



Current Density Measurements of an Annular-Geometry Ion Engine

Abstract: The concept of the annular-geometry ion engine, or AGI-Engine, has been shown to have many potential benefits when scaling electric propulsion technologies to higher power. However, the necessary asymmetric location of the discharge cathode away from thruster centerline could potentially lead to non-uniformities in the discharge not present in conventional geometry ion thrusters. In an effort to characterize the degree of this potential non-uniformity, a number of current density measurements were taken on a breadboard AGI-Engine. Fourteen button probes were used to measure the ion current density of the discharge along a perforated electrode that replaced the ion optics during conditions of simulated beam extraction. Three Faraday probes spaced apart in the vertical direction were also used in a separate test to interrogate the plume of the AGI-Engine during true beam extraction. It was determined that both the discharge and the plume of the AGI-Engine are highly uniform, with variations under most conditions limited to $\pm 10\%$ of the average current density in the discharge and $\pm 5\%$ of the average current density in the plume. Beam flatness parameter measured 30 mm from the ion optics ranged from 0.85 – 0.95, and overall uniformity was shown to generally increase with increasing discharge and beam currents. These measurements indicate that the plasma is highly uniform despite the asymmetric location of the discharge cathode.



Current Density Measurements of an Annular-Geometry Ion Engine

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Presentation Outline

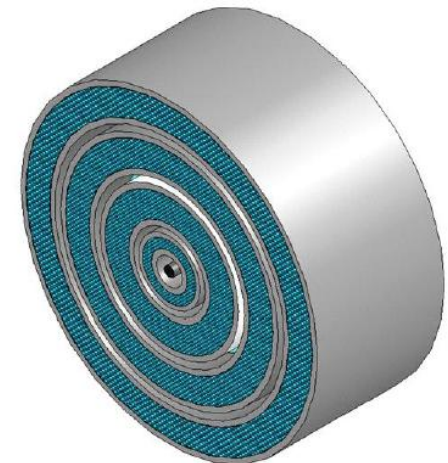


- Background and motivation
- Experimental setup
 - Description of test article
 - Phase 1 – discharge chamber measurements with simulated beam extraction
 - Phase 2 – plume measurements with true beam extraction
- Phase 1 Results
 - Representative current density profiles
 - Calculated non-uniformity
 - Effects of main mass flow rate
- Phase 2 Results
 - Representative current density profiles
 - Variation in profiles at constant beam current and beam power supply voltage
 - Calculated non-uniformity and flatness parameter
- Conclusions

Background and Motivation

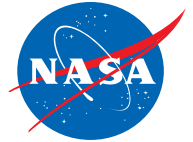


- Annular-geometry ion engines are the core technology for a new concept of electric propulsion thrusters
- Such a geometry has many potential benefits
 - Reduces span-to-gap for large beam areas which facilitates use of flat optics
 - Flat optics allows use of pyrolytic graphite that reduces grid wear and extends thruster lifetime
 - Scalability to higher power and higher current thrusters, with nesting potential between other annular ion thrusters and/or Hall thrusters (hybrids)
- Such geometries require asymmetric location of discharge cathode off thruster centerline, leading to potential plasma non-uniformities
- Current density measurements of the discharge and plume at numerous locations have been made to characterize and quantify this non-uniformity



*Images taken from Patterson, M. J., Herman, D. A., Shastry, R., Vannoord, J. L., and Foster, J. E., "Annular-Geometry Ion Engine: Concept, Development Status, and Preliminary Performance," Presented at the 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA-2012-3798, Atlanta, GA, July 29 - August 1, 2012.

Experimental Setup – Test Article

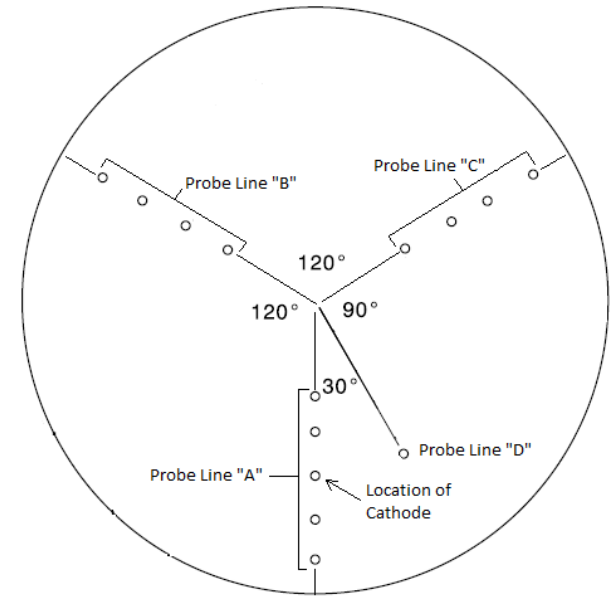


- Testing performed on breadboard annular-geometry ion engine (AGI-Engine)
- Designed in collaboration with the University of Michigan and fabricated at GRC in 2011 using a combination of components originally manufactured for an EM model of NEXT along with components specific for this thruster
- All testing performed within Vacuum Facility 7 at GRC
- Thruster operated with perforated plate in place of ion optics for simulated beam extraction in Phase 1 of study (discharge only)
- Thruster operated with ion optics from EM model of NEXT, with tantalum foil on upstream side of screen grid to mask outer edges and central zone of extraction area

