KTH ROYAL INSTITUTE OF TECHNOLOGY

Plasma properties and non-Maxwellian electron energy probability functions in the far-plume of a SPT-100 Hall thruster

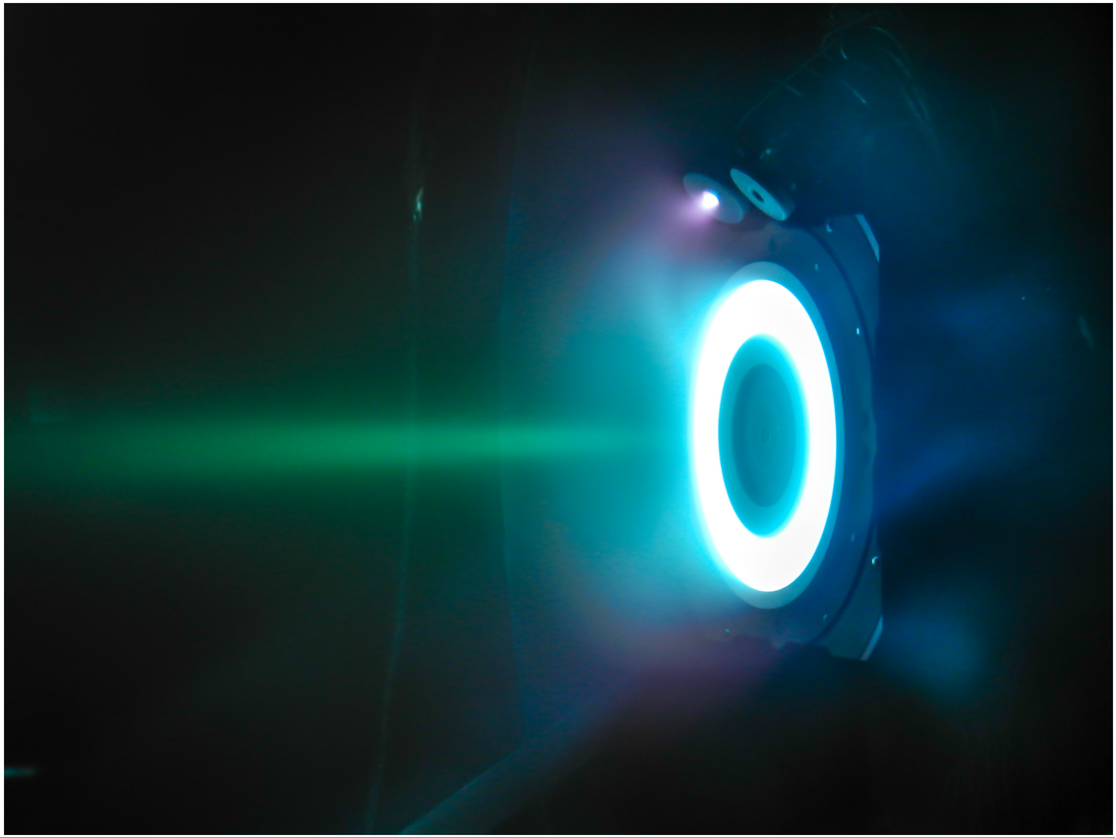
Gabriel Giono[1,2], Stéphane Mazouffre[3], Dimitry Loubère[4], Lara Popelier[4], Christophe Théroude[4], Käthe Dannenmayer[5], Fabien Marguet[5], Jon Tomas Gudmundsson[1,6], Nickolay Ivchenko[1], Georgi Olentsenko[1] and Mario Merino[7]

(1): Department of Space and Plasma Physics, School of Electrical Engineering, KTH-Royal Institute of Technology, Stockholm, Sweden.
(2): Leibniz-Institute of Atmospheric Physics (IAP), Kühlungsborn, Germany
(3): ICARE, Centre National de la Recherche Scientifique, 1c, Av. de la recherche scientifique, CS 50060, 45071 Orléans, France
(4): Airbus Defence and Space, 31 Rue des Cosmonautes, 31400 Toulouse, France
(5): ESTEC, European Space Agency, Keplerlaan 1, PO Box 299, NL-2201 AZ Noordwijk, The Netherlands
(6): Science Institute, University of Iceland, Dunhaga 3,IS-107 Reykjavik, Iceland
(7): Aerospace Engineering department, Universidad Carlos III de Madrid, Avda. de la Universidad 30, 28911 Leganés, Madrid, Spain

Purpose of the experiment

The MODEX project (Airbus-DS, ESA, UC3M, ONERA, CNRS and KTH) aims at refining the modelling of plasma plume, in particular the electron cooling mechanism.
For this purpose, measurements of the **electron density**, **electron temperature**, **plasma potential** and **electron energy distribution function (EEDF)** along the plume axis as well as angularly were required to confront the electron cooling models.

A SPT-100 1.5 kW-class Hall thruster was used, and measurements were carried out at distances from 500 to 1550 mm from its exit.



Six operating points of the thruster were investigated:

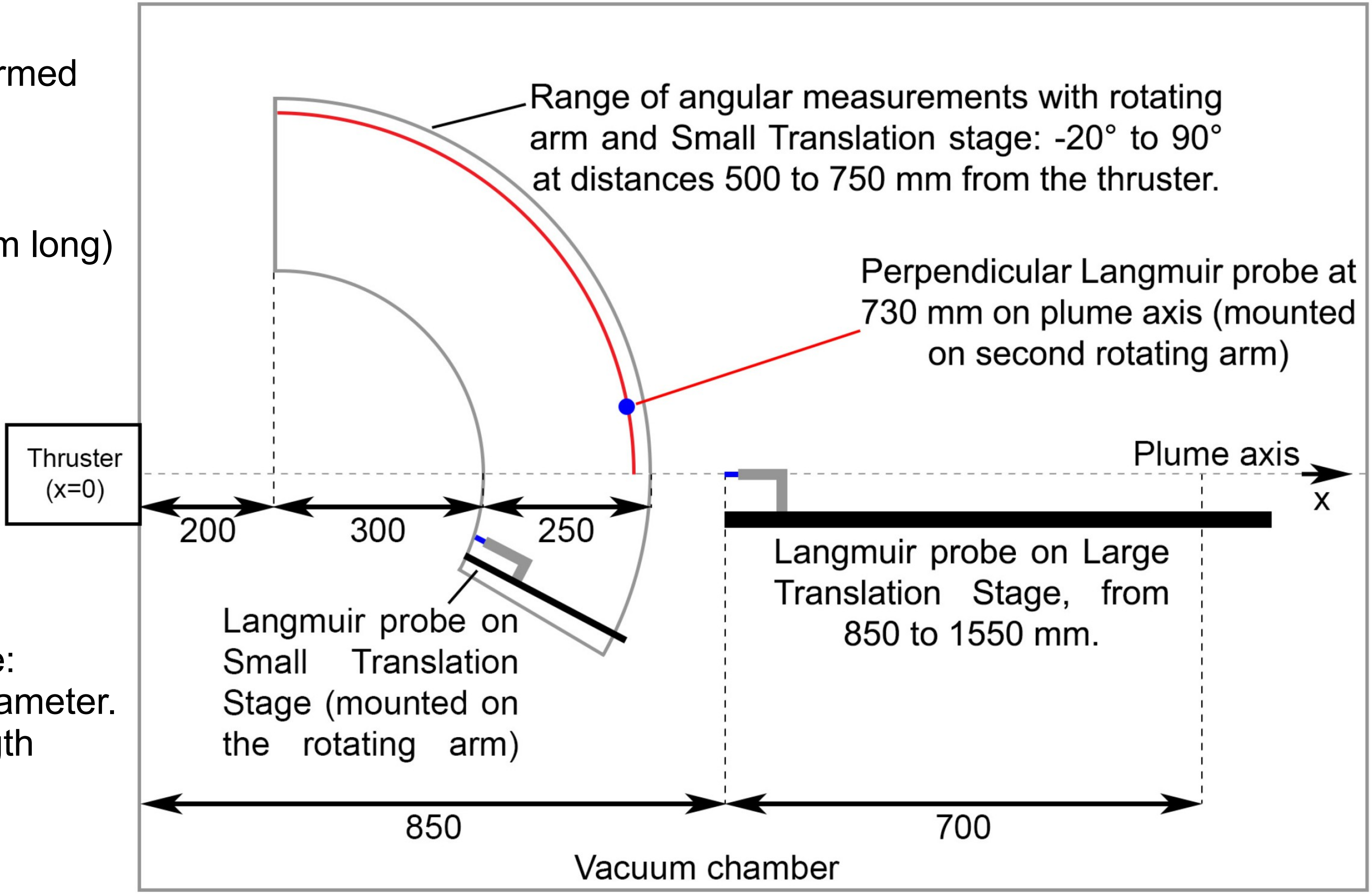
- 300 V and 4 mg/s
- 300 V and 2 mg/s
- 400 V and 2 mg/s
- 225 V and 2 mg/s
- 150 V and 2 mg/s
- 150 V and 4 mg/s

