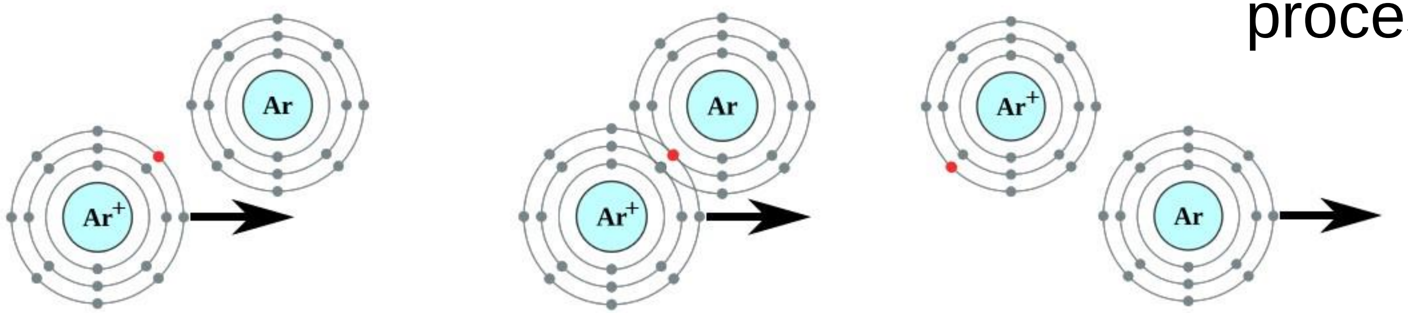


Illustration of a charge exchange collision [2]

2. Mean free path

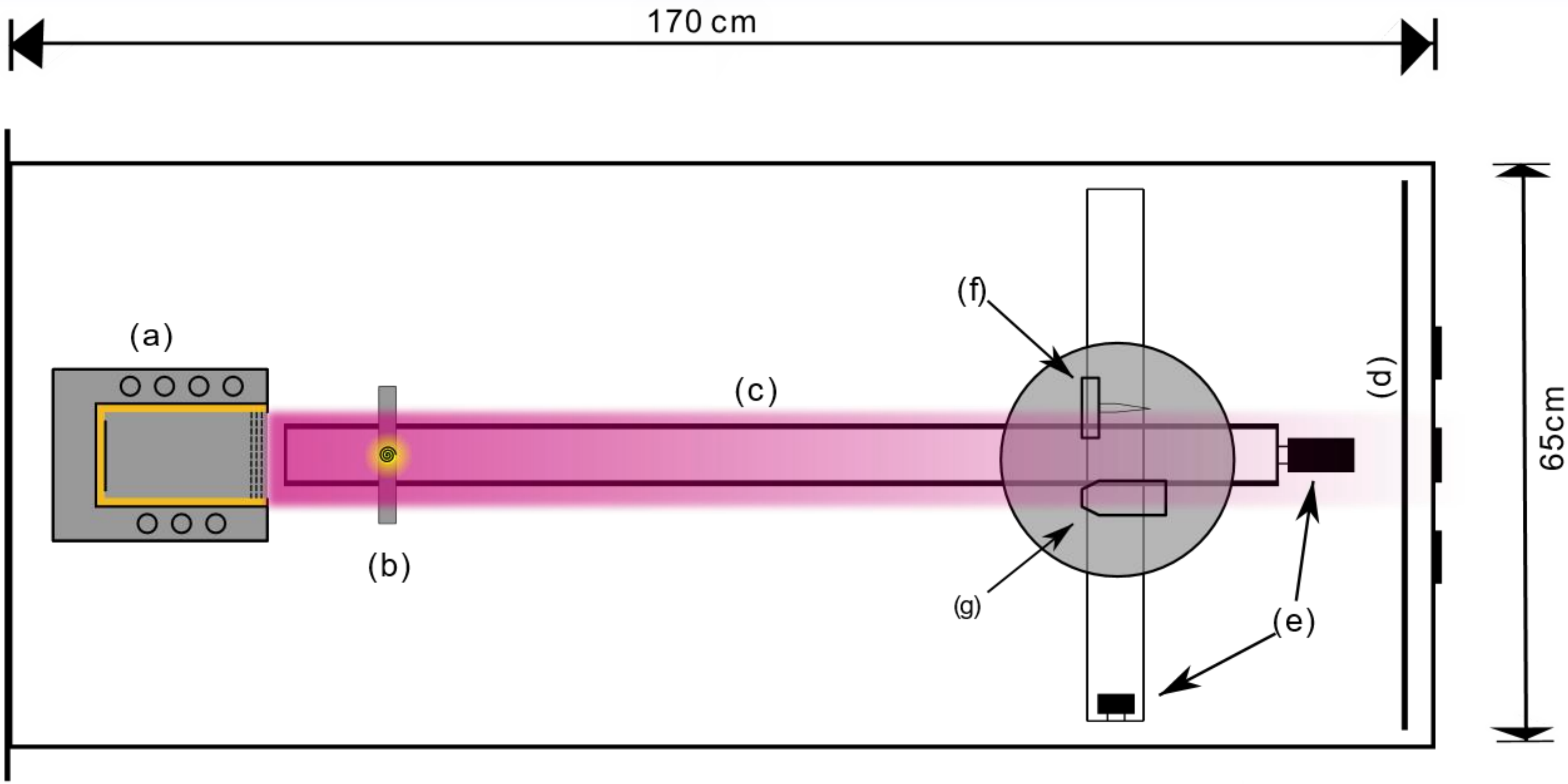
- Average distance over which a particle can travel before having a collision

$$\lambda_{cx} = \frac{1}{n_n \cdot \sigma_{cx}} \quad [1]$$

- Assessment for the frequency of this process

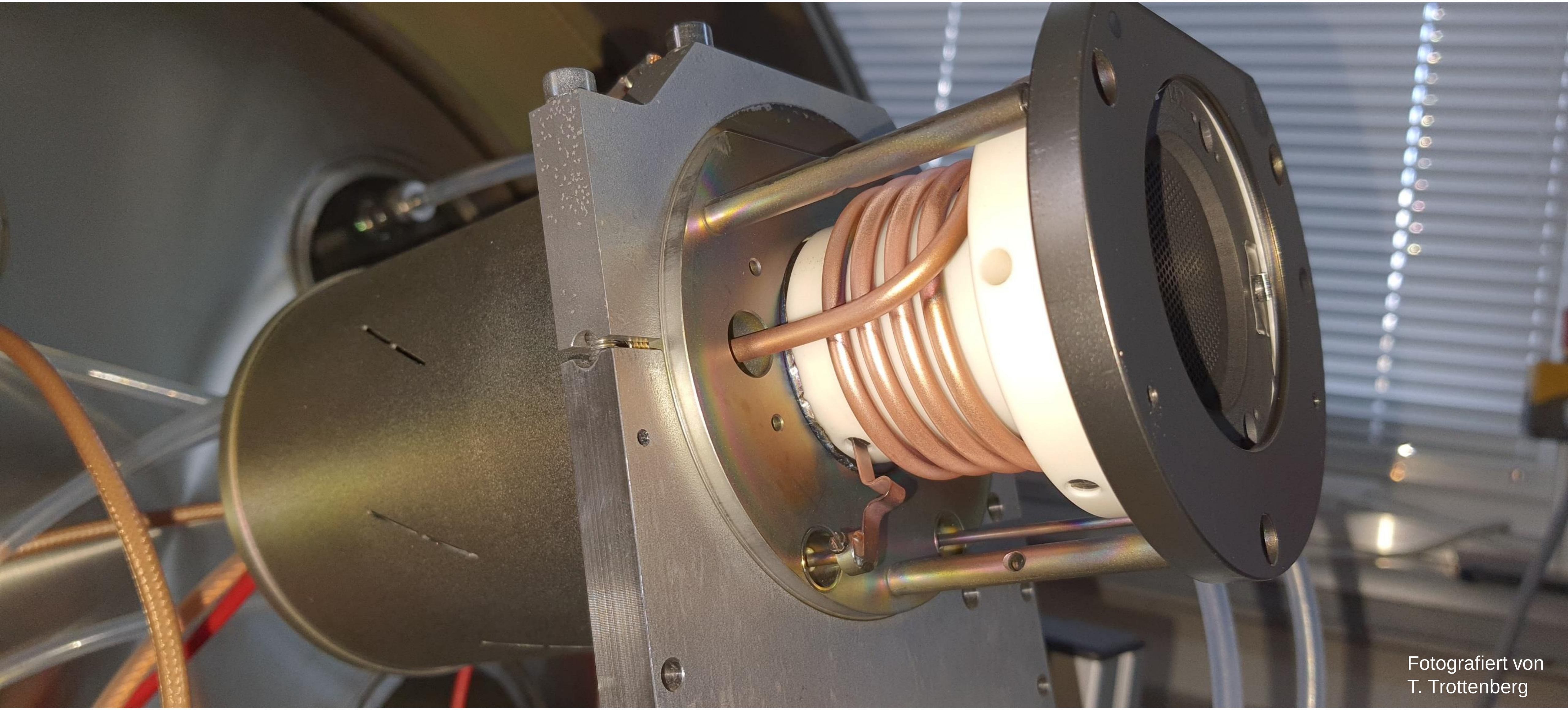
[1] Liebermann, Lichtenberg, *Principles of plasma discharges and materials processing*, 1994
[2] A.Prediger, Masterarbeit, 2023