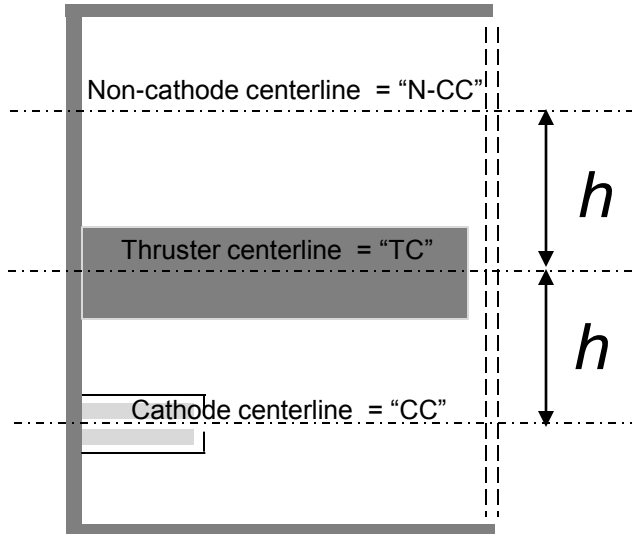
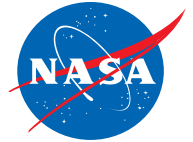
Experimental Setup – Phase 1



- Fourteen button probes were placed within the perforated plate along various radial “lines” and spaced apart azimuthally to interrogate the discharge plasma during conditions of simulated beam extraction
- This layout allowed for determination of mirror symmetry about the thruster mid-plane as well as points sufficiently far away from discharge cathode to assess overall uniformity
- Each button probe was composed of a planar disc of molybdenum 6.4 mm in diameter
- Probe currents was measured using a bank of power resistors that were connected to a power supply which biased the probes 30 V below anode potential
- A total of 11 operating conditions were tested – five of which were from 12 – 19 A discharge current (representative of NEXT throttling table) and six of which were from 24 – 48 A discharge current to test the increased discharge/beam current capabilities of this geometry

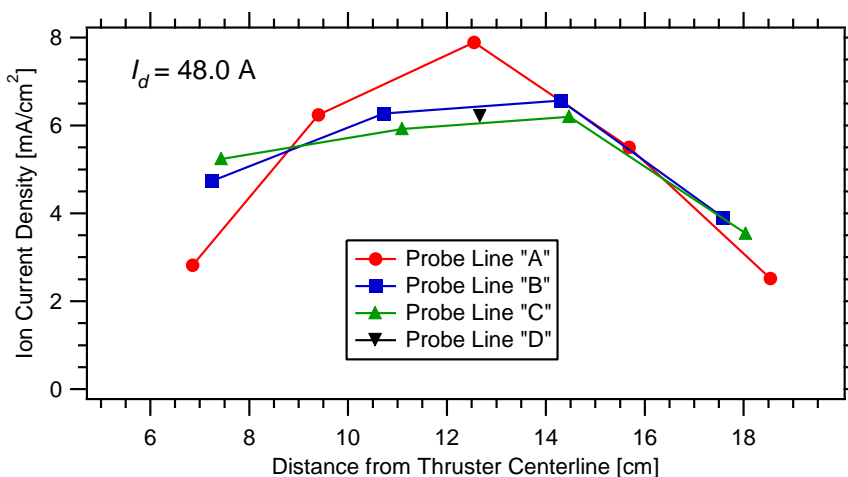
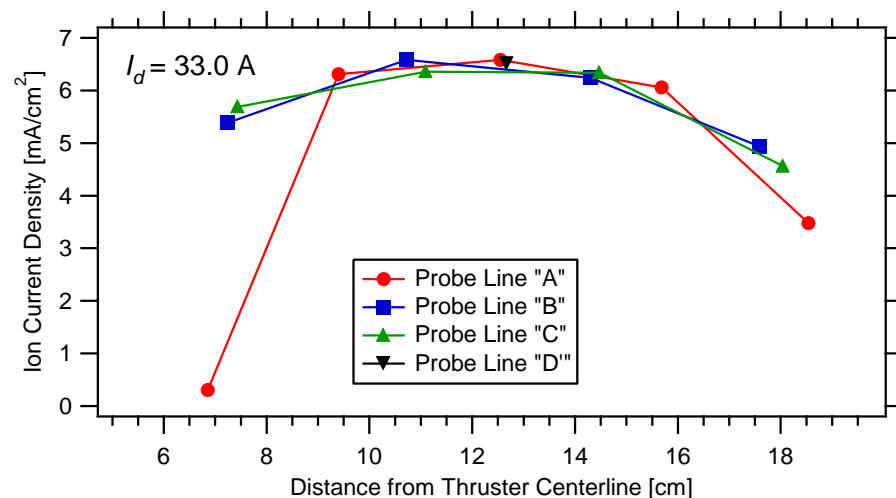
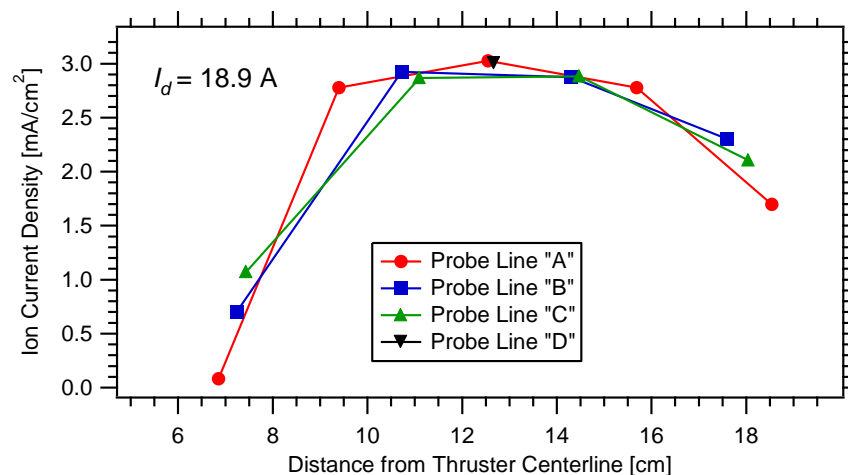
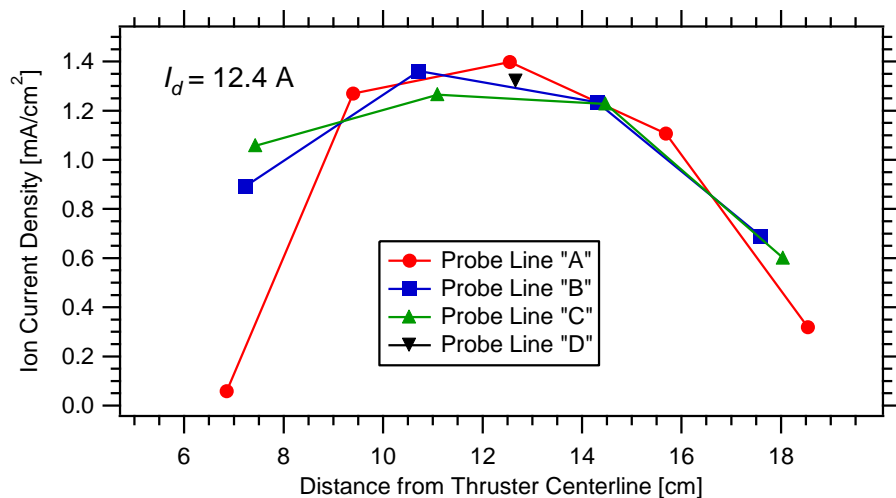
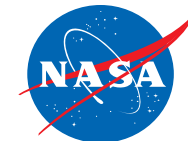