Overview of the setup

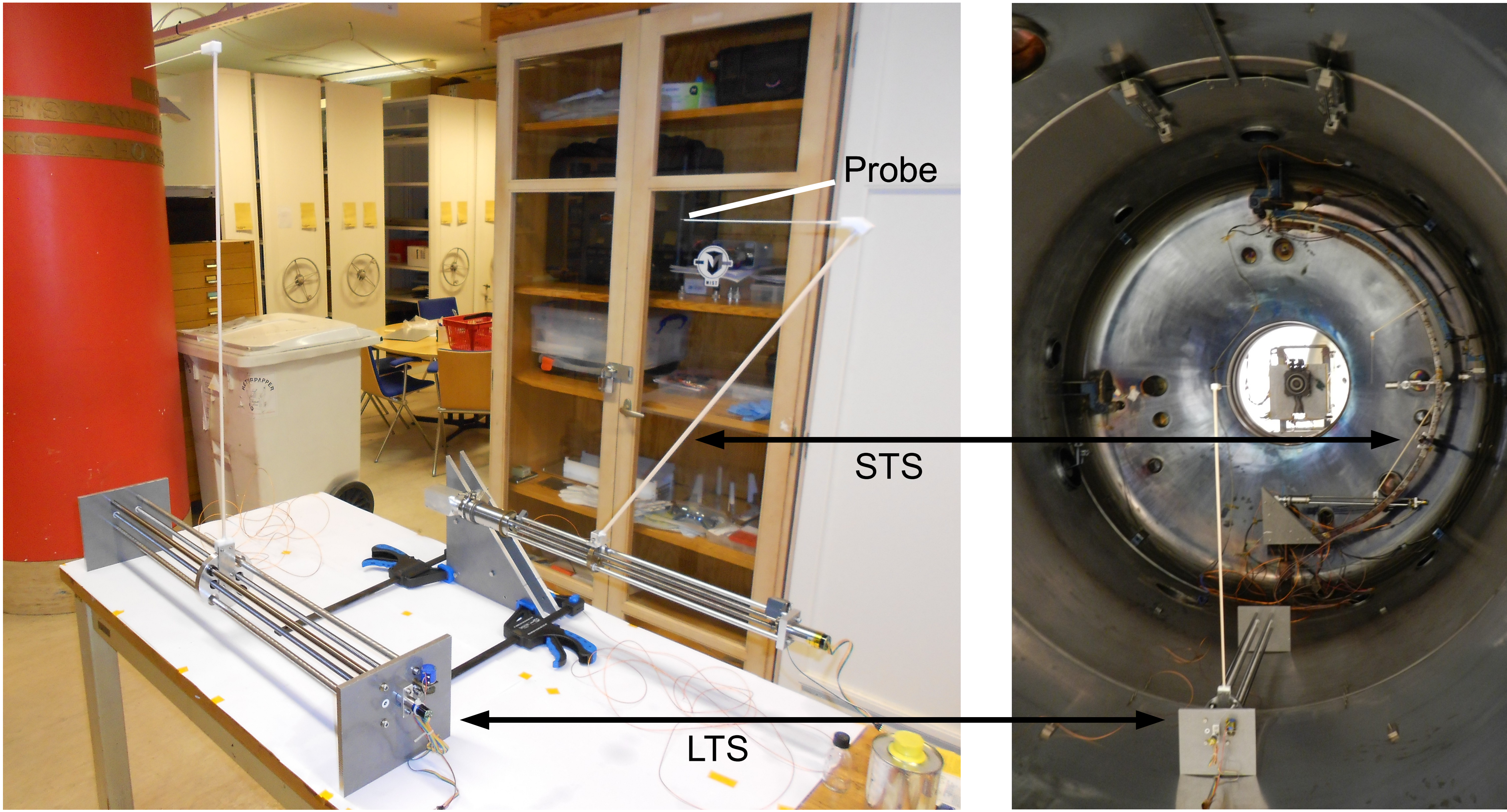
Test performed inside the CORONA chamber.
(2-m ϕ, 4-m long)

Probe size:
0.4 mm diameter.
5 mm length

Material:
Tungsten

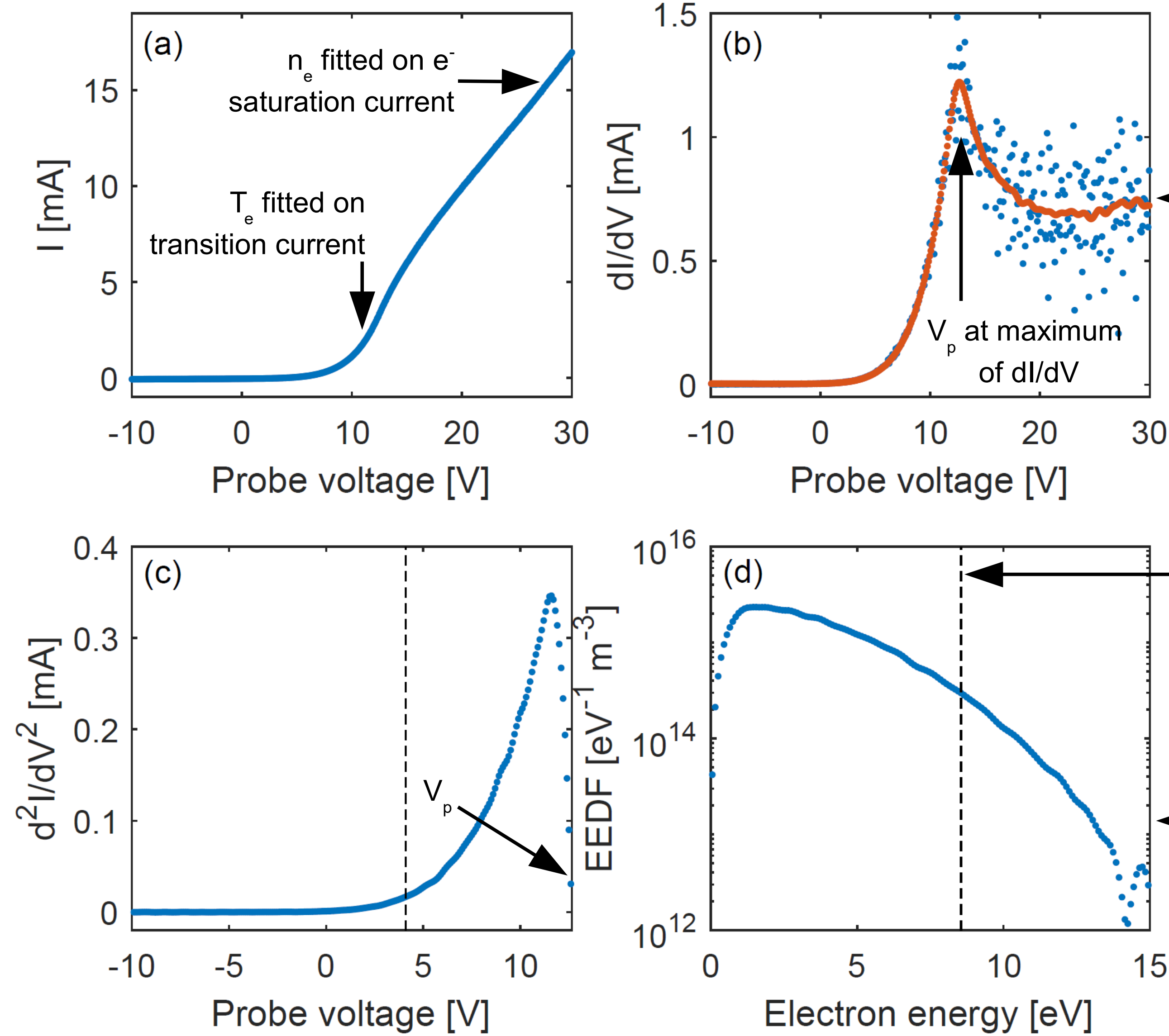


Probes and translation stages



Example of IV curve measurement and analysis

(a) IV curve
↓
(b) dI/dV
↓
(c) d^2I/dV^2
↓
(d) EEDF

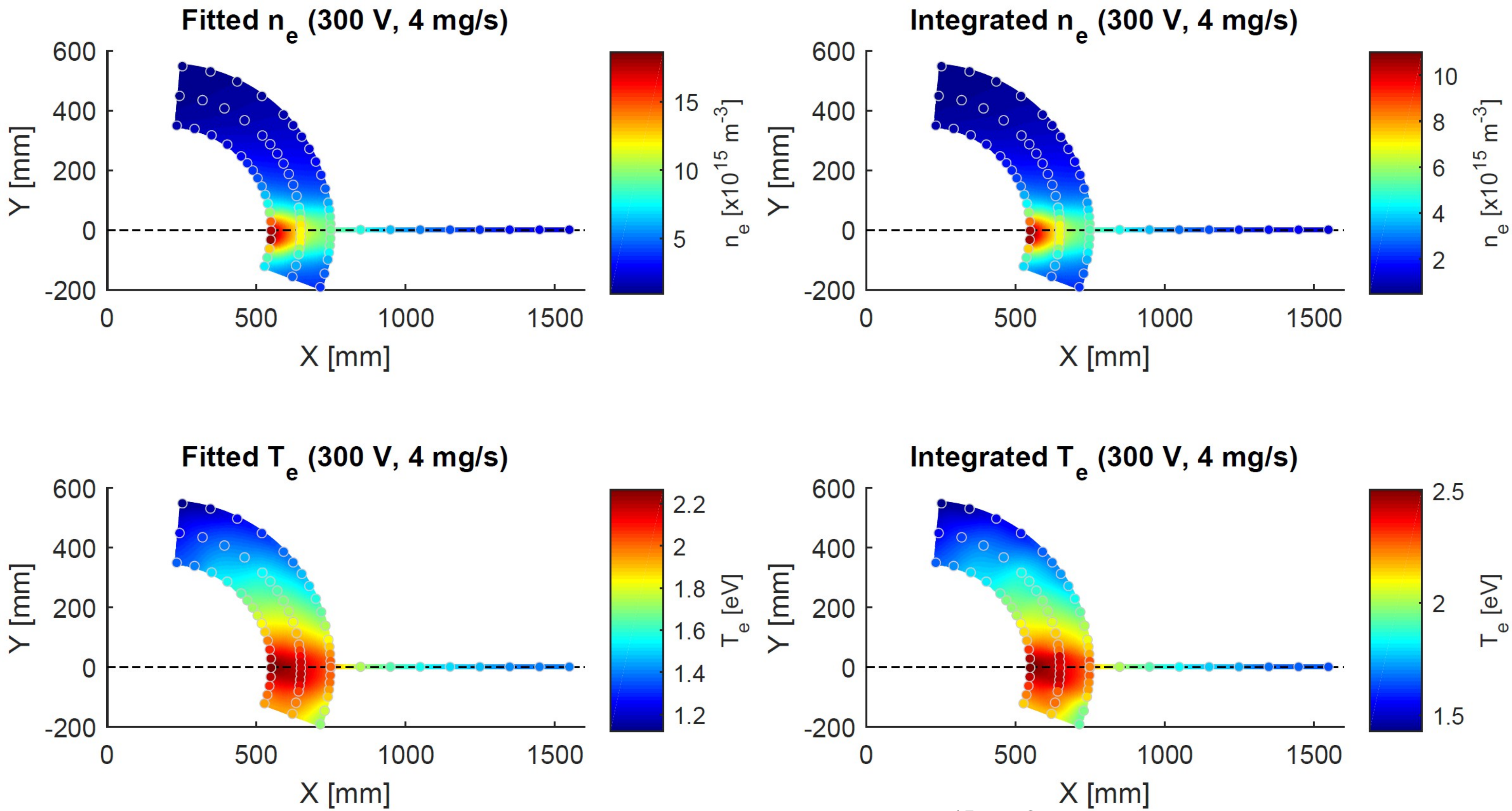


First derivative smoothed by convolution with a Blackman window

Floating potential energy

n_e and T_e obtained by integrating the EEPF.