Horizontal Ion Beam Experiment



(a) gridded ion source (b) hot cathode (c) Translation stage with movable probes
(d) Beam dump (e) Stepper motor (f) Force probe (g) Faraday cup

The ion beam source SCIA RF37i



Fotografiert von
T. Trottenberg

Ion beam source

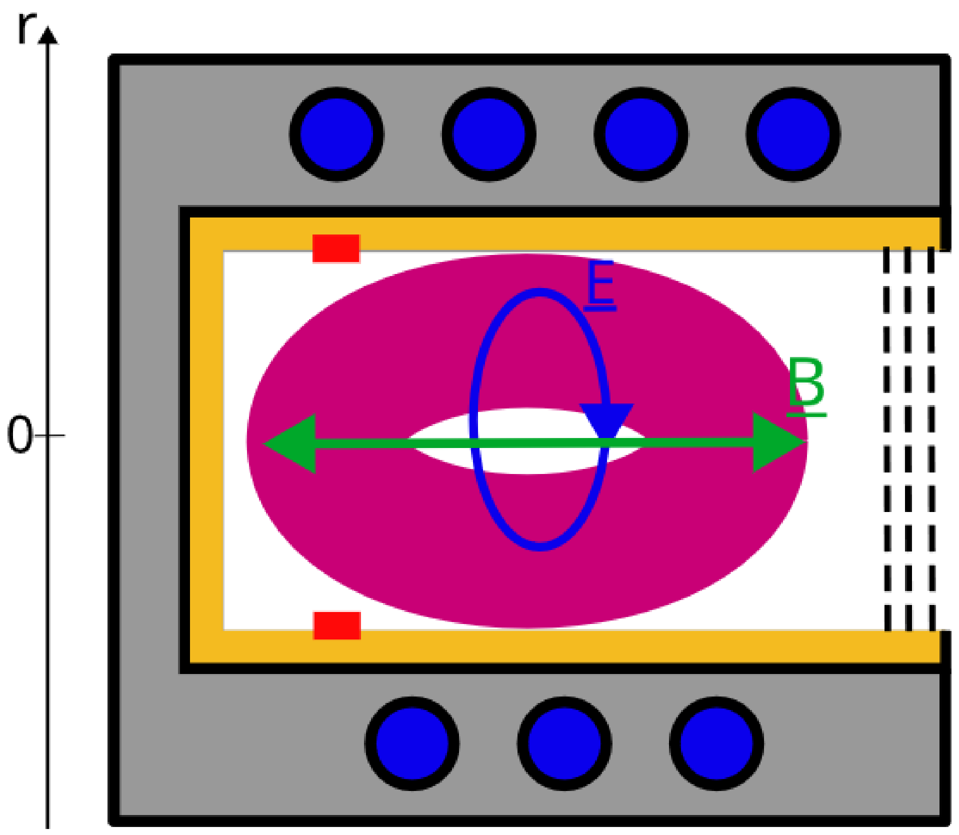


Illustration of an IC ion beam source

- Inductive Coupled Plasma (ICP)