Experimental Setup – Phase 2

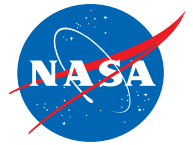


- A vertical probe rake comprised of three Faraday probes was used to measure ion current density in the plume during true beam extraction
- Radial sweeps were taken in three planes: the plane of thruster centerline (TC); the plane of cathode centerline (CC); and the plane of cathode centerline mirrored about thruster centerline, the non-cathode centerline (N-CC)
- Four downstream distances (measured from the geometric center of the optics to the probe along thruster centerline) were used: 30 mm, 500 mm, 850 mm, and 1050 mm from the optics
- Each probe was comprised of a 11.1-mm diameter molybdenum electrode (collector) surrounded by a stainless steel shell (guard ring)
- Probe currents were measured using a power resistor bank connected to a power supply which biased the probes 20 V below facility ground
- A total of 40 operating conditions were characterized, taken from the standard NEXT throttle levels (TL) as well as extended throttle levels (ETL). Beam power supply voltage varied from 275 – 1800 V and beam current varied from 1.00 to 3.52 A

Current Density Profiles– Phase 1

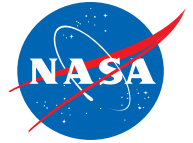


Calculated Non-Uniformity – Phase 1

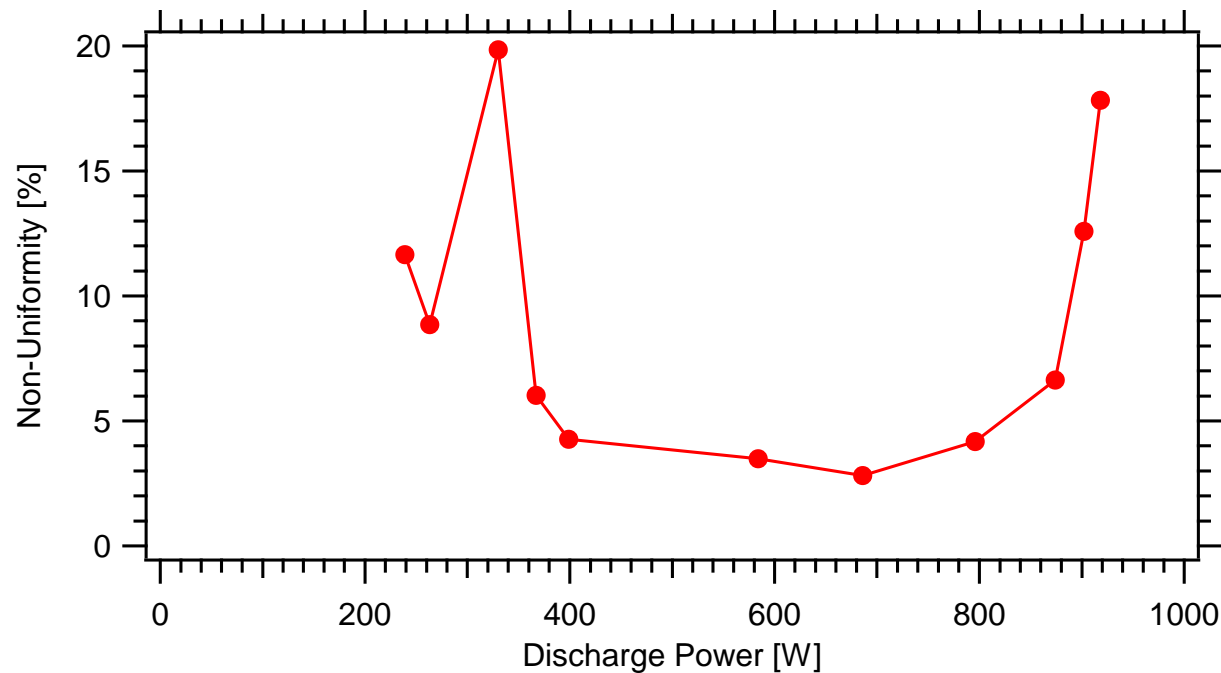


$$\% \text{ Non-Uniformity} = \frac{\frac{j_{b,\max} - j_{b,\min}}{2}}{\frac{j_{b,\max} + j_{b,\min}}{2}} \times 100$$

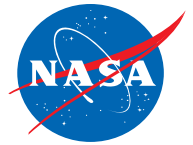
Calculated Non-Uniformity – Phase 1



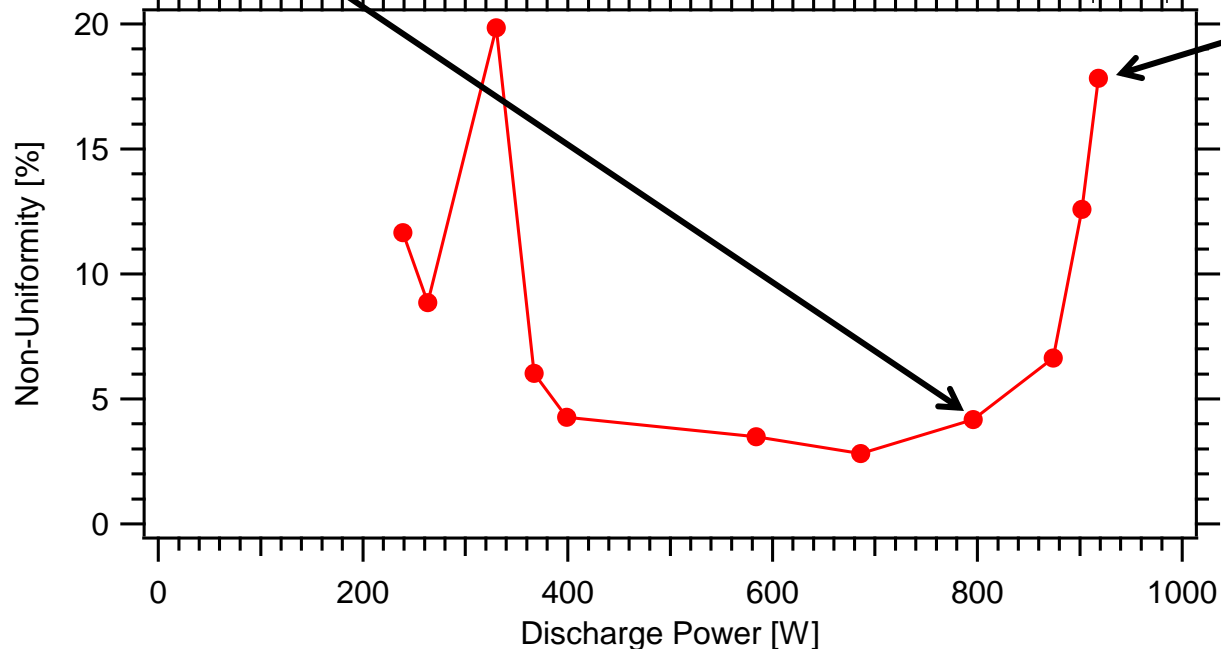
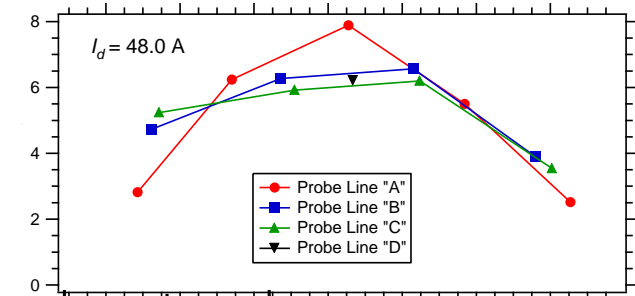
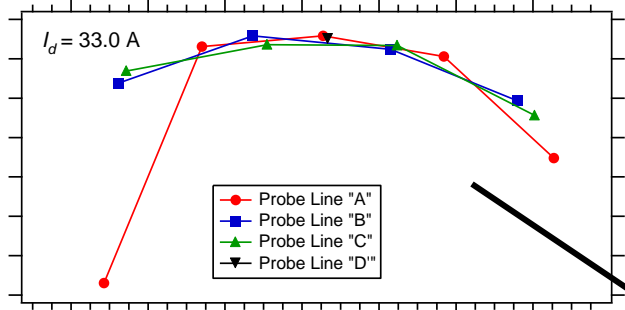
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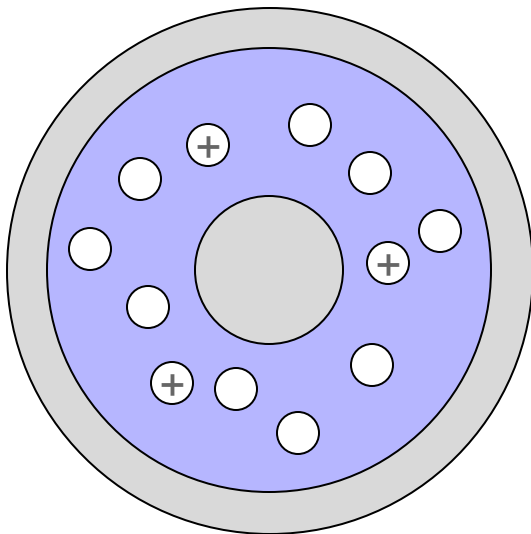
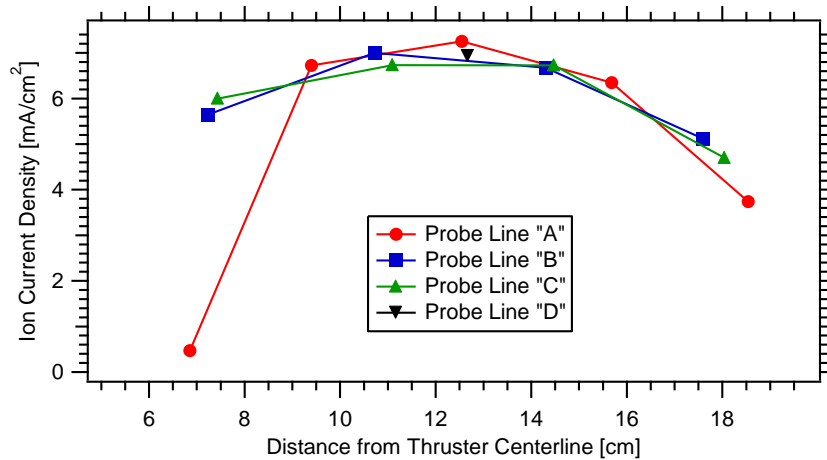
Calculated Non-Uniformity – Phase 1



