

Spatially Resolved Momentum Flux Measurements for Thruster Plume Diagnostics

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Abstract: This paper reports on our new realization of a force and simultaneously current measuring probe for ion, plasma and gas beams with spatial resolution. First measurements have been performed in an ion beam experiment based on a three-grid electron cyclotron resonance ion source. Inside a 530-liter test chamber a two axes movable measurement platform carries simultaneously the force probe together with a Faraday cup and an emissive probe enabling axial and radial scans inside the plume.

Nomenclature

r	= radial distance to the axis of the ion source
z	= axial distance to the ion source
$p_{chamber}$	= target chamber pressure
U_{anode}	= anode voltage of the ion source
U_{grid}	= outer (accelerator) grid potential of the ion source
U_{pp1}	= plasma potential in the ion source (measured relative to the walls)
U_{pp2}	= plasma potential in the vacuum chamber (measured relative to the walls)
E_{ion}	= beam ion energy
F_{beam}	= force acting on the target of the force probe
p_{beam}	= beam pressure onto the target of the force probe
I_{beam}	= current onto the target of the force probe
j_{beam}	= current density onto the target of the force probe resp. collector of the Faraday cup

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I. Introduction

Neutral particles in the plume of an electric propulsion thruster can arise from various reasons. There is always a small fraction of cold neutral gas that unintentionally leaves the thruster. The speed of such gas molecules is relatively small in comparison to the electrostatically accelerated ions and, therefore, this neutral component does not contribute much to the momentum flux in the plume and the thrust. More important for the momentum fluxes are collisions, especially charge-exchange collisions between accelerated plume ions and neutral gas. This neutral gas could be the above mentioned not ionized propellant from the thruster itself or, in space, stem from the atmosphere in low earth orbits. Test chambers are unavoidably contaminated with neutral propellant gas that originates from the beam dump and chamber walls where the plume ions recombine. Powerful cryo pumps and traps can reduce this contamination, but do not eliminate it completely. Consequently, the collisions transfer is a part of the ion momentum to the neutral gas.

For spatially resolved plume characterization, commonly electrostatic diagnostics (i.e. Faraday cups and retarding field analyzers) are used. However, these diagnostics are not able to detect the energetic neutrals and, therefore, a calculation of thrust from measurements with electrostatic diagnostics implies significant uncertainties due to the described effects. Thrust balances [1,2,3], on the other hand, measure the 'real' and total thrust, but their construction might be a challenge in case of thrusters in the μN -range. With the standard equipment, i.e. thrust balance and electrostatic probes, one encounters this complementarity: one measures the thrust (integrated momentum flux) or the spatial distribution of the related momentum flux in uncertain quantities.

This contribution describes a technique which allows a spatially resolved momentum flux measurement including all momentum carrying plume components. We present the second version of the galvanometric force probe [4] based on the principle of force compensation with the option to measure currents simultaneously. The diagnostic is operated in a recently built 530-liter test chamber together with a three-grid electron-cyclotron resonance microwave ion source. The pressure in the target chamber is about 4×10^{-2} Pa, which is quite high in comparison to common thruster test chambers, in order to enhance the momentum transfer between beam ions and neutral background gas. A two axes movable measurement platform carries simultaneously the force probe, a Faraday probe and an emissive probe, and allows radial and axial scans of the plume.

II. Experimental Setup

A. Horizontal Ion Beam Experiment (HIBEX)

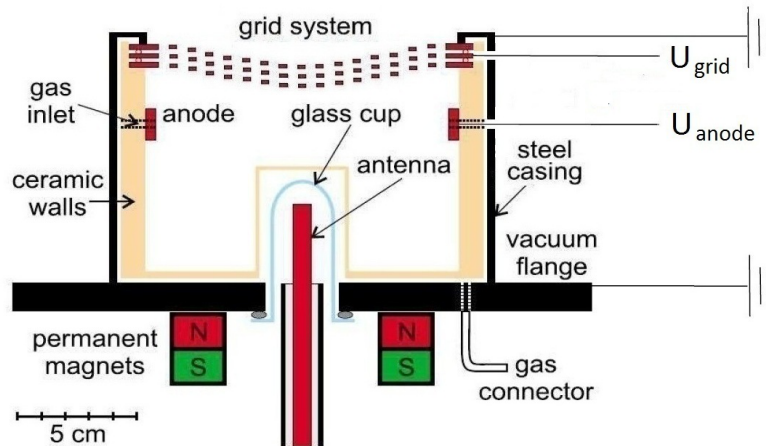


Figure 1. Electron cyclotron resonance ion source with a spherically curved grid system.