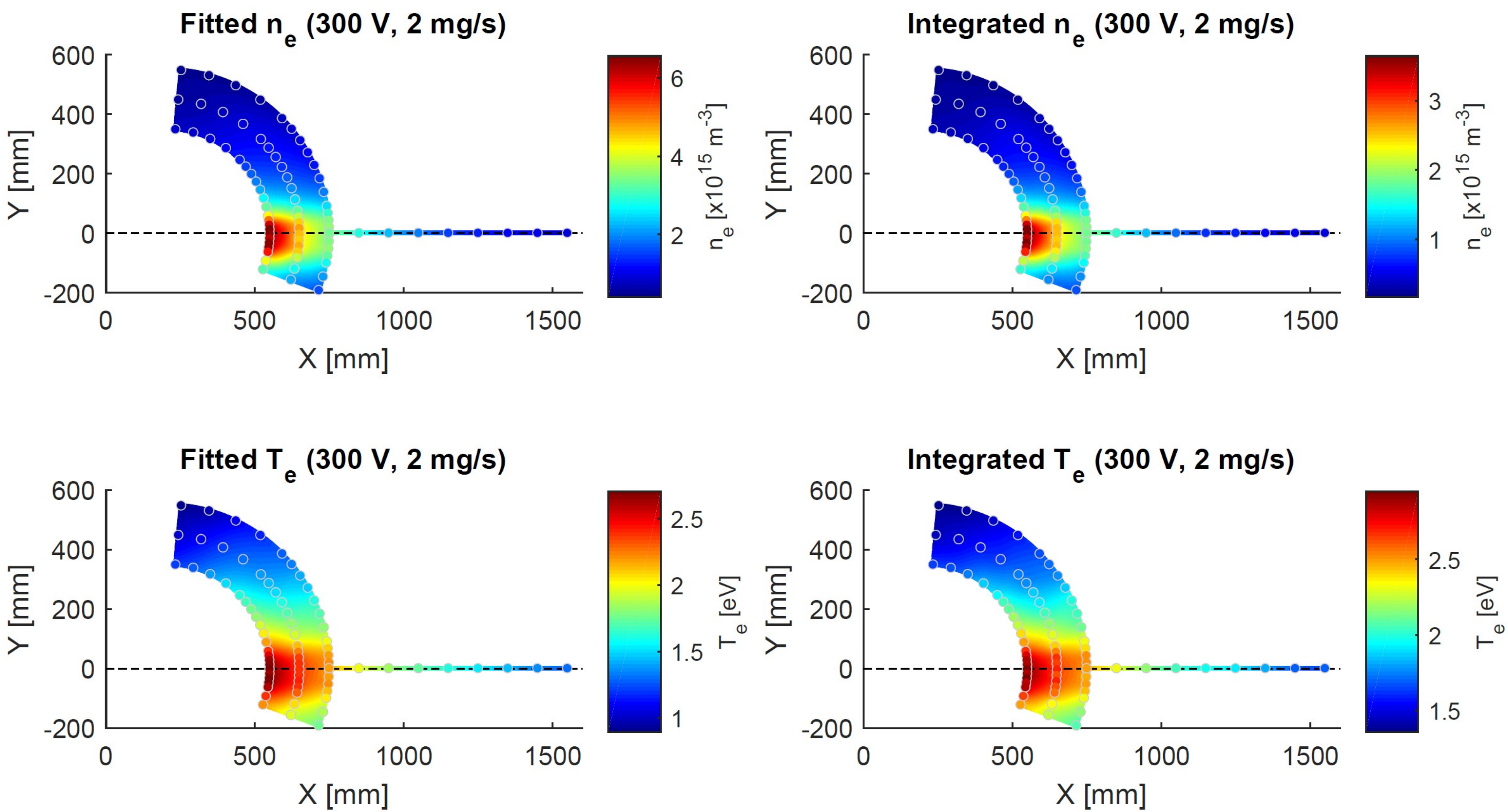
Maps: 300 V, 4 mg/s



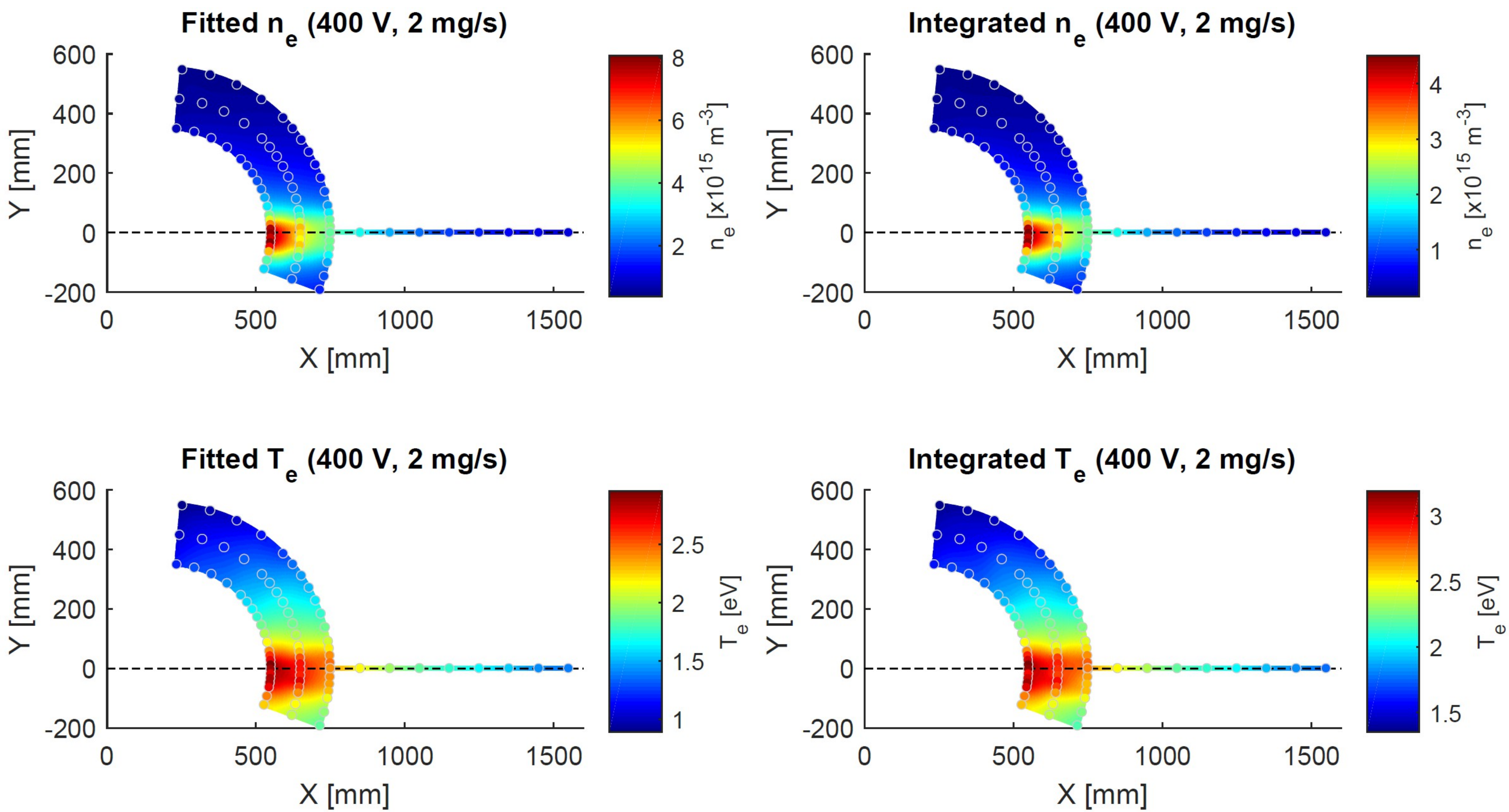
Fitted n_e is about 30% larger than the integrated one (~3×10^{15} m^{-3} in average).

Fitted T_e is about 15% lower than the integrated one (~0.3 eV in average).