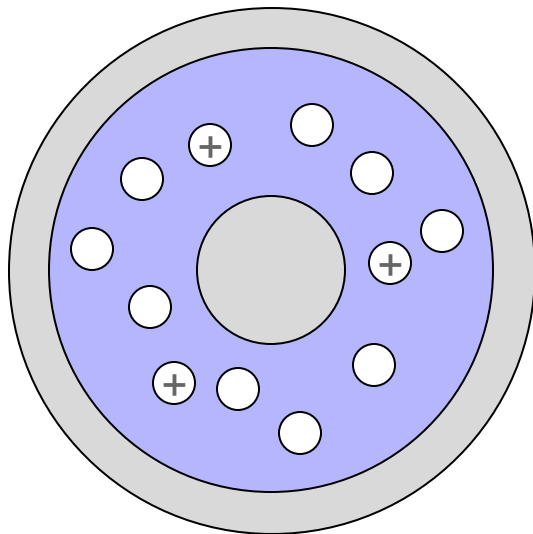
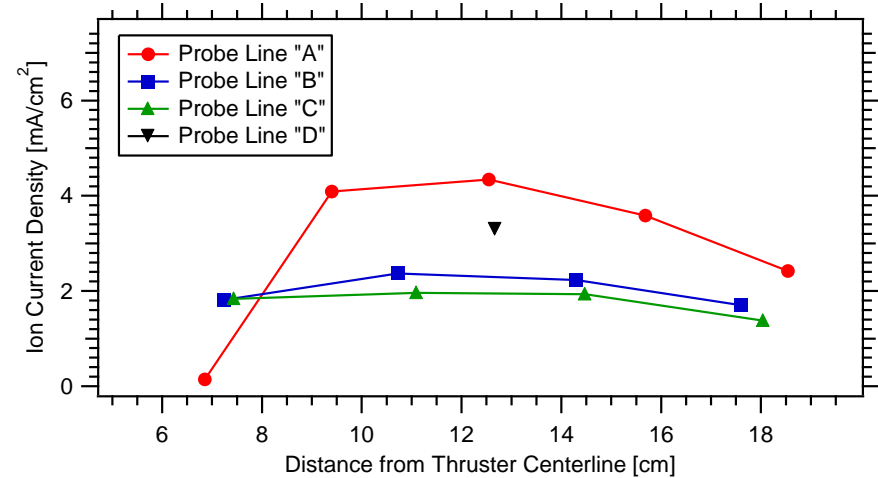
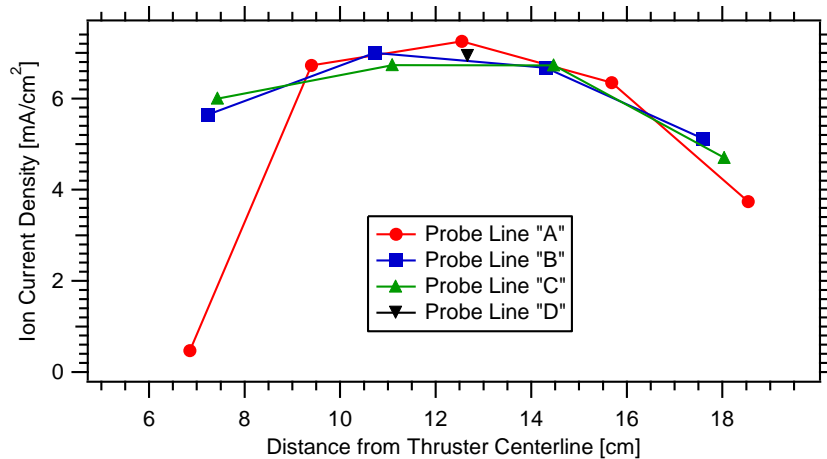
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Effects of Mass Flow Rate – Phase 1