The ion beam is generated by a three-grid broad beam ion source (fig. 1) with a functional principle comparable to [5]. An argon plasma is produced by microwaves and electron cyclotron resonance. Permanent magnets provide the magnetic field, and an antenna emits approximately 360 W of 2.4 GHz microwaves

through a quartz cup into the source chamber. Three spherically curved molybdenum grids with a curvature with a radius of 300 mm extract, accelerate and focus the ion beam. The inner (extraction) grid is floating, the middle (accelerator) grid potential is $U_{grid} = -300$ V and the outer (decelerator) grid is grounded throughout this paper. An anode ring in the ceramic source chamber allows to shift the potential of the source plasma by means of the voltage $U_{anode} = +(0 \dots 1400)$ V to corresponding positive potentials $U_{anode} + U_{pp1}$. Measurements with cylindrical Langmuir probes revealed an anode sheath potential drop in the range of $U_{pp1} = +(60 \pm 10)$ V.

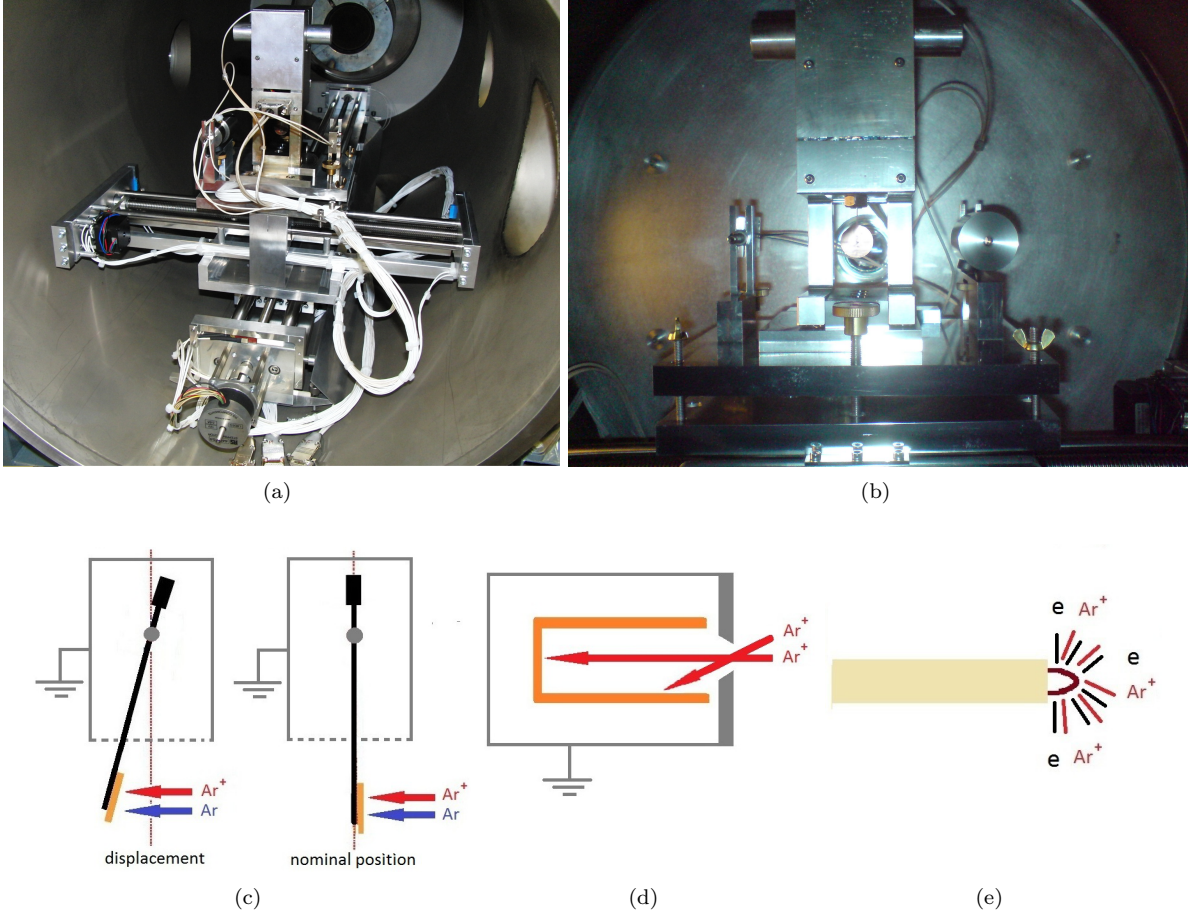


Figure 2. (a) View into the vacuum chamber in direction of the source: axial and radial carriage unit, measurement platform with probes, source grid in the background. (b) View in the opposite direction onto emissive probe's wire loop (left), force probe's target (middle), Faraday cup's outer casing with aperture (right) on the measurement platform, beam dump in the background. (c) Sketch of the force probe with target. (d) Sketch of the Faraday cup with collector. (e) Sketch of the emissive probe with wire loop.

The vacuum chamber is basically a stainless steel cylinder with an inner diameter of 65 cm and a length of 160 cm. The pressure in the target chamber is 4×10^{-2} Pa. The ion beam leaves the source, passes the vacuum chamber horizontally above the carriage unit (fig. 2a) and ends after a length of approximately 140 cm at the opposed beam dump. The plasma potential U_{pp2} in the target chamber at $U_{anode} = 1200$ V was measured radially and axially with an emissive probe and is found to be in the range of $U_{pp2} = +(37 \pm 8)$ V. The energy of the beam ions $E_{ion} = e(U_{anode} + U_{pp1} - U_{pp2})$ results from the potential drop between source and target plasma.

B. Measurement platform with force probe, Faraday cup, and emissive probe

The measurement platform (fig. 2) carries three types of supplementary probes: In this case, the novel galvanometric force probe, a Faraday cup, and an emissive probe are mounted on the measurement platform. A two axes carriage unit allows radial and axial scans of the plume, particularly, measurements with each

probe at same positions are possible.