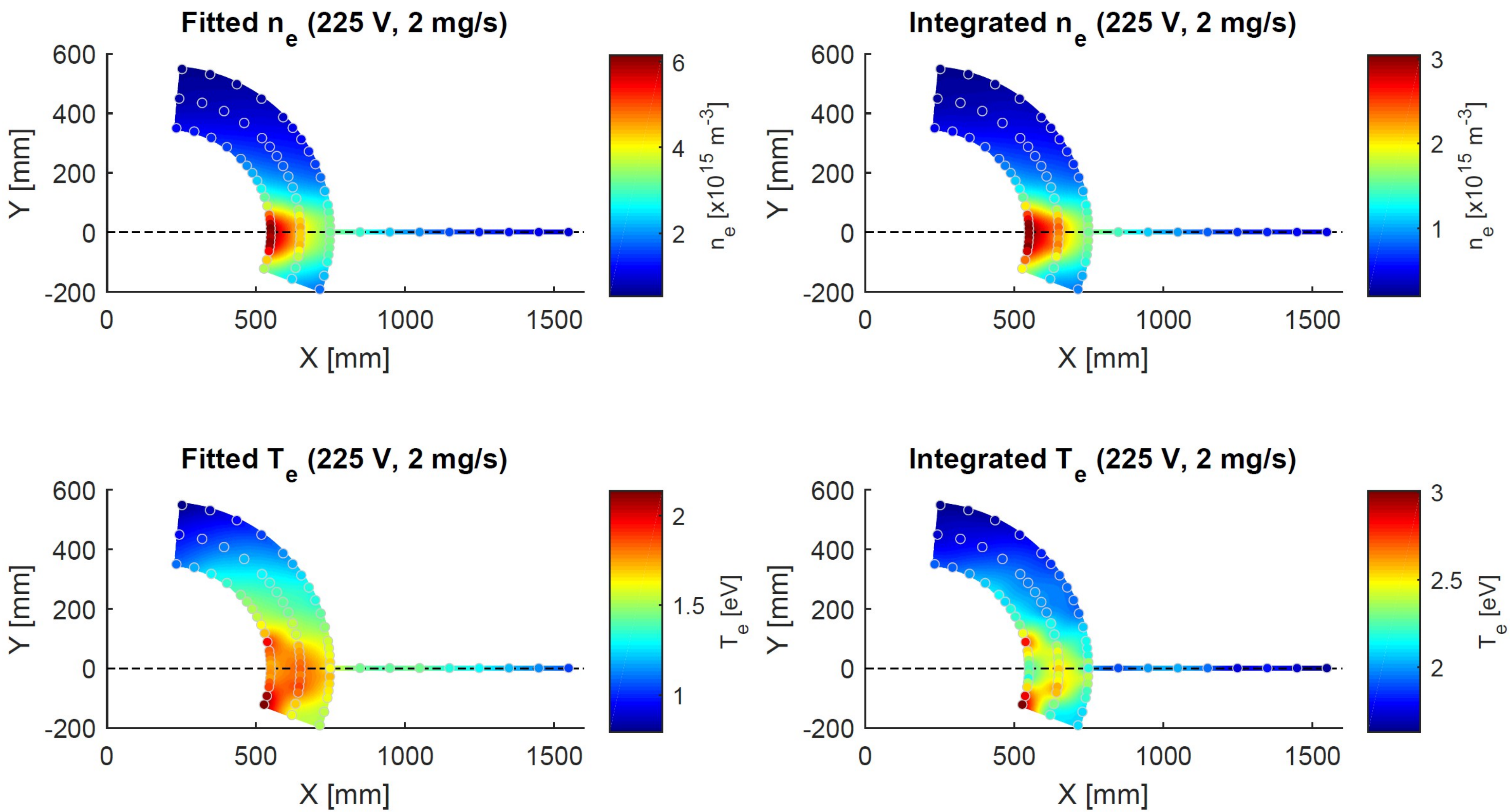
Maps: 300 V, 2 mg/s



Maps: 400 V, 2 mg/s

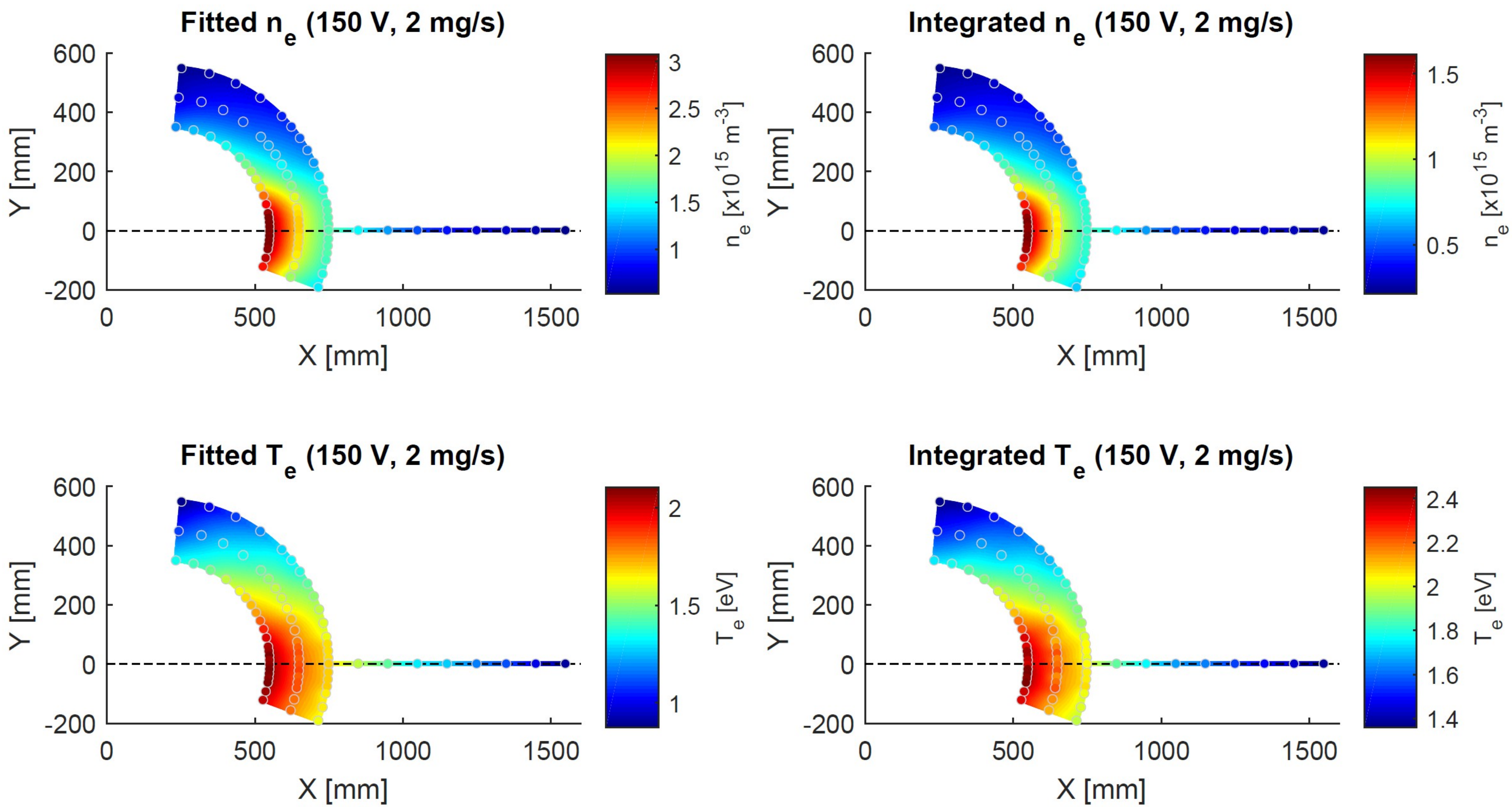


Maps: 225 V, 2 mg/s



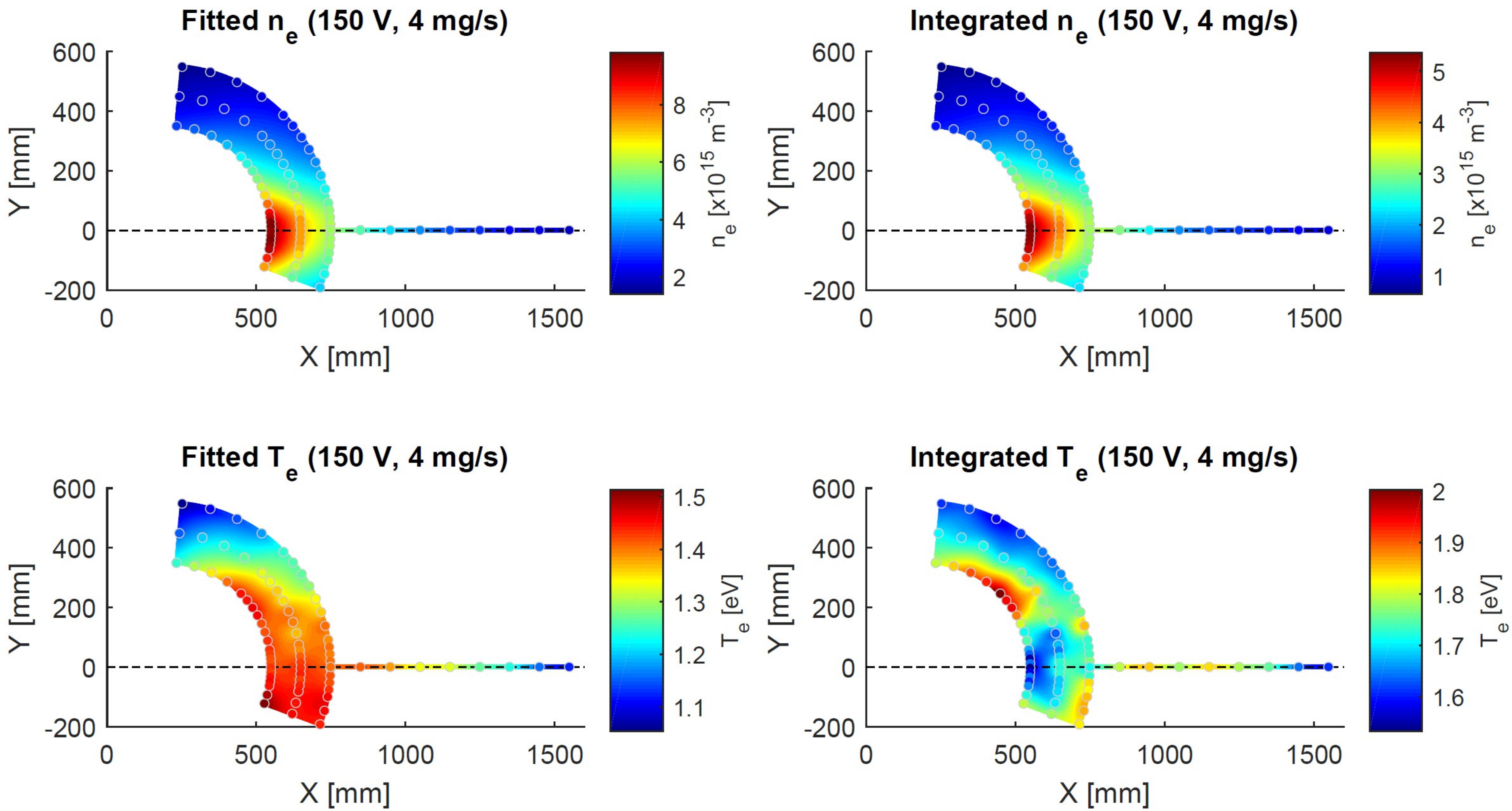
Integrated T_e is less consistent due to a larger measurement noise at this operating point.