$$\vec{\nabla} \times \vec{E} = -\dot{\vec{B}}$$

$$I(t) = I_0 \cdot e^{i\omega t}$$

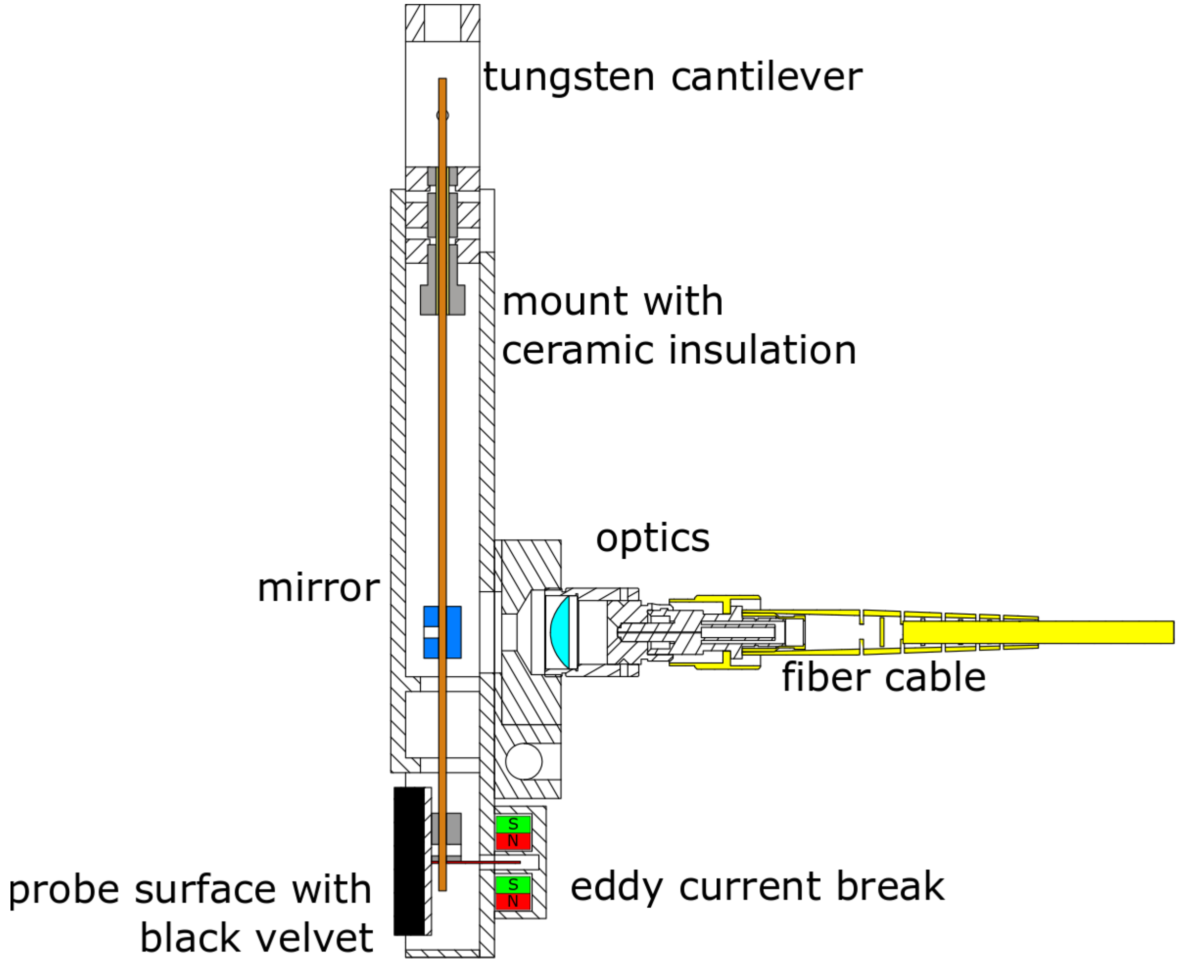
$$B(t) = \eta \frac{\mu_0 N}{L} I(t)$$

$$E(t) = \frac{1}{2} \eta \frac{\mu_0 N}{L} r\omega I(t)$$

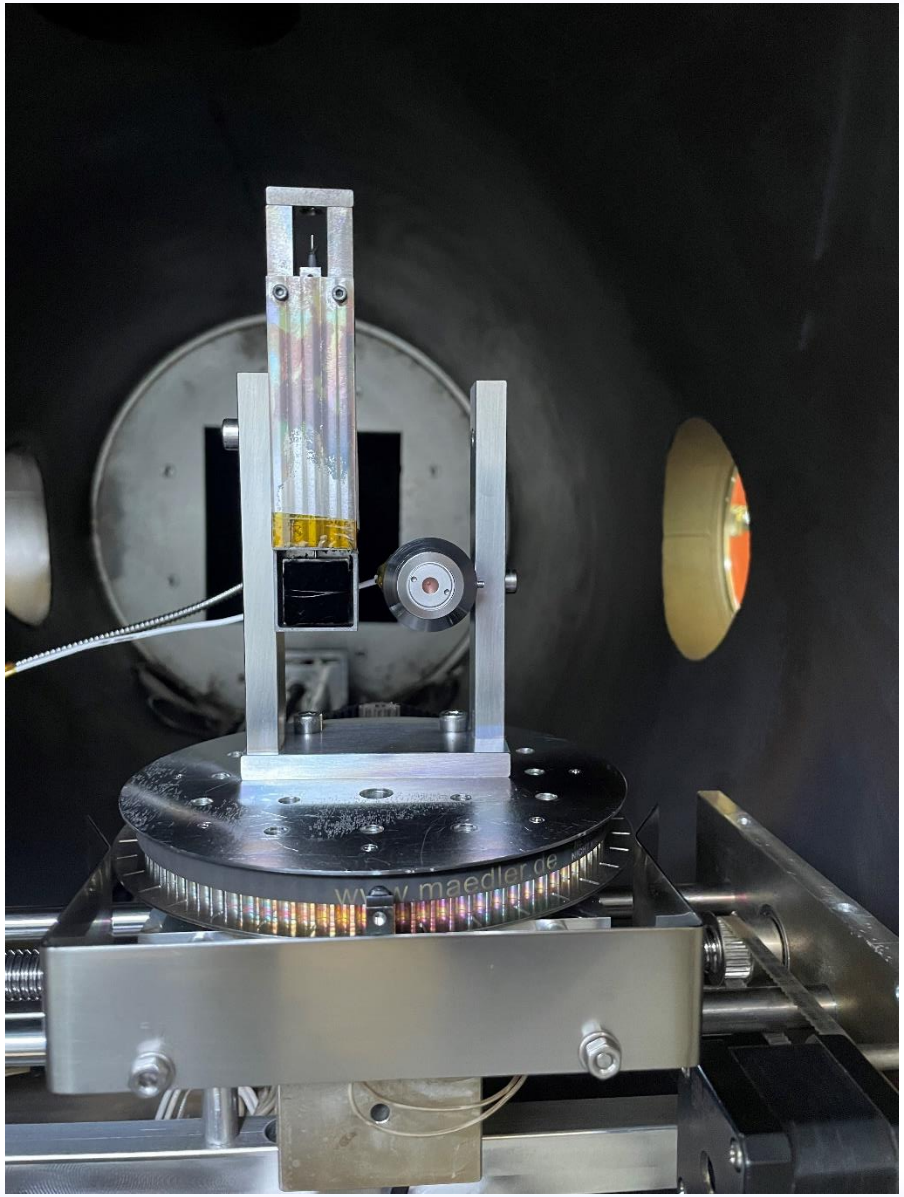
- Free electrons cause impact ionization of the neutral gas atoms

Equation from: Holste, et al., *Ion thrusters for electric propulsion: Scientific issues developing a niche technology into a game changer*, 2020

The force probe

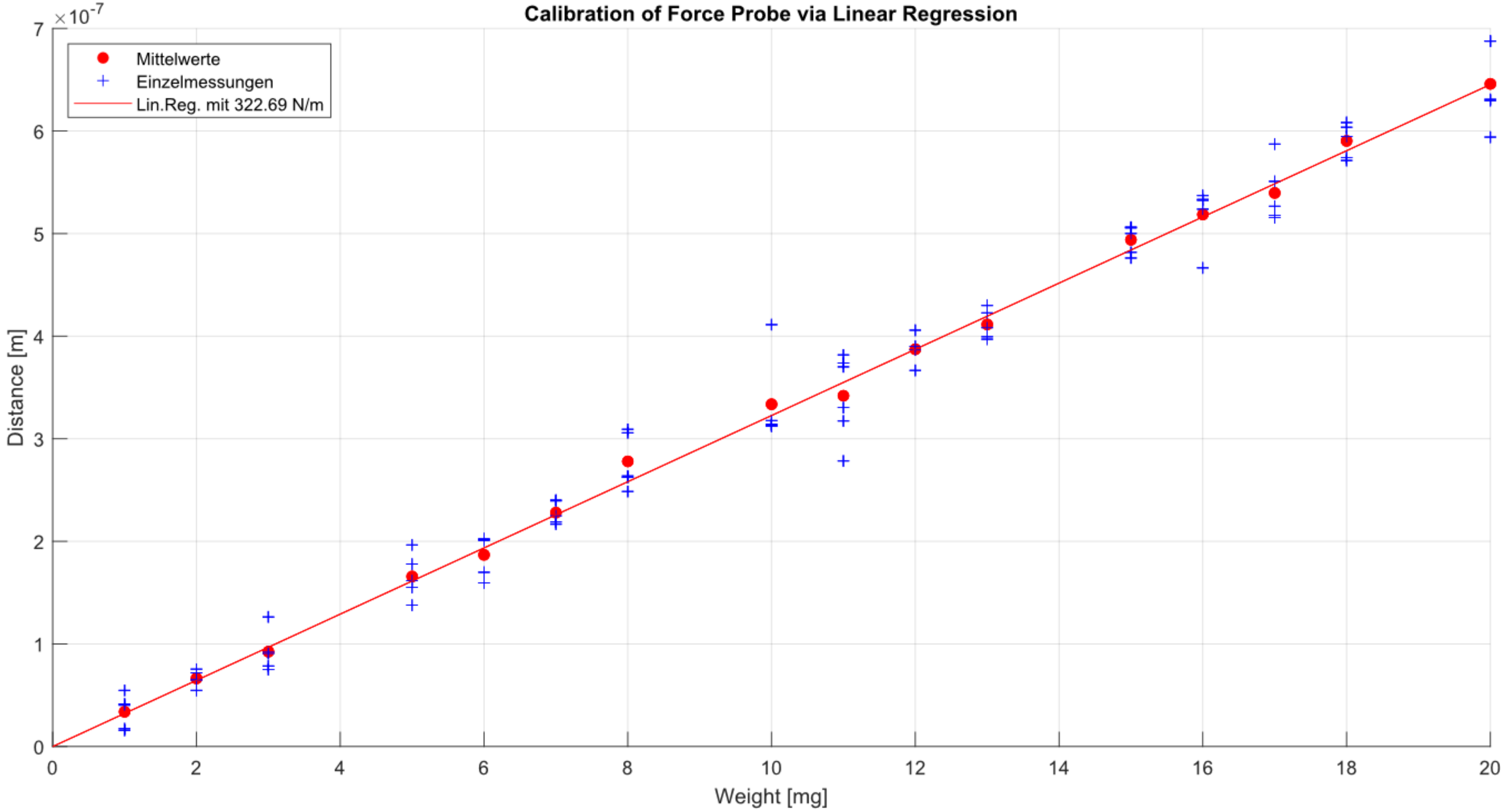


cross section of the force probe [1]