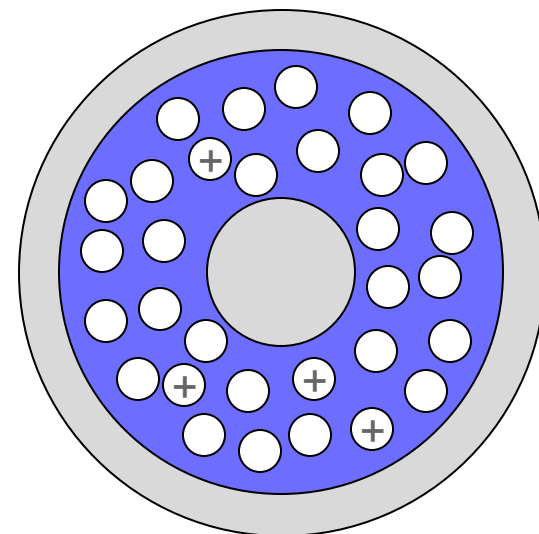
Effects of Mass Flow Rate – Phase 1



Constant I_d

\dot{m}_m ↑

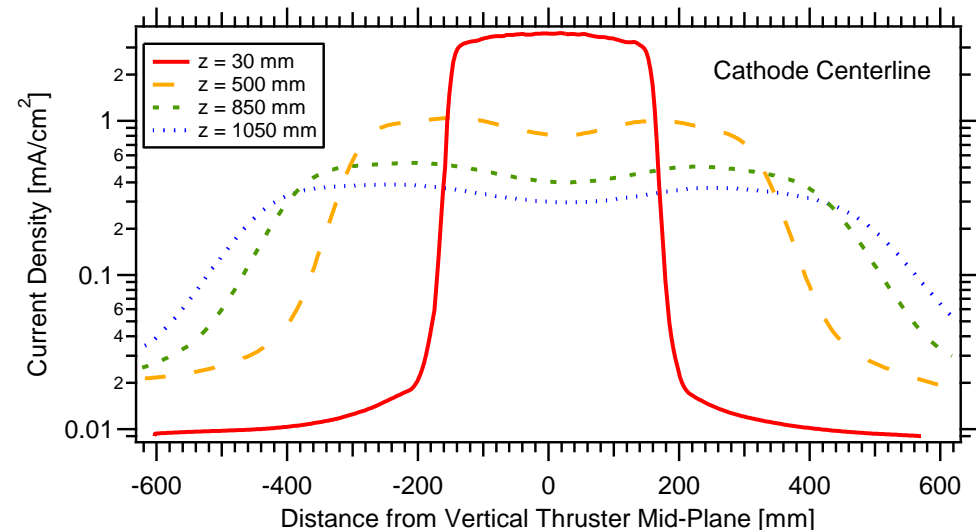
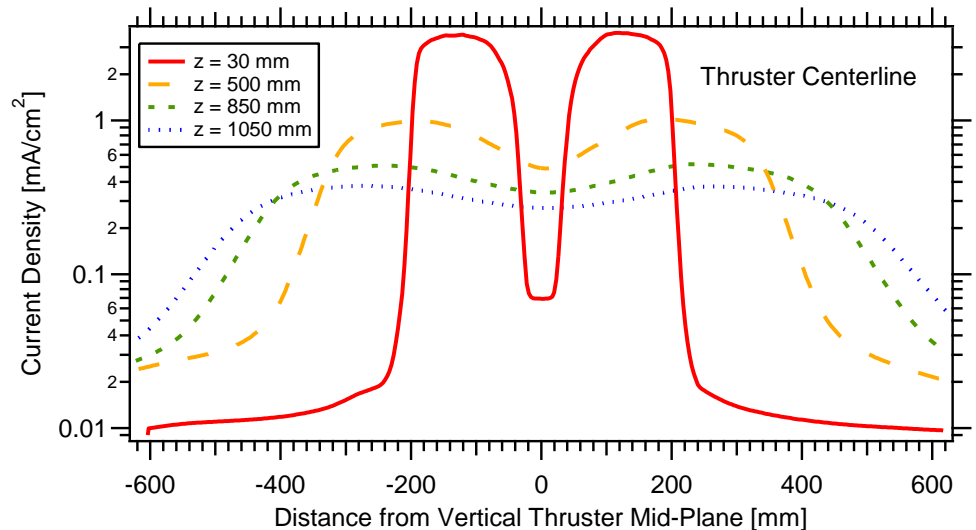
Uniformity ↓