Maps: 150 V, 2 mg/s



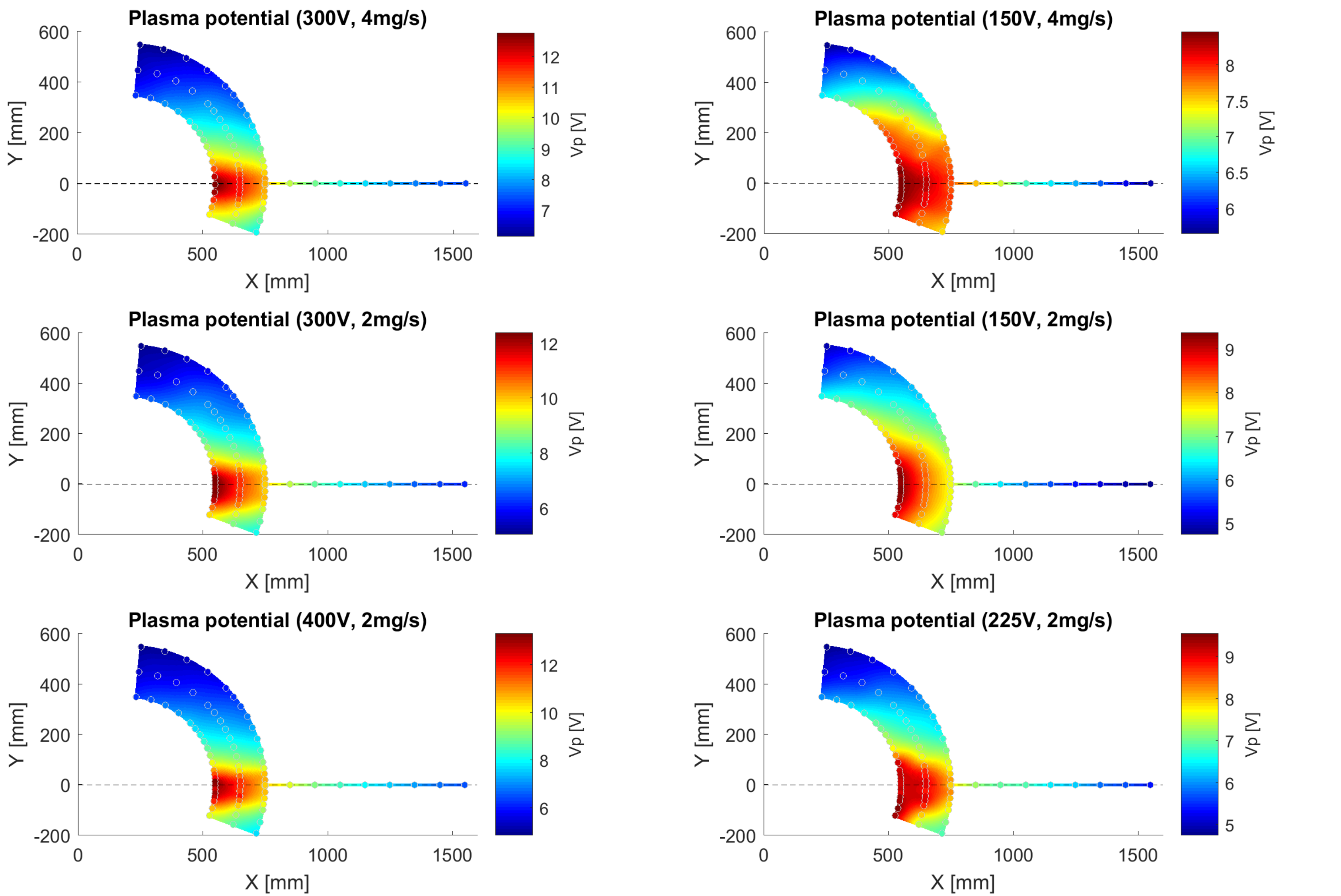
Shape of the plume was less collimated at 150 V due to a different current oscillation mode.

Maps: 150 V, 4 mg/s

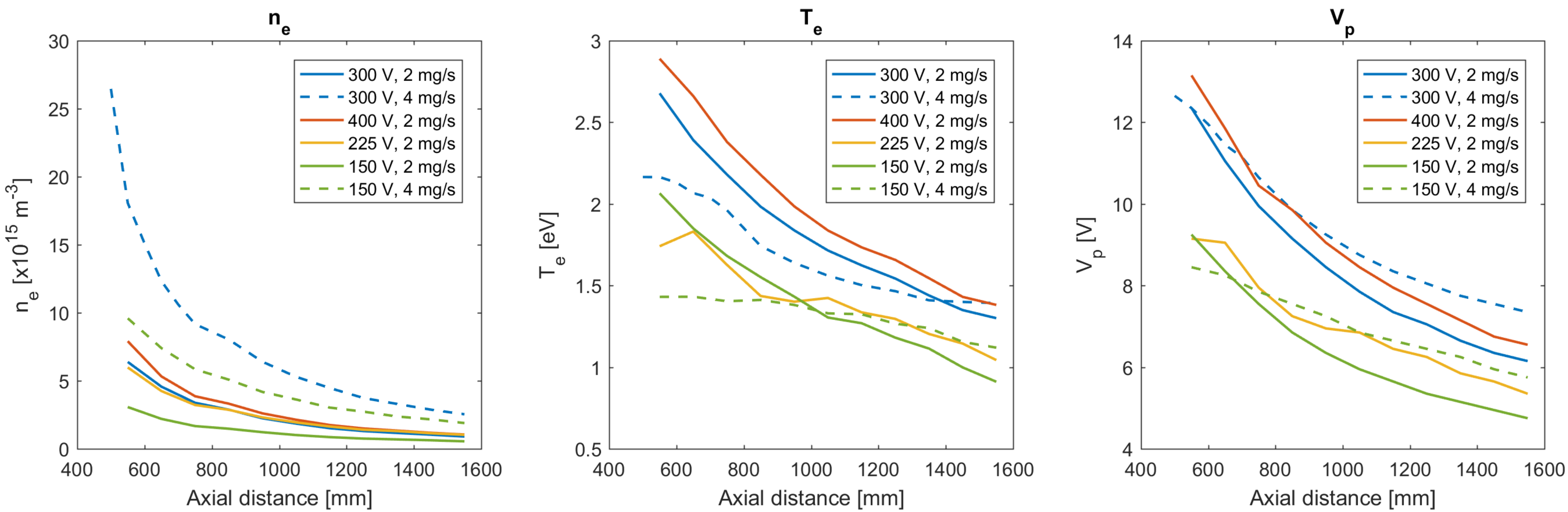


Integrated T_e is less consistent due to a larger measurement noise at this operating point.

Maps: Plasma potential



Plasma parameters along the plume (IV fitting)



- Electron density x3-5 when mass flow rate x2, and slight linear dependency on discharge voltage.
- Electron temperature decreases with mass flow rate increase, and increases with discharge voltage.
- Plasma potential slightly increases with both discharge and mass flow rate increase. Change of mass flow rate also changes the shape of the axial dependency.