[1] M.Klette, M. Maas, T. Trottenberg, H. Kersten, J. Vac. Sci. Technol. A 38, 033013 (2020)

Evaluation of the force probe measurement



$$F = k \cdot \Delta x$$

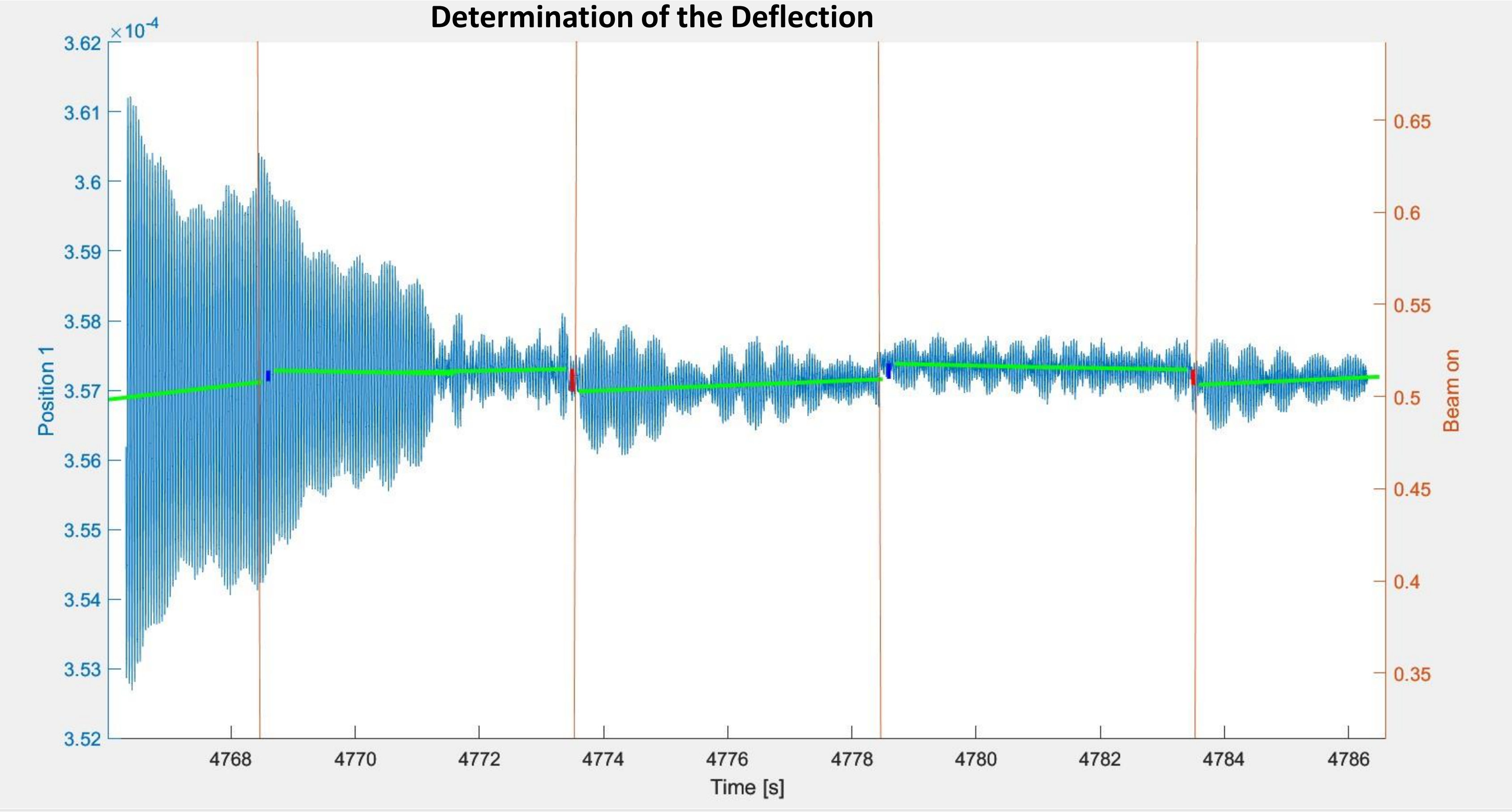
Calibration is carried out using test weights:

$$k_{cali} = (322,69 \pm 24,78)\ \mathrm{N/m}$$

Theoretical value from Euler-Bernoulli beam theory:

$$k_{theo} \approx 319,69\ \mathrm{N/m}$$

Evaluation of the force probe measurement



$$\Gamma_{beam}(z) = \frac{1}{A}\frac{F(z)}{p_{Ar}} \qquad (1)$$

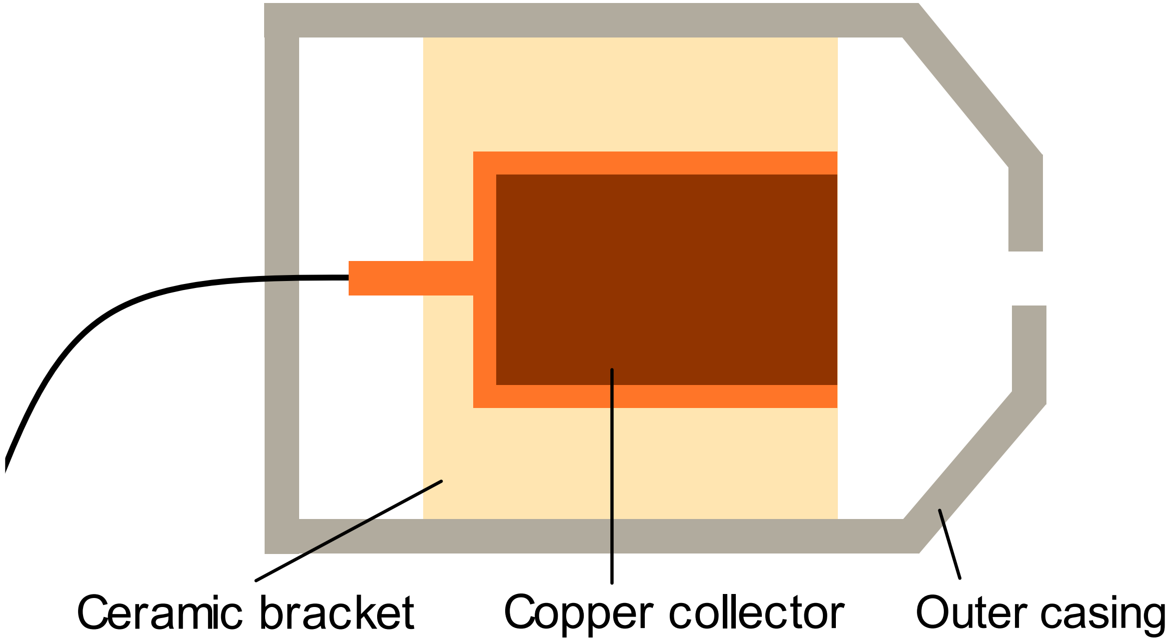
$$p_{Ar} = m_{Ar} \cdot v_{Ar} \qquad (2)$$