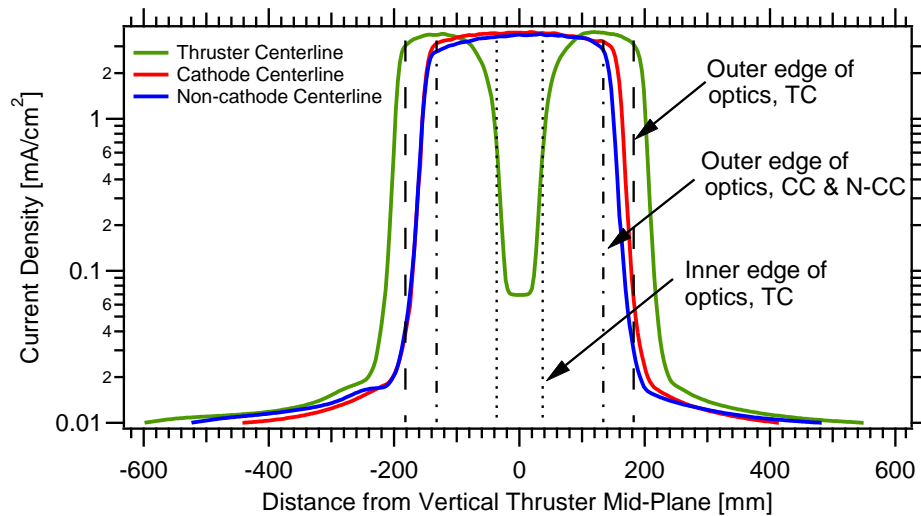
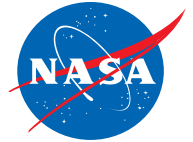
Current Density Profiles – Phase 2



- Representative profiles at $V_b = 1179$ V, $I_b = 3.52$ A
- Double hump structure seen in “TC” profile at $z = 30$ mm from ion optics
- “CC” profile doesn’t pass through central area that is masked, so it contains a flat, single hump structure
- Both profiles flatten and widen as plume expands, with similarity between profiles increasing as downstream distance increases

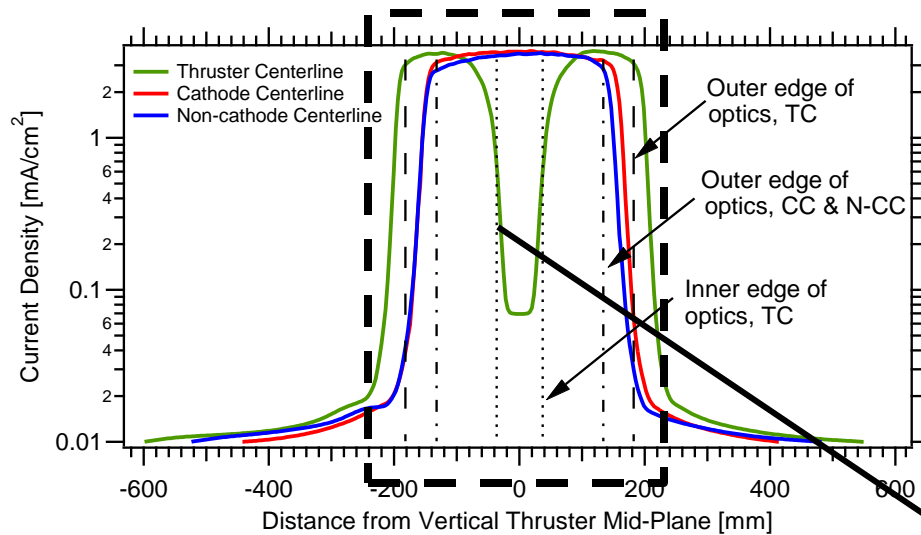


Current Density Profiles – Phase 2



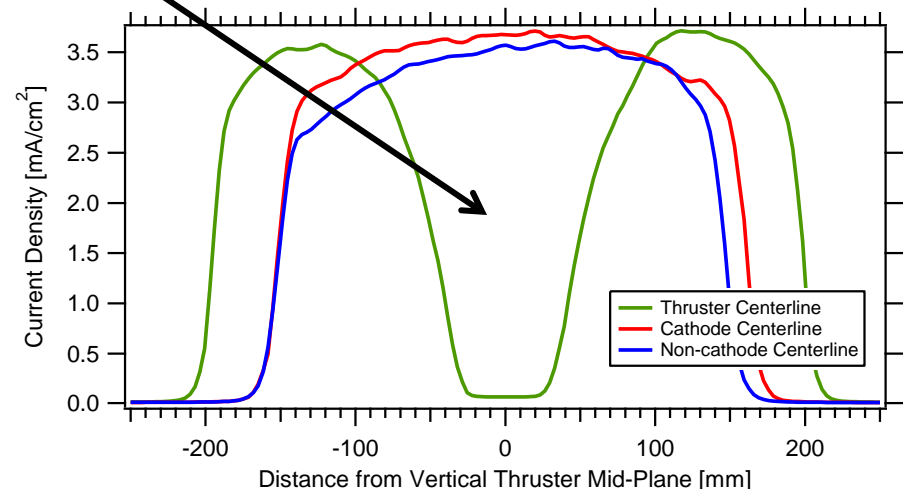
- Sharp dropoffs in current density seen to correlate with radial bounds of ion optics
- Excellent similarity between “CC” and “N-CC” profiles
- Peak current density from all three profiles are very similar, indicating a high degree of azimuthal uniformity