The new galvanometric force probe enables simultaneous measurements of both momentum fluxes and currents onto the same target. It is based on a pendulum with a target and a counter weight on the other side of the pendulum axis (fig. 2c). Momentum fluxes onto the target with a diameter of 20 mm lead to a displacement of the pendulum. An active galvanometric force compensation drives the pendulum back to the vertical nominal position. This compensation is recorded as a measure for the exerted momentum flux onto the target. Simultaneously, the current onto the target in the nominal position of the pendulum is detected.

The Faraday cup (fig. 2d) consists of an outer hollow cylindric casing of metal with a centric aperture bevelled inwards of 5.7 mm diameter. Inside a hollow cylinder of copper with an inner diameter of 10 mm is open in the direction of the casing aperture and is closed at its rear side. While the outer cylindric casing is grounded in order to repel secondary electrons, the inner cylinder serves as collector. All beam ions passing the aperture should be caught by the collector as well as secondary electrons generated at the collector's inner walls.

The emissive probe (fig. 2e) consists basically of a wire loop of tungsten jutting out of an isolating ceramic tube. By heating the wire loop, thermionic emission of electrons could be induced. The potential of a plasma can be determined by searching for the balance of ion and electron flows between wire loop and plasma. The floating potential of the wire loop coincides with the plasma potential for an appropriate wire temperature [6].

III. Spatially resolved plume diagnostic

In the following spatially resolved measurements of momentum fluxes and currents performed with the force probe and Faraday cup are presented. Scanning at different axial and radial positions enables to record an intersecting surface of the plume, especially to compare the measurements of both probes.

A. Radial-axial measurements

Spatially resolved measurements of momentum fluxes (fig. 3a) and currents (fig. 3b) along a radial-axial surface of ($r = -120 \dots +120$ mm, $z = 460 \dots 1260$ mm) intersecting the beam of $U_{anode} = 1200$ V are performed. Both measurements were performed simultaneously with the force probe on the same target. The plots in figure 3 show that the currents decrease distinctly faster than the corresponding momentum fluxes for increasing axial distances from the source. In contrast, the radial profiles are alike (disregarding the absolute height). This can be explained by the variable composition of the beam that changes only in axial direction [7]. While the current considers the ionic part only, the momentum flux represents both ionic and neutral components of the beam.