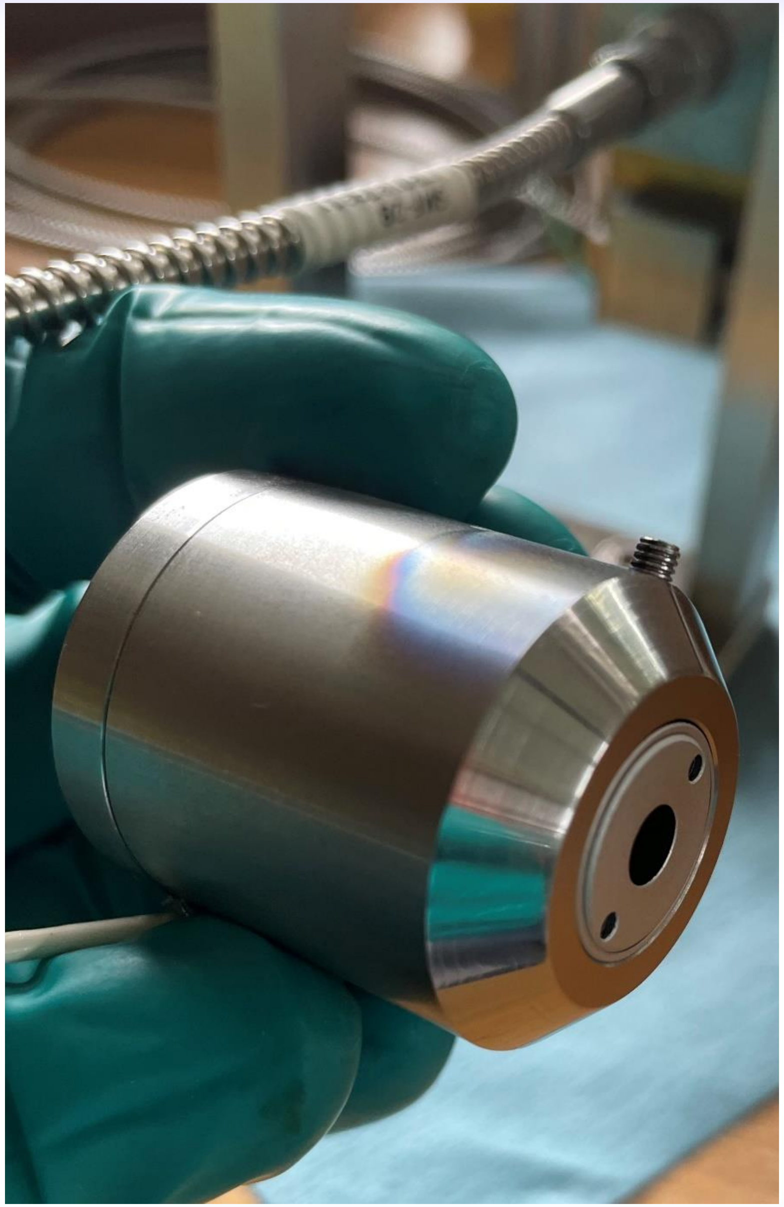
$$U \cdot e_0 = \frac{1}{2} m_{Ar} v_{Ar}^2 \qquad (3)$$

$$v_{Ar} = \sqrt{\frac{2Ue_0}{m_{Ar}}}$$

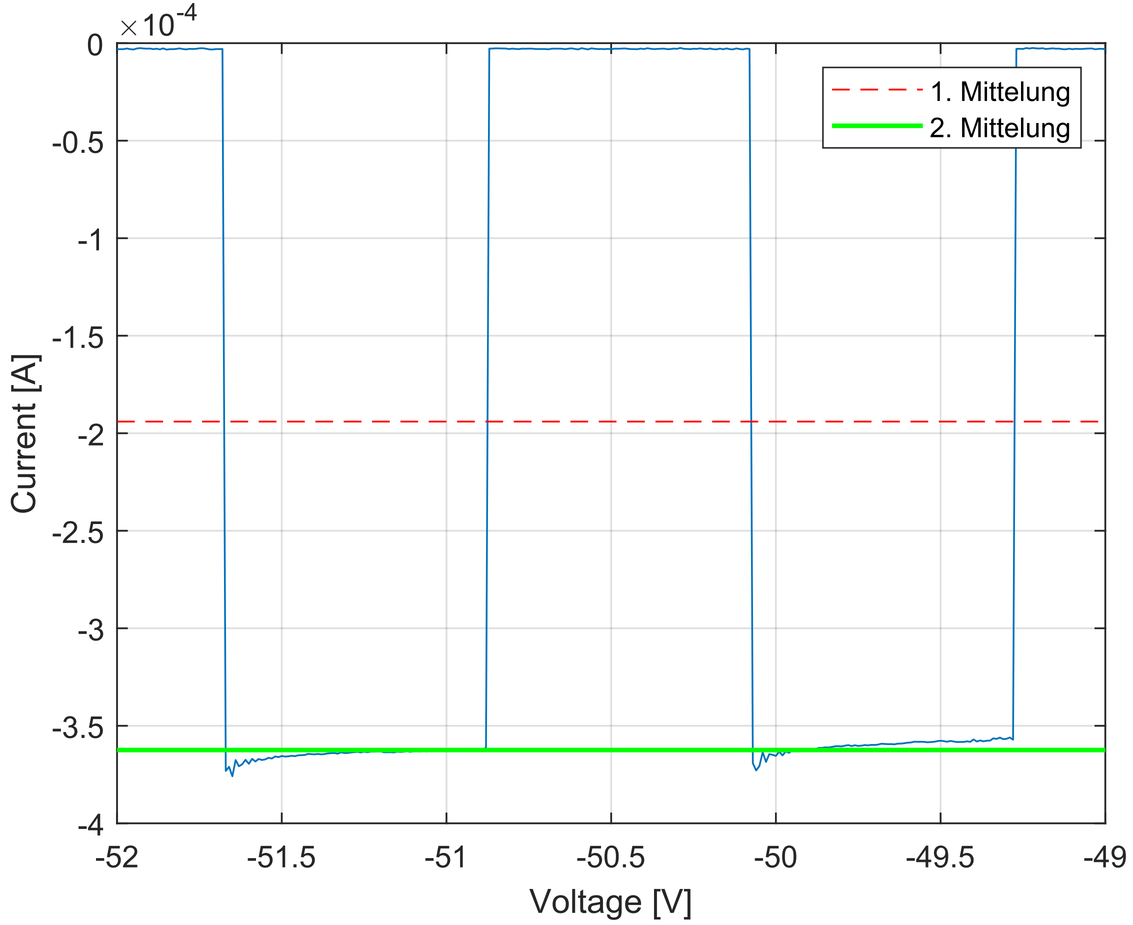
$$\Rightarrow \Gamma_{beam}(z) = \frac{F(z)}{A \cdot \sqrt{2Ue_0 m_{Ar}}}$$