Ratio of specific heats γ

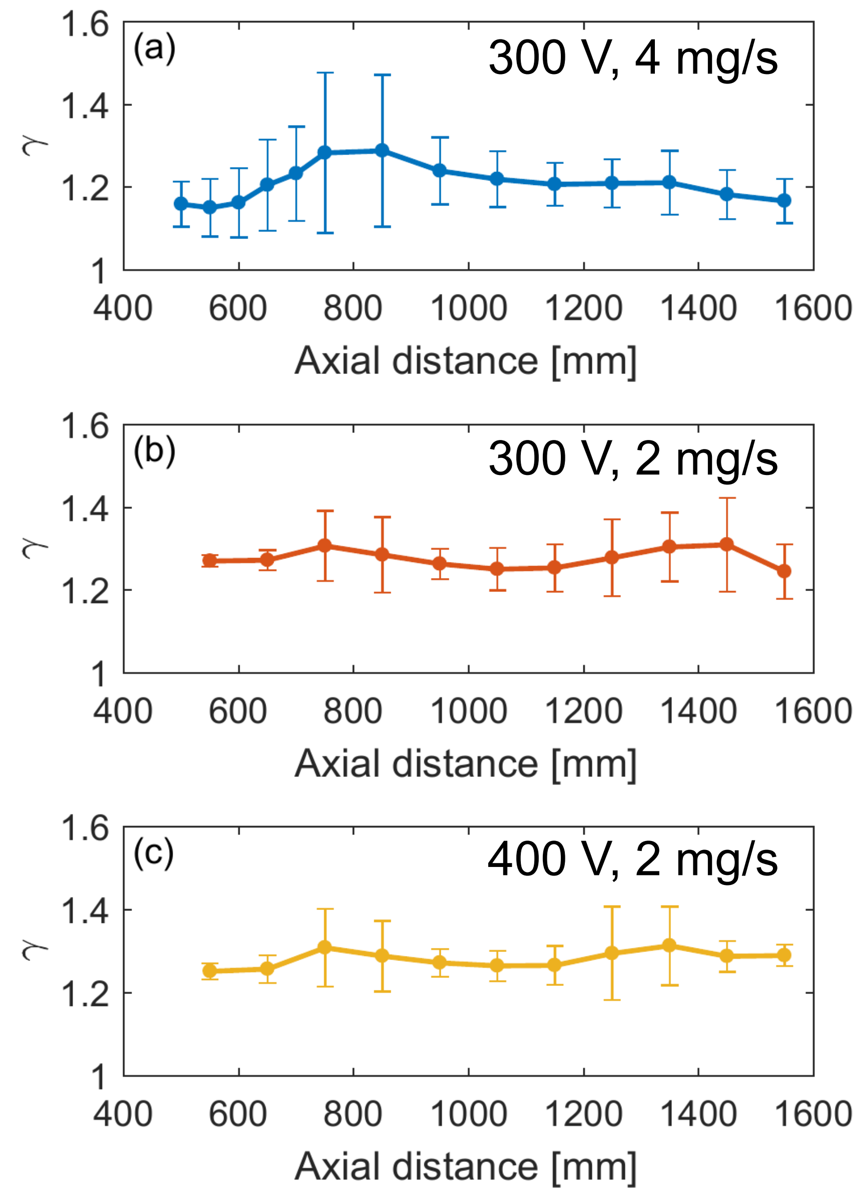
The ratio of specific heats relates the electron density and temperature as:

$$\left(\frac{n_\mathrm{e}}{n_\mathrm{e}^*}\right)^\gamma = \left(\frac{T_\mathrm{e}}{T_\mathrm{e}^*}\right)^{\frac{\gamma}{\gamma-1}}$$

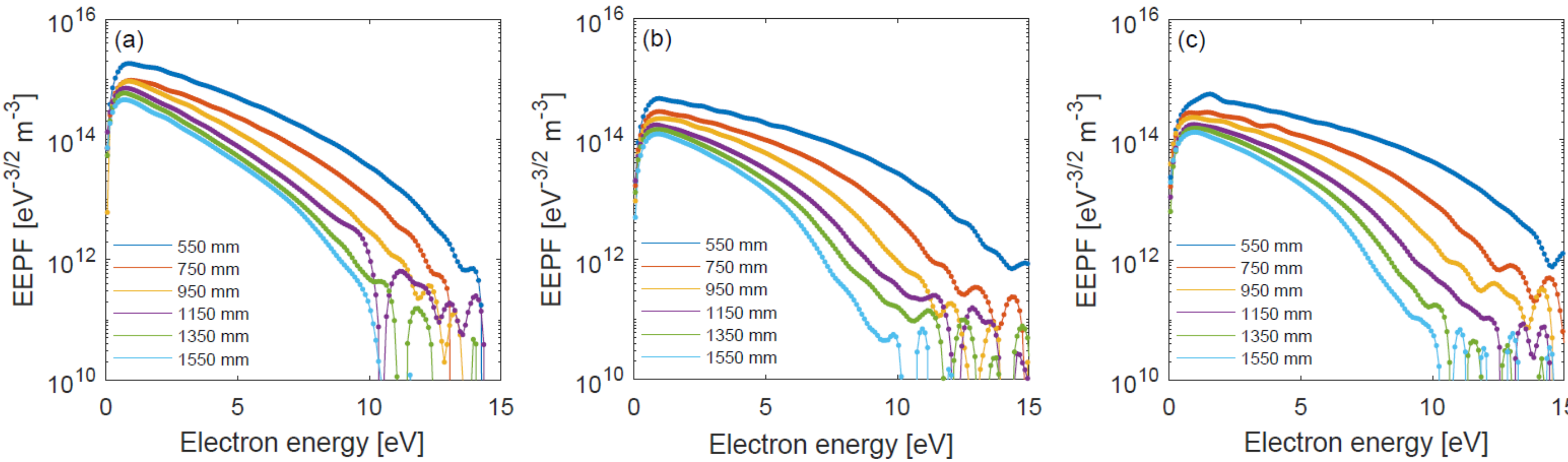
where the both electron density and temperature are normalized at a given location.

The normalization can be made at any point along the plume: γ is the average of the results each point, with error determined as the standard deviation (1-σ).

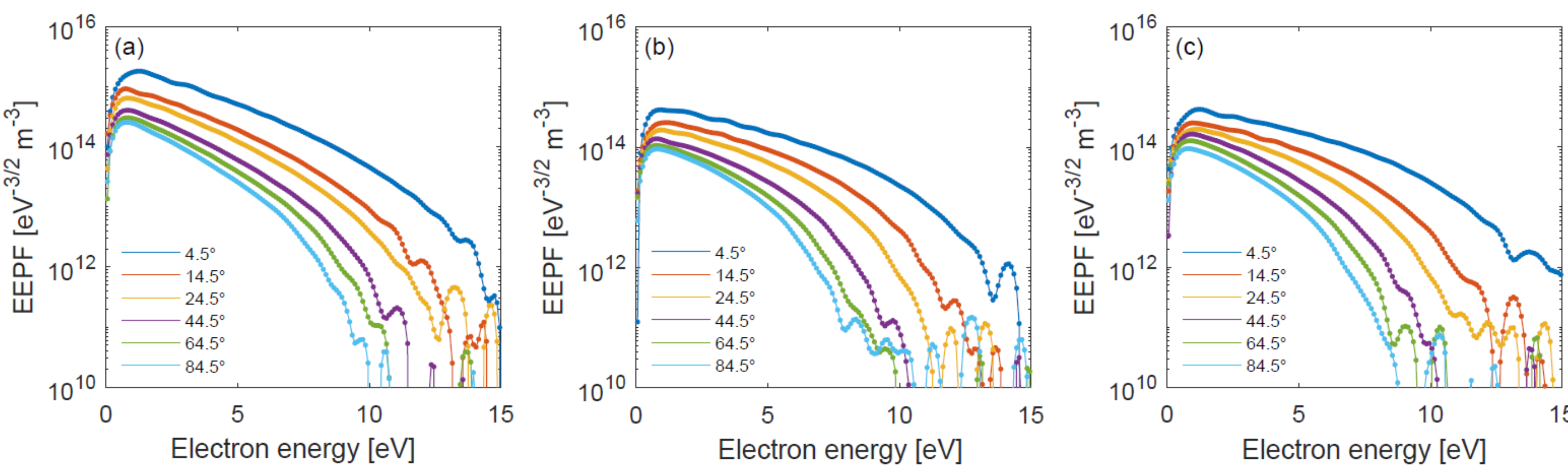
γ values are roughly constant along the plume, with values lower than the adiabatic 5/3 (1.66) value. Hence, the plasma is **not in local thermodynamic equilibrium**. Also, a **larger mass flow rate seems to decrease γ.**



EEPFs



Axial
(a) 300V, 4mg/s
(b) 300V, 2mg/s
(c) 400V, 2mg/s



Angular
(a) 300V, 4mg/s
(b) 300V, 2mg/s
(c) 400V, 2mg/s

Shape of the EEPF (1/2)

A general formulation for the EEPF is:

$$g_{\mathrm{p}}(\mathcal{E}) = n_{\mathrm{e}} \frac{3\alpha}{T_{\mathrm{eff}}^{\frac{3}{2}}} \frac{\left[2\Gamma\left(\frac{5}{2\alpha}\right)\right]^{\frac{3}{2}}}{\left[3\Gamma\left(\frac{3}{2\alpha}\right)\right]^{\frac{5}{2}}} \exp\left\{ -\left[\frac{2\Gamma\left(\frac{5}{2\alpha}\right)}{3\Gamma\left(\frac{3}{2\alpha}\right)} \frac{\mathcal{E}}{T_{\mathrm{eff}}}\right]^{\alpha} \right\}$$

where the exponent α describe the curvature of the EEPF. α=1 is for a Maxwellian distribution whereas α=2 is for a Druyvesteyn distribution.