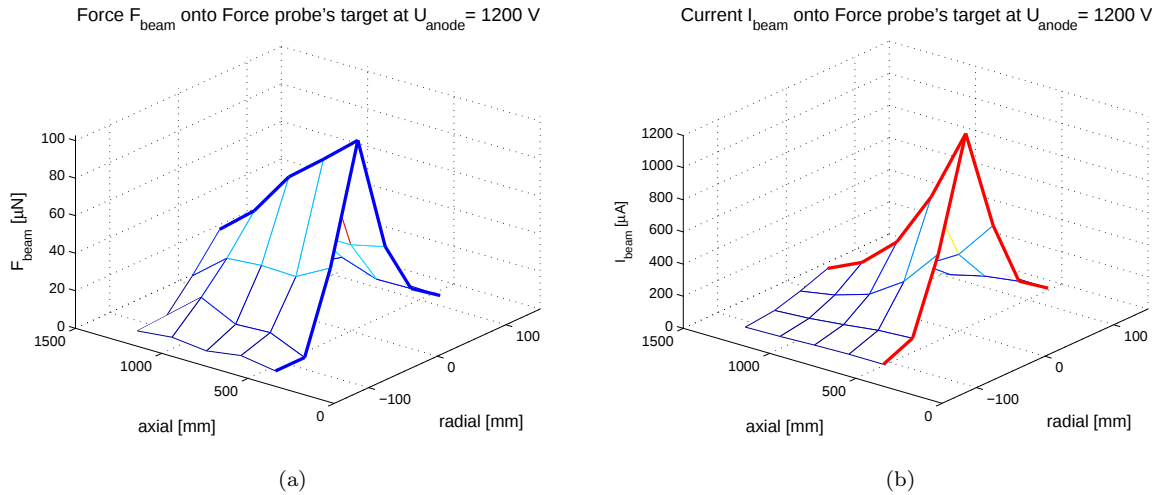


Figure 3. Radial-axial measurements with the force probe. (a) Force onto the target, (b) current onto the same target.

In figure 4 the measurements are normalized to the area of the force probe's target intended to compare with the Faraday cup measurements. In figure 4a the beam pressure onto the force probe's target and in figure 4b the current densities onto the force probe's target and the Faraday cup's collector are plotted. The Faraday cup measurements were done alternately, because of the spatial separation of force probe and Faraday cup on the measurement platform. In figure 4b both current densities of force probe and Faraday cup are nearly identical.

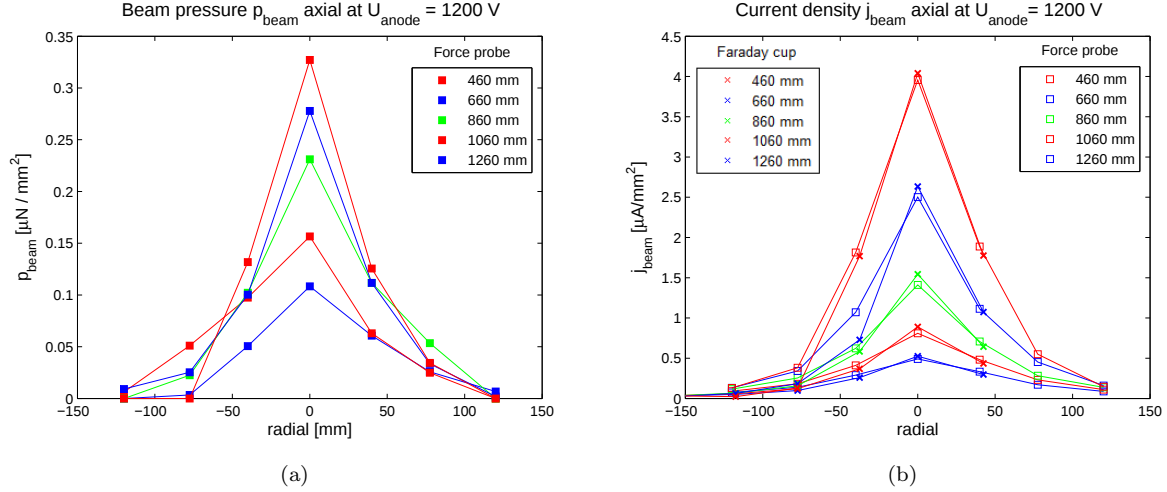


Figure 4. Radial-axial measurements with force probe and Faraday cup. (a) Beam pressure onto the target, (b) current densities onto the same target and onto the Faraday cup's collector at nearly the same positions.