Faraday cup

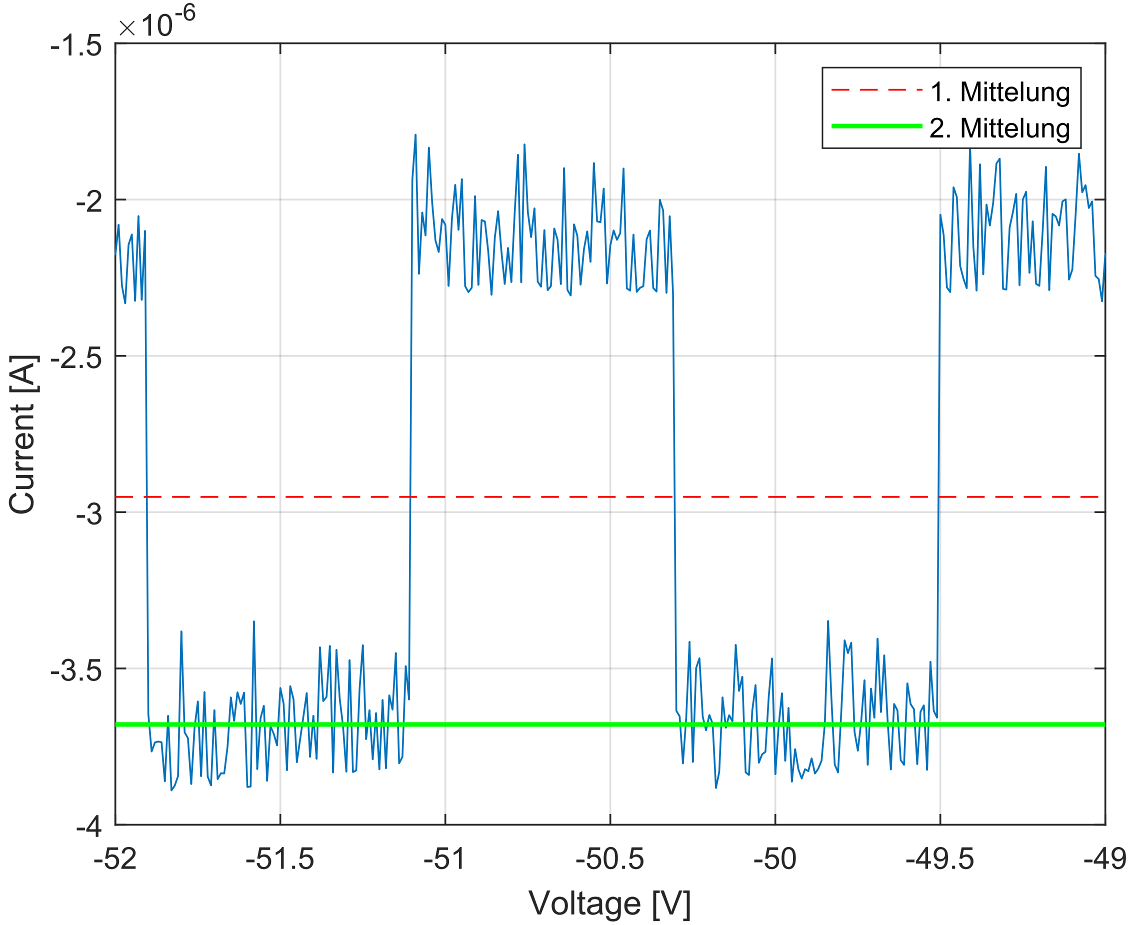




Evaluation of the Faraday cup measurement



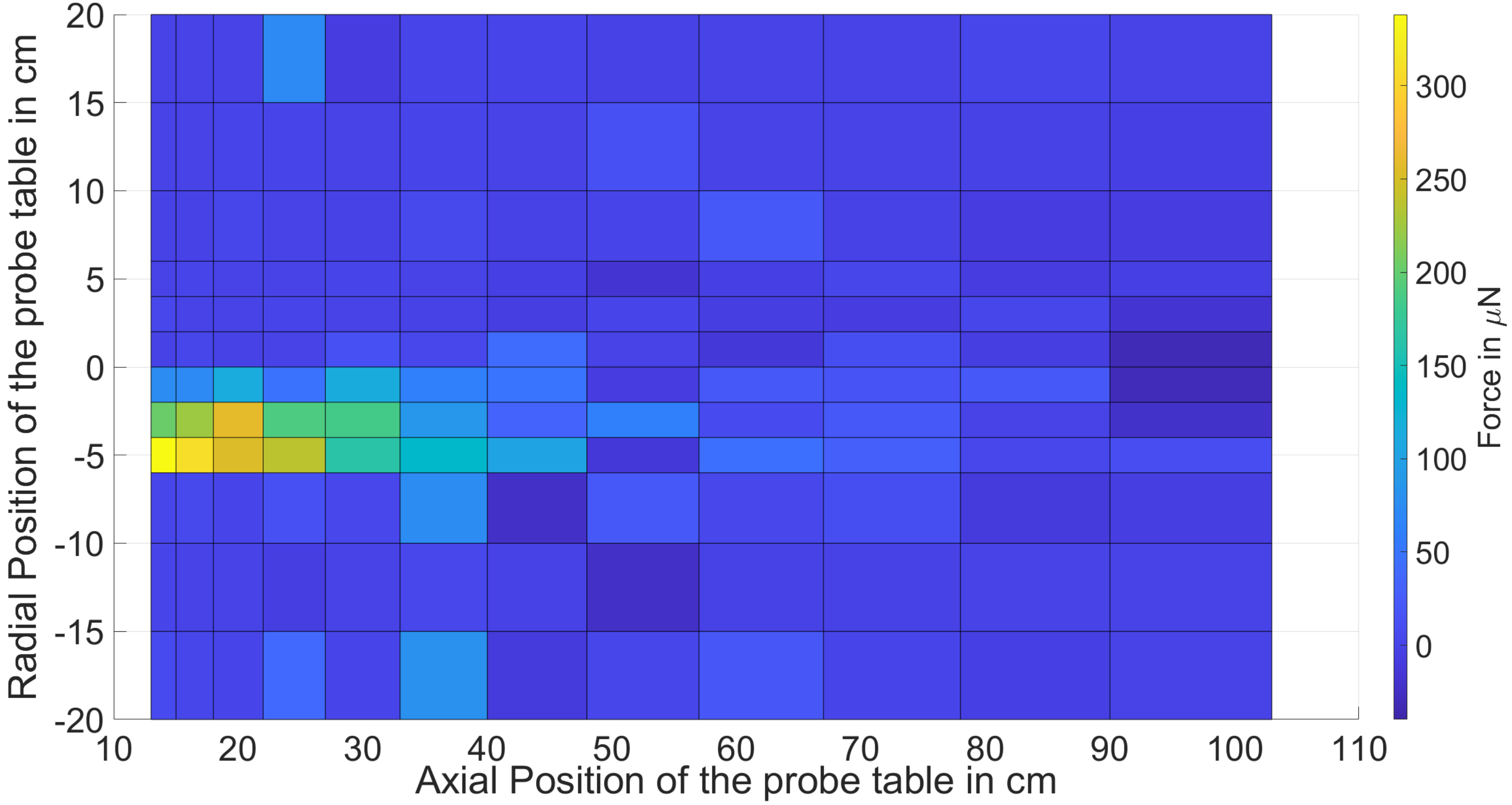
FC measurement at the point (0,-20)