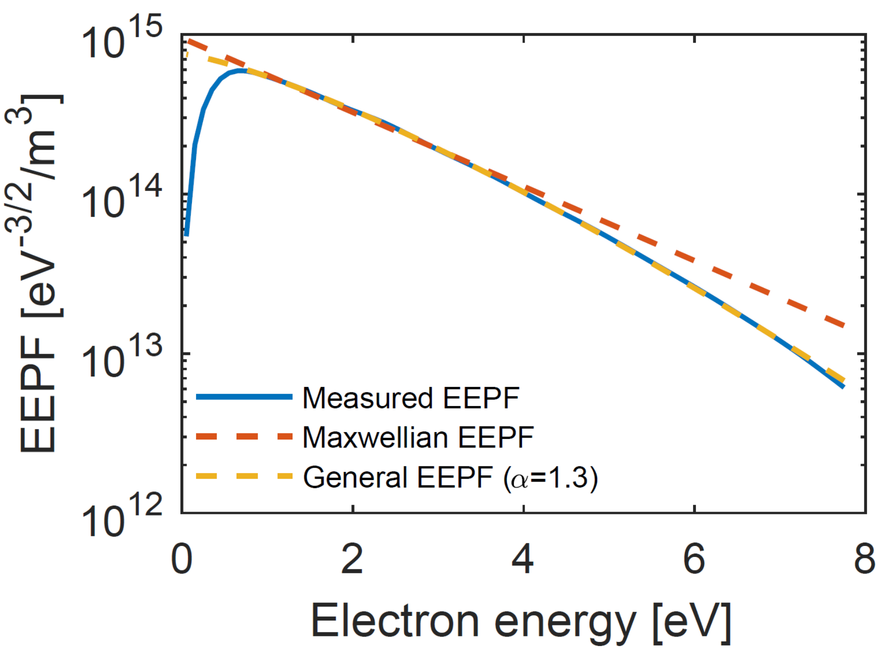
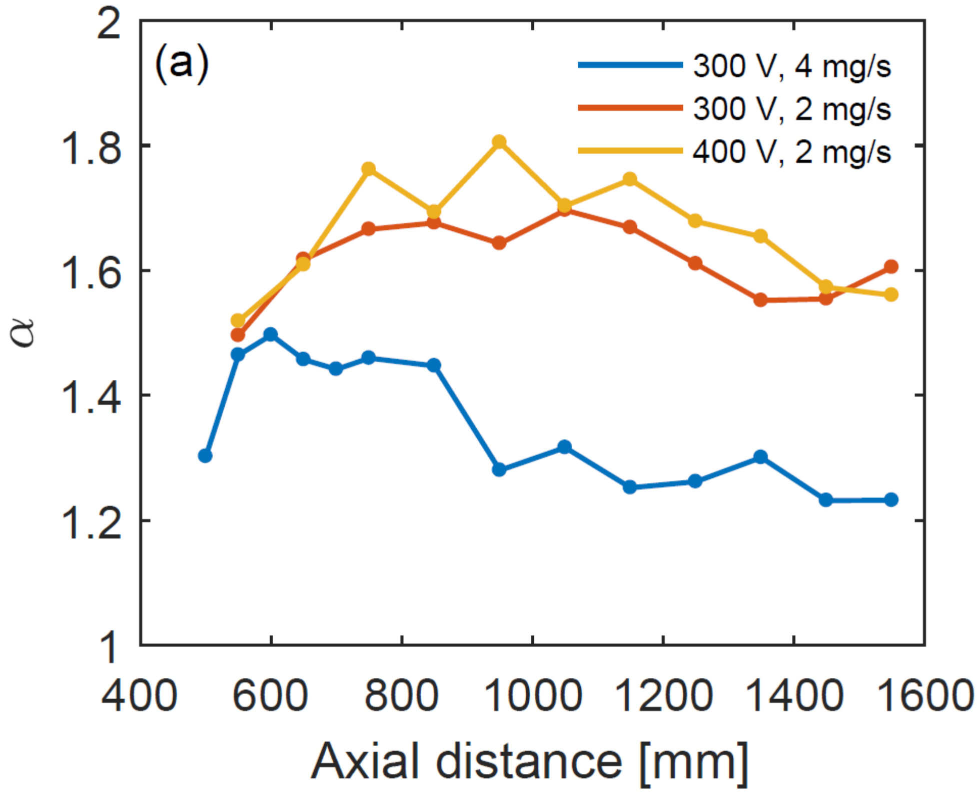


Figure: Example of fitting on the measured EEPF. The measured EEPF are clearly not Maxwellian.

α is a measure of how much high energy electrons are missing (i.e. how low the probability of having high energy electron is compared to the Maxwellian case).

Shape of the EEPF (2/2)

Change of the exponent α along the plume axis (a) and across the angles (b), at 550 mm:



The shape of the distribution seems to be affected by the mass flow rate of the thruster:
Higher mass flow rate brings the distribution closer to a Maxwellian.
Is the shape of the EEPF determined by collision closer to the thruster exit?

More in Giono et. al. (2017), submitted to *Plasma Sources Science and Technology*

Conclusion

Experiment / Data set

- The electron density, electron temperature and plasma potential were successfully measured in the far-plume for six different operating points.
- The EEDFs were successfully obtained for four of these operating points.

Future

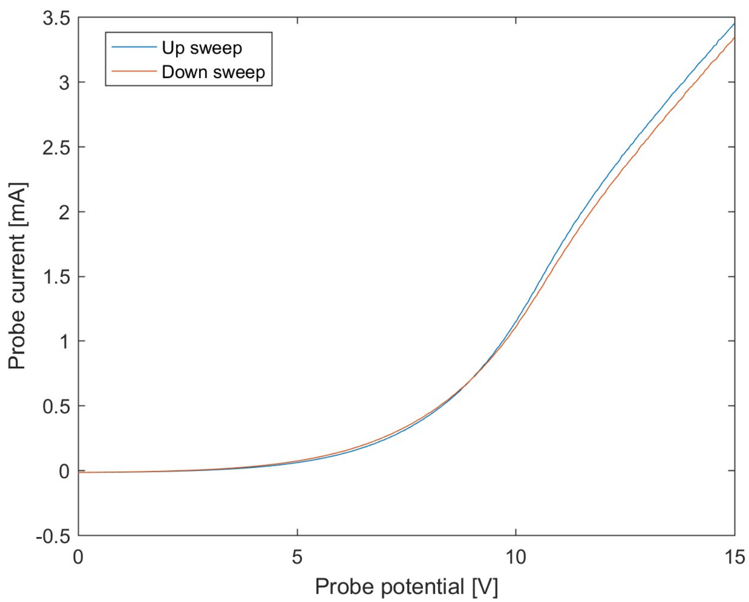
- These measurements will be confronted to simulation in order to improve the models.
- What kind of additional measurements would be needed for improving the simulation/modelling?

Extra slides

Error on the measurement

5 up and 5 down sweeps measurements were taken at the same location to estimate the measurement and hysteresis errors.

	Measurement error	Hysteresis error	RSS	Unit
n_e (IV fitting)	9.88×10^{13}	1.89×10^{14}	2.13×10^{14}	m^{-3}
n_e (EEDF integration)	8.26×10^{13}	2.45×10^{14}	2.58×10^{14}	m^{-3}
T_e (IV fitting)	0.027	0.204	0.206	eV
T_e (EEDF integration)	0.049	0.251	0.256	eV
V_p	0.08	0.30	0.31	V

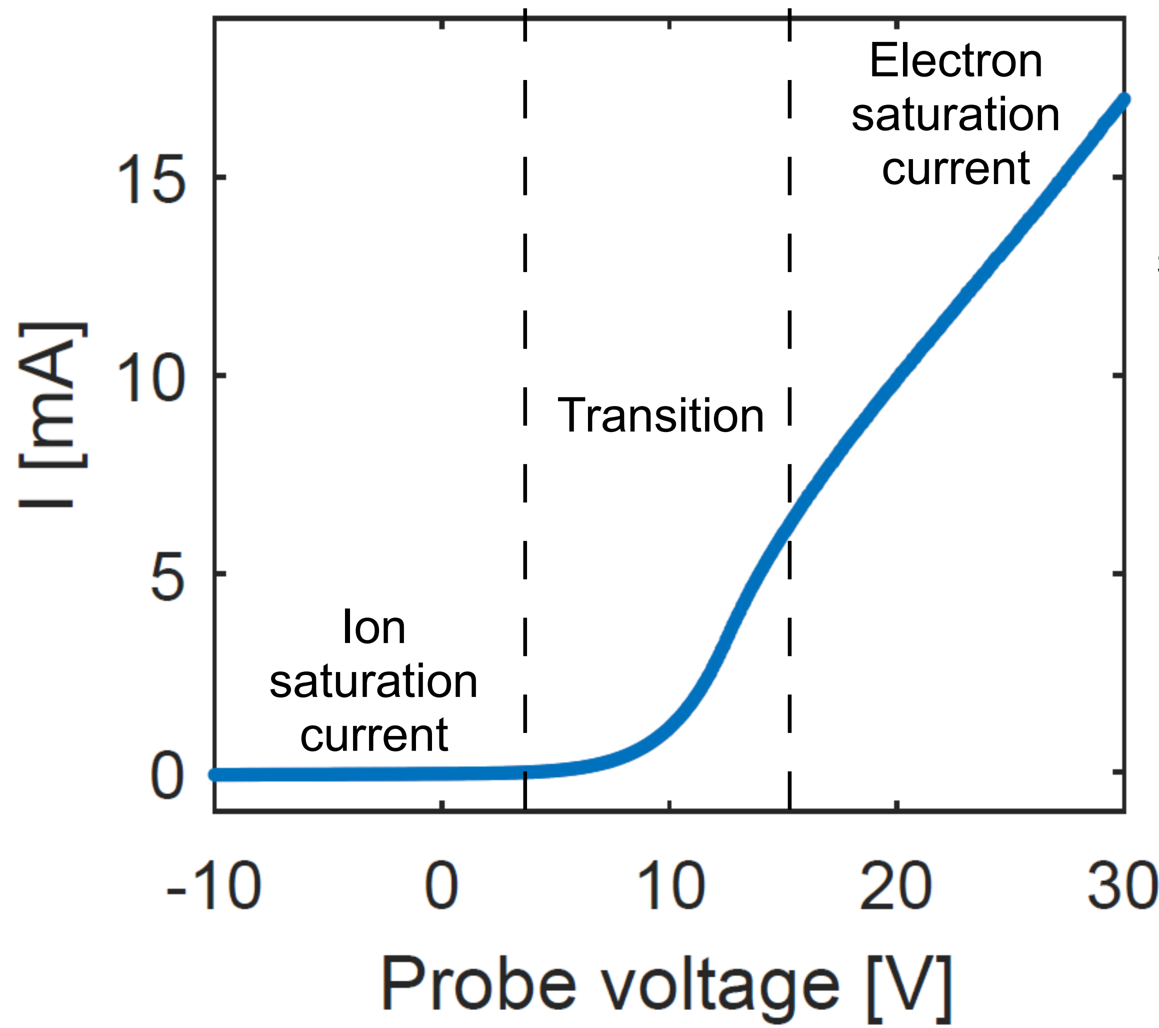


Error on n_e and T_e is about 5%, for both methods.

Error on V_p is about 3%.

Figure: Example of hysteresis

Recorded current-voltage characteristic



Measurements were performed using a Keithley 2440 sourcemeter.