B. Radial energy-dependent measurements

Radial energy-dependent measurements of momentum fluxes and currents from $r = -120$ to $+120$ mm were performed at a fixed axial distance of $z = 460$ mm to the source with $U_{\text{anode}} = 400$ to 1200 V. In figure 5a, the beam pressures onto the force probe's target and in figure 5b the current densities onto the force probe's target and the Faraday cup's collector are plotted. Again measurements at anode voltages up to 1000 V with both probes show almost the same radial current density profiles.

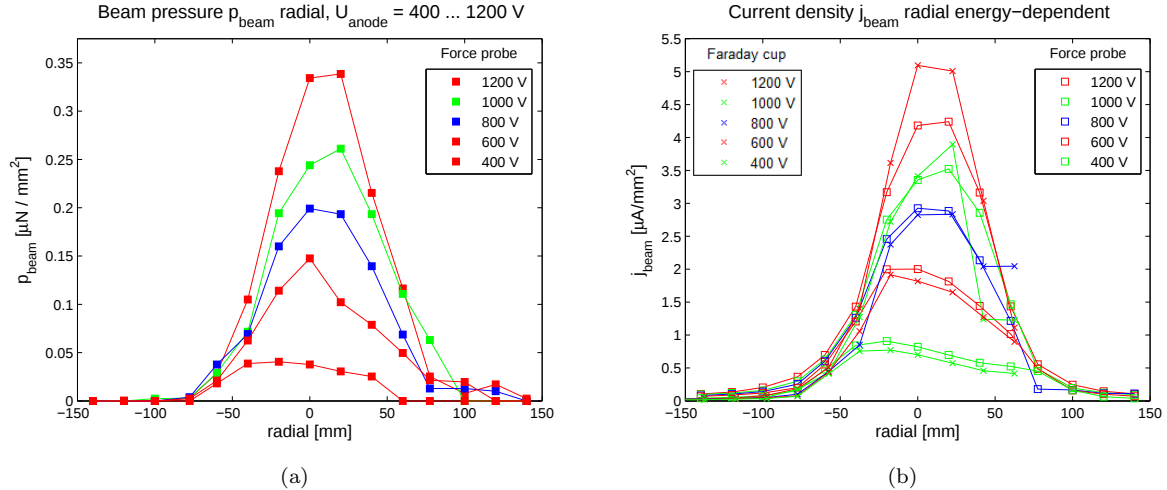


Figure 5. Radial-axial energy-dependent measurement with force probe and Faraday cup. (a) Beam pressure onto the target, (b) current densities onto the same target and onto the Faraday cup's collector at nearly the same positions.

C. Axial energy-dependent measurements

Axial energy-dependent measurements of forces and currents from $z = 460$ to 1260 mm at a fixed radial centered position related to the source ($r = 0$ mm) at $U_{anode} = 400 \dots 1200$ V are performed. As already noticed before, in radial-axial measurements at $U_{anode} = 1200$ V (ch. III.A), the axial decrease of currents is faster compared to the decrease of the forces.