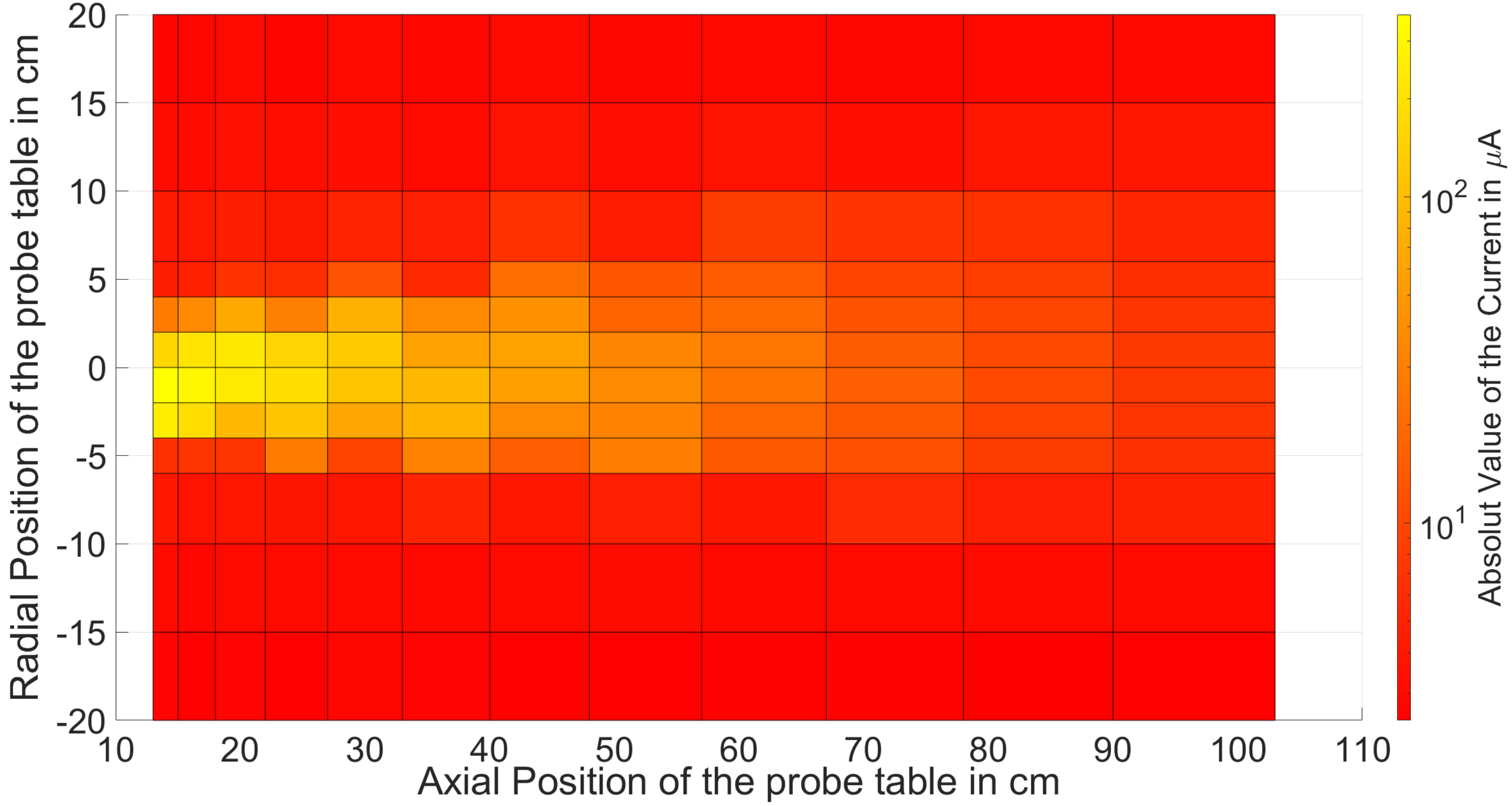
FC measurement at the point (-900,100)