Each IV curve is a single “up” sweep from -15 V to +35 V.

Deriving the plasma parameter (1/2)

- The plasma potential V_p is determined as the maximum of dI/dV (after smoothing with the Blackman window convolution).

- The EEDF is calculated from the d^2I/dV^2 (calculated from the smoothed dI/dV) using the Druyvesteyn formula:

$$g_\mathrm{e}(\mathcal{E}) = \frac{2m_\mathrm{e}}{e^2 A}\sqrt{\frac{2e\mathcal{E}}{m_\mathrm{e}}}\frac{\mathrm{d}^2 I}{\mathrm{d}V^2}$$

- The EEPF is obtained by multiplying the EEDF by the inverse of the square root of the energy:

$$g_\mathrm{p}(\mathcal{E}) = \mathcal{E}^{-1/2} g_\mathrm{e}(\mathcal{E})$$

Deriving the plasma parameter (2/2)

- Two methods were used to get the electron density and temperature:

  - **Fitting on the IV curve**

    T_e from the transition current (I_t) taken from V_p-4 V to V_p, assuming a negligible ion current in the transition region.

$$T_e^{-1} = \frac{d \ln I_t}{dV}$$

    n_e from the electron saturation current squared (I_{es}) taken from V_p to +30V, assuming OML regime.

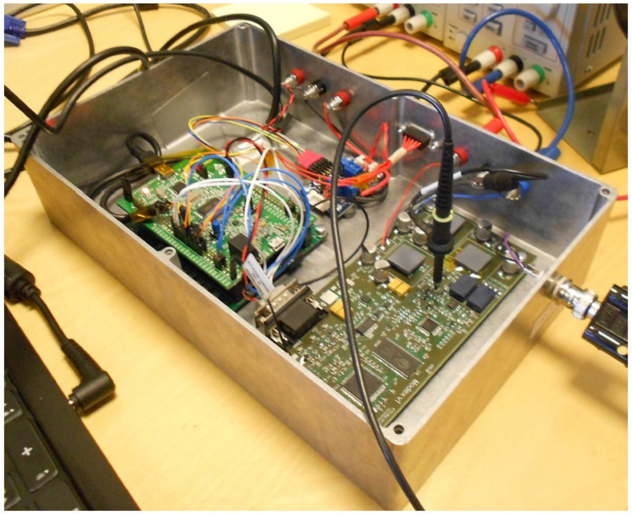
$$n_e = \sqrt{\frac{dI_{es}^2}{dV}} \sqrt{\frac{m_e}{2e}} \frac{\pi}{eA}$$

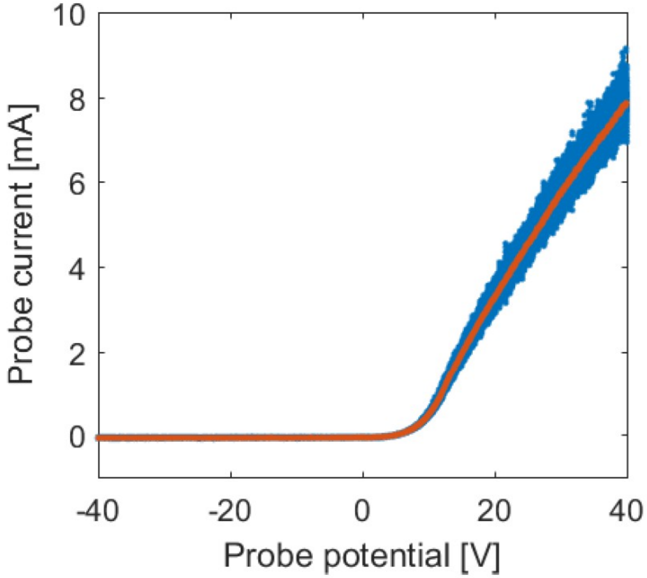
  - **Integrating the EEDF** from 0 to the largest energy recorded, assuming a negligible second derivative of the ion current.

$$n_{\mathrm{e}} = \int g_{\mathrm{e}}(\mathcal{E}) \mathrm{d}\mathcal{E} \qquad T_{\mathrm{eff}} = \frac{2}{3n_{\mathrm{e}}} \int \mathcal{E} g_{\mathrm{e}}(\mathcal{E}) \mathrm{d}\mathcal{E}$$

Comparing with KTH readout electronics (1/2)

A custom read-out electronics was developed by KTH. Measurements were conducted at 300 V and 2 mg/s. Sweeps were taken from -45 to 45 V with a 1.6 mV step, recording multiple up and down sweeps (5x10^5 points per sweeps) in about 10s (Keithley single up sweep from -15 V to 35 V takes 1.5 minutes).
However, the noise was to large for accurate EEDF measurements and the Keithley was used to ensure proper EEDF measurements.





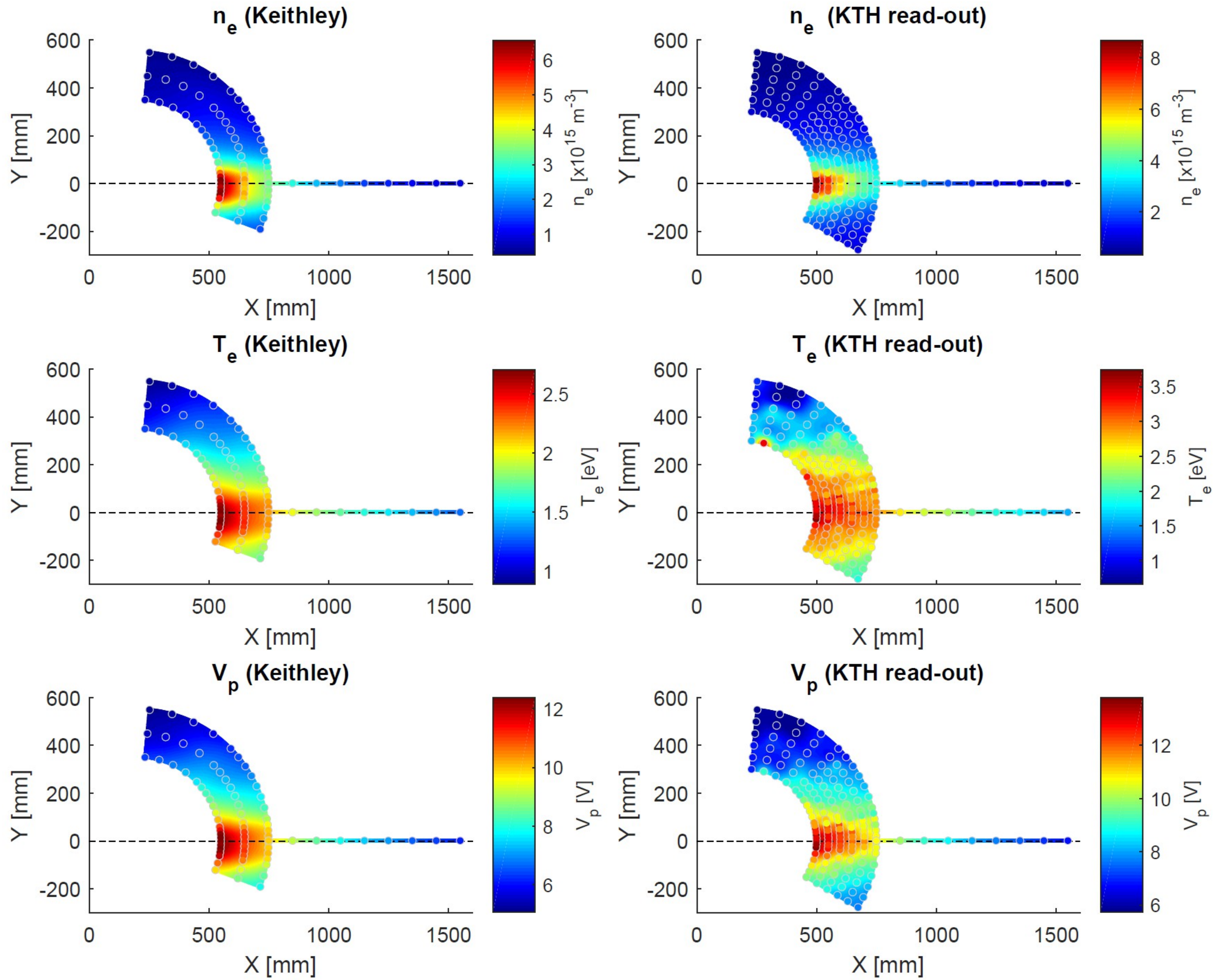
Left: KTH read-out
Right: Raw IV curve (blue) and binned IV curve (red).

The probe voltage was ensured by a 16-bit DAC and the current was recorded using a 16-bit ADC. The sweeps were operated using an FPGA and a STM32 board is used for the user interface/communication.

Comparing with KTH readout electronics (2/2)

Similar results for n_e and V_p.
Larger uncertainty on T_e.

More improvement on the electronics is needed but the performance are encouraging:
- Faster and more flexible system for a very small fraction of the price.



Acknowledgements

This work was performed in the framework of the “Model and Experimental validation of spacecraft thruster Interactions (erosion) for electric propulsion thrusters plumes” (MODEX) project.

MODEX is a collaboration between Airbus-DS, ESA, UC3M, ONERA, CNRS-ICARE and KTH aiming to provide a better understanding of the plasma properties in the far-plume of a Hall thruster. The project aimed at providing experimental measurements to better constrain the modelling, and therefore includes both the theoretical/modelling aspect (UC3M and ONERA) and the experimental aspect (KTH, CNRS, ESA and Airbus-DS). The test campaign was conducted at ESA/ESTEC in April-May 2017, using a SPT-100 Hall thruster provided by Airbus-DS.

The project was partially supported by the Swedish Government Agency for Innovation Systems (VINNOVA) contracts nos. 2014-0478 and 2016-04094.