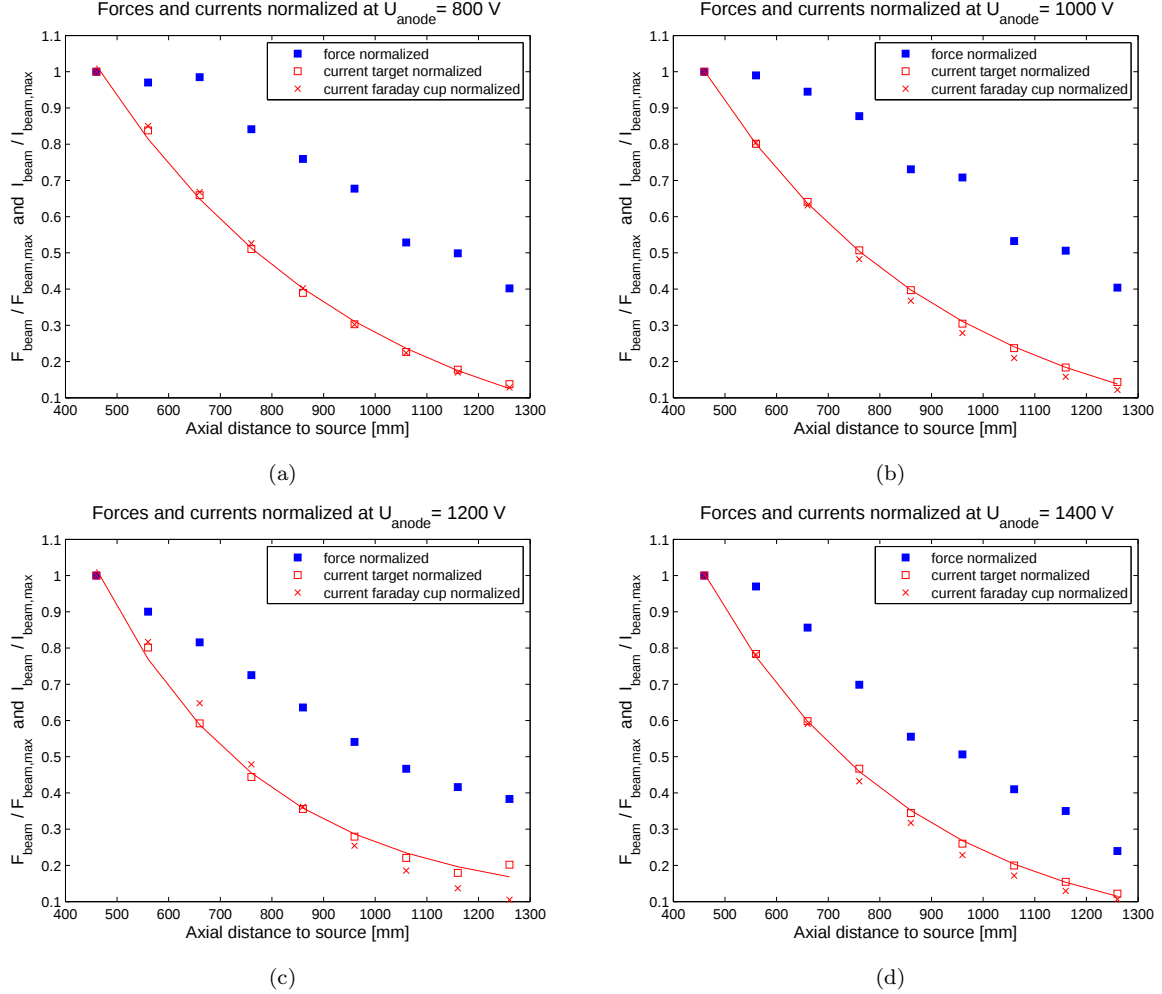


Figure 6. Axial energy-dependent measurements with force probe and Faraday cup at (a) $U_{anode} = 800$ V, (b) $U_{anode} = 1000$ V, (c) $U_{anode} = 1200$ V, and (d) $U_{anode} = 1400$ V

In figure 6 both forces and currents are normalized to their respective maximum values. Apparently, the decrease of currents is higher compared to the forces which were simultaneously measured onto the same target. Especially at $U_{anode} = 1200$ V (fig. 6c) the almost curve linearity of the forces appeared before in the radial-axial force measurement (fig. 3a). Again measurements of current densities with Force probe and Faraday cup show almost the same axial current density profiles.

IV. Conclusion

Development and testing of ion thrusters require sophisticated beam diagnostics and thrust measurements. Especially charge-exchange collisions are often neglected with conventional ion beam diagnostics (i.e. Faraday cups and retarding field analyzers). In this contribution, a novel galvanometric force probe with the ability to measure both the and current density simultaneously on the same target has been introduced. Additional measurements with a Faraday cup, mounted on the same measurement platform, were performed. The measured current densities were compared to the Faraday cup measurements, and a very good agree-

ment was found. In comparison to the simultaneously measured momentum fluxes, the current densities show a faster axial decrease due to charge-exchange collisions.

Acknowledgments

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