$$\Gamma_i(z) = \frac{I(z)}{A \cdot e_0}$$

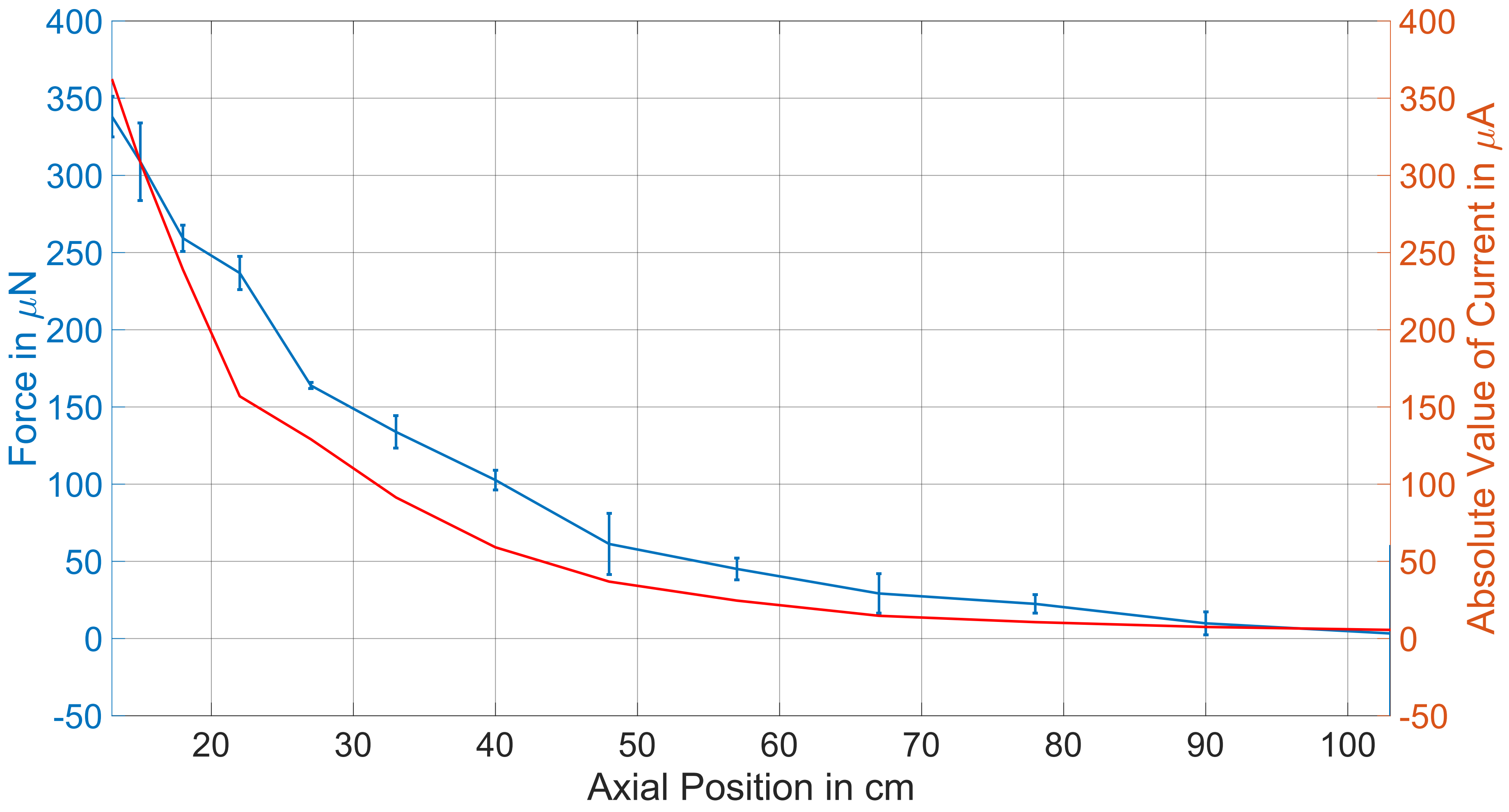
Measurement results



Measurement results



Comparison of probe measurements



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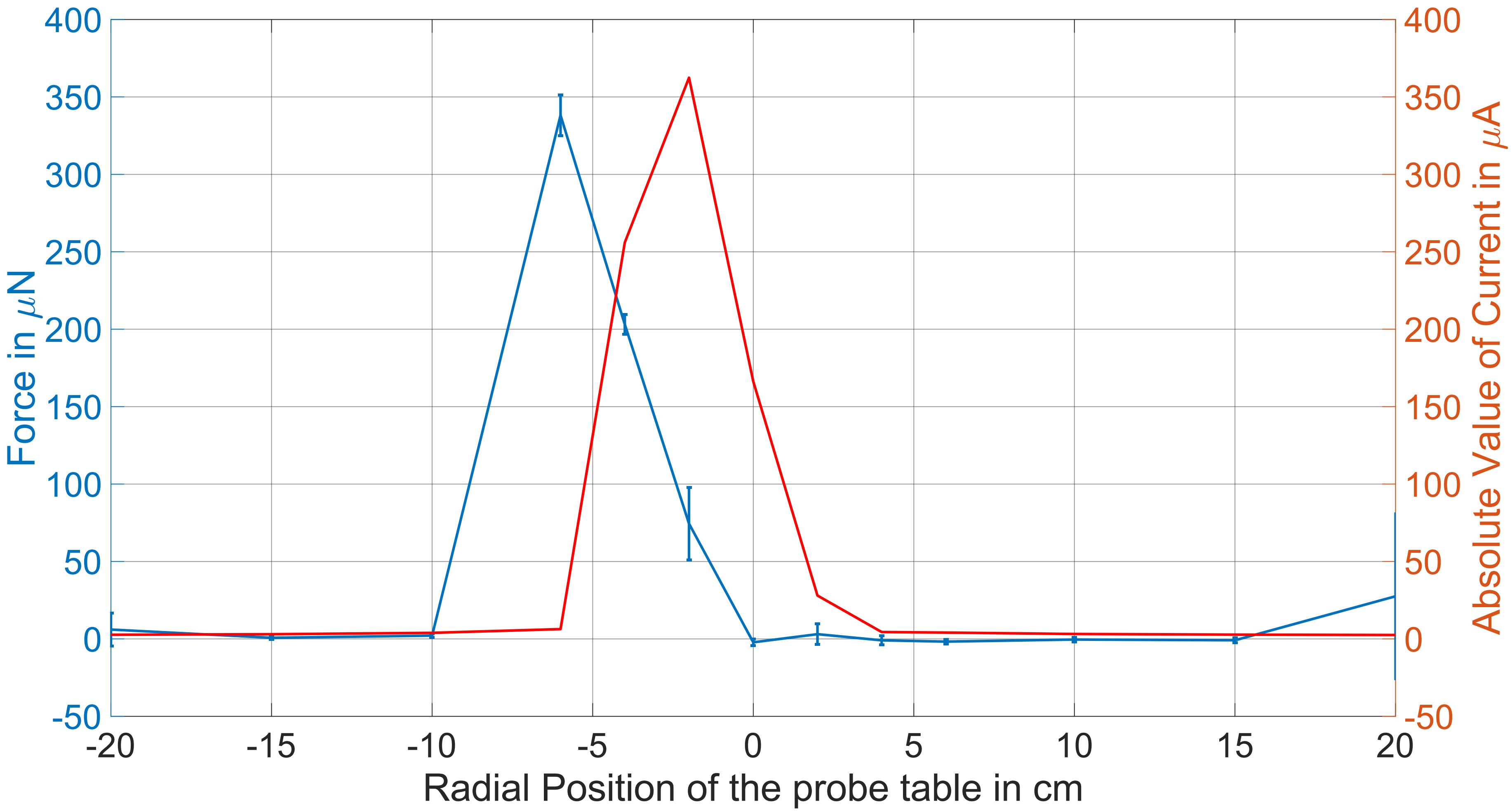


Calculation of the mean free path

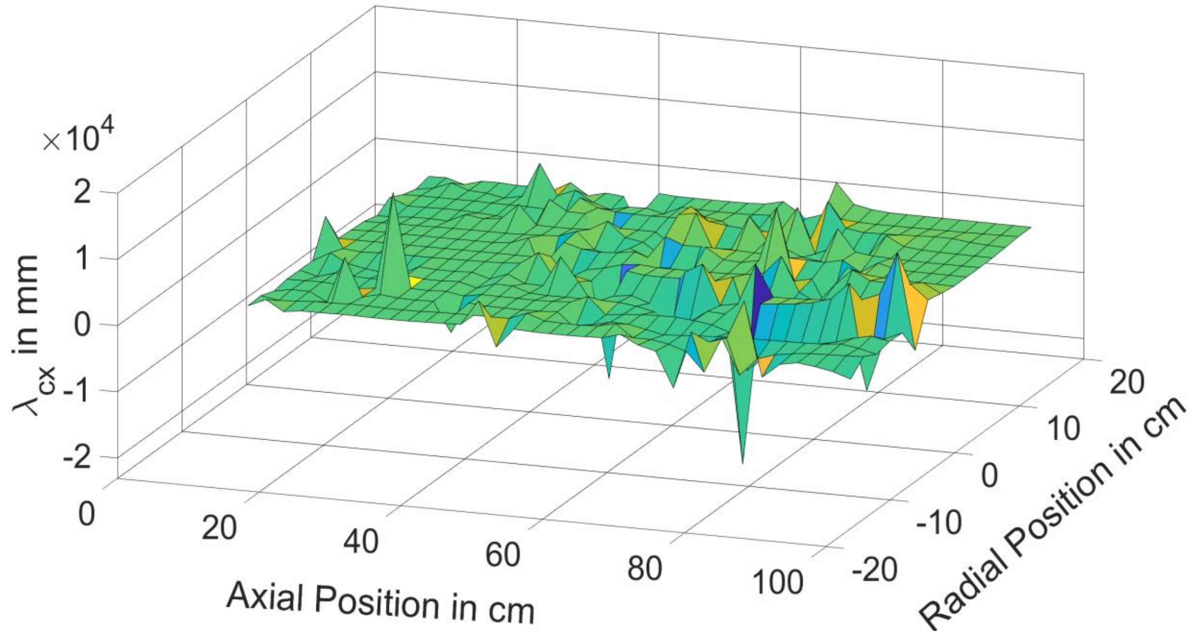
$$\lambda_{\mathrm{cx}}(x) = -\frac{x}{\ln\left(\Gamma_{\mathrm{i}}(x)/\Gamma_{\mathrm{beam}}(x)\right)}$$

$$\Gamma_{\mathrm{i}}(x) = \frac{I(x)}{A_{\mathrm{FC}} \cdot e_0} \qquad \Gamma_{\mathrm{beam}}(x) = \frac{F(x)}{A_{\mathrm{FP}}\sqrt{2Ue_0 m_{\mathrm{Ar}}}}$$

$$\underline{\underline{\lambda_{\mathrm{cx,exp}} = (610 \pm 357)\ \mathrm{mm}}}$$

$$\lambda_{\mathrm{cx,theo}} = \frac{k_{\mathrm{B}}T}{p\sigma_{\mathrm{cx}}}$$

$$\underline{\underline{\lambda_{\mathrm{cx,theo}} \approx 509{,}59\,\mathrm{mm}}}$$



Summary and Outlook

- Secondary ions can cause damage to the sources and also to satellites
- The measurement of the mean free path for charge exchange collisions can be achieved through the use of a Faraday cup and a force probe
- Many error sources have been identified and fixed
- Now, similar measurements with different parameters would be interesting like:
  - Gas type
  - Different ion beam sources
  - comparisons with different measurement methods, e.g. retarding potential analyzer and calorimetric probes

Thank you for your attention

Quellen

[1] https://solarsystem.nasa.gov/news/731/10-things-looking-back-at-deep-space-1/
[2] Yalin, et al., *42nd AIAA/ASME/SAE/ASEE Joint Prop. Conf.*, 2006
[3] Trottenberg, et al., *An in-flight plasma diagnostic package for spacecraft with electric propulsion*, 2021
[4] Trottenberg, et al., *Measurement of the force on microparticles in a beam of energetic ions and neutral atoms*, 2010
[5] Masterarbeit von M. Klette, 2018
[6] Masterarbeit von A. Prediger, 2023
[7] Holste, et al., *Ion thrusters for electric propulsion: Scientific issues developing a niche technology into a game changer*, 2020
[8] S. Weis, Dissertation, 2006 (Gießen)
[9] A.Piel, *Plasma Physics: An Introduction to Laboratory, Space, and Fusion Plasmas*, 2017
[10] D. Goebel, I. Katz, *Fundamentals of Electric Propulsion: Ion and Hall Thrusters*, 2008
[11] von Keudell, *Einführung in die Plasmaphysik (Vorlesungs-Skript)*, 2017
[12] Phelps, et al., *Collision cross sections for argon atoms with argon atoms for energies from 0.01 eV to 10 keV*, 2000
[13] H.Kersten, *Vorlesungs-Folien*, 2021