Current Density Profiles – Phase 2

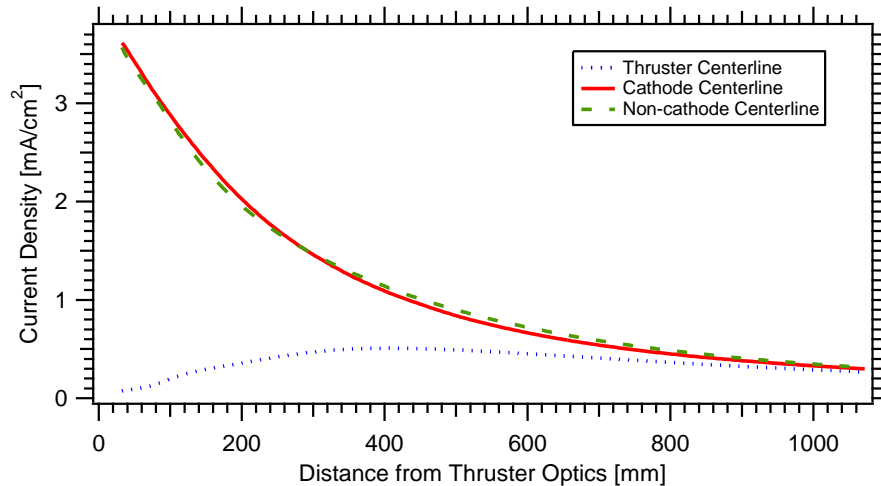


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- Better illustrated on linear scale and zoomed into area downstream of ion optics
- All peak current densities are very close, indicating a high degree of azimuthal uniformity
- “CC” and “N-CC” profiles are very similar, and appear to exhibit a high degree of beam flatness

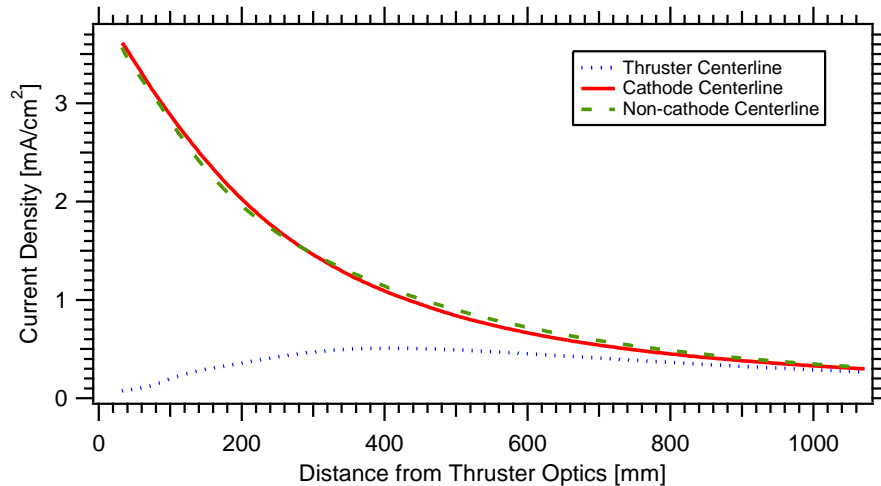
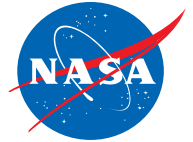


Current Density Profiles – Phase 2

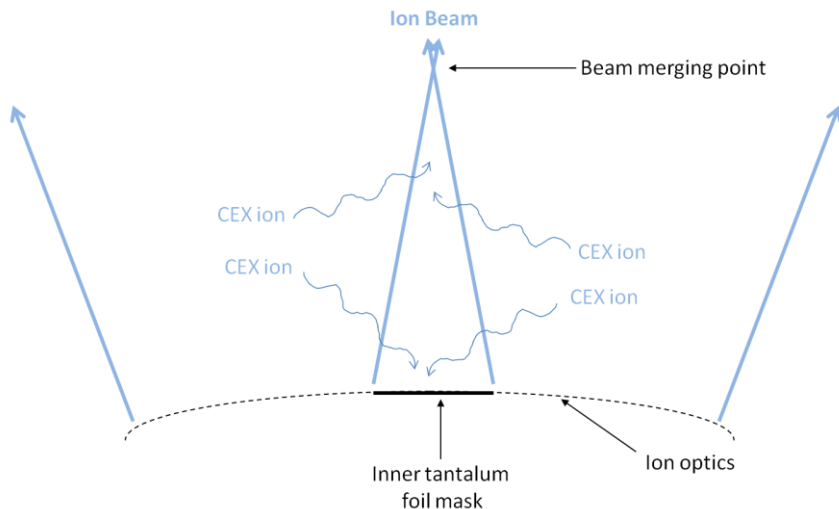


- “CC” and “N-CC” profiles continue to exhibit a high degree of similarity
- “CC” and “N-CC” profiles show exponential decay with downstream distance
- “TC” profile shows an initial increase followed by decay

Current Density Profiles – Phase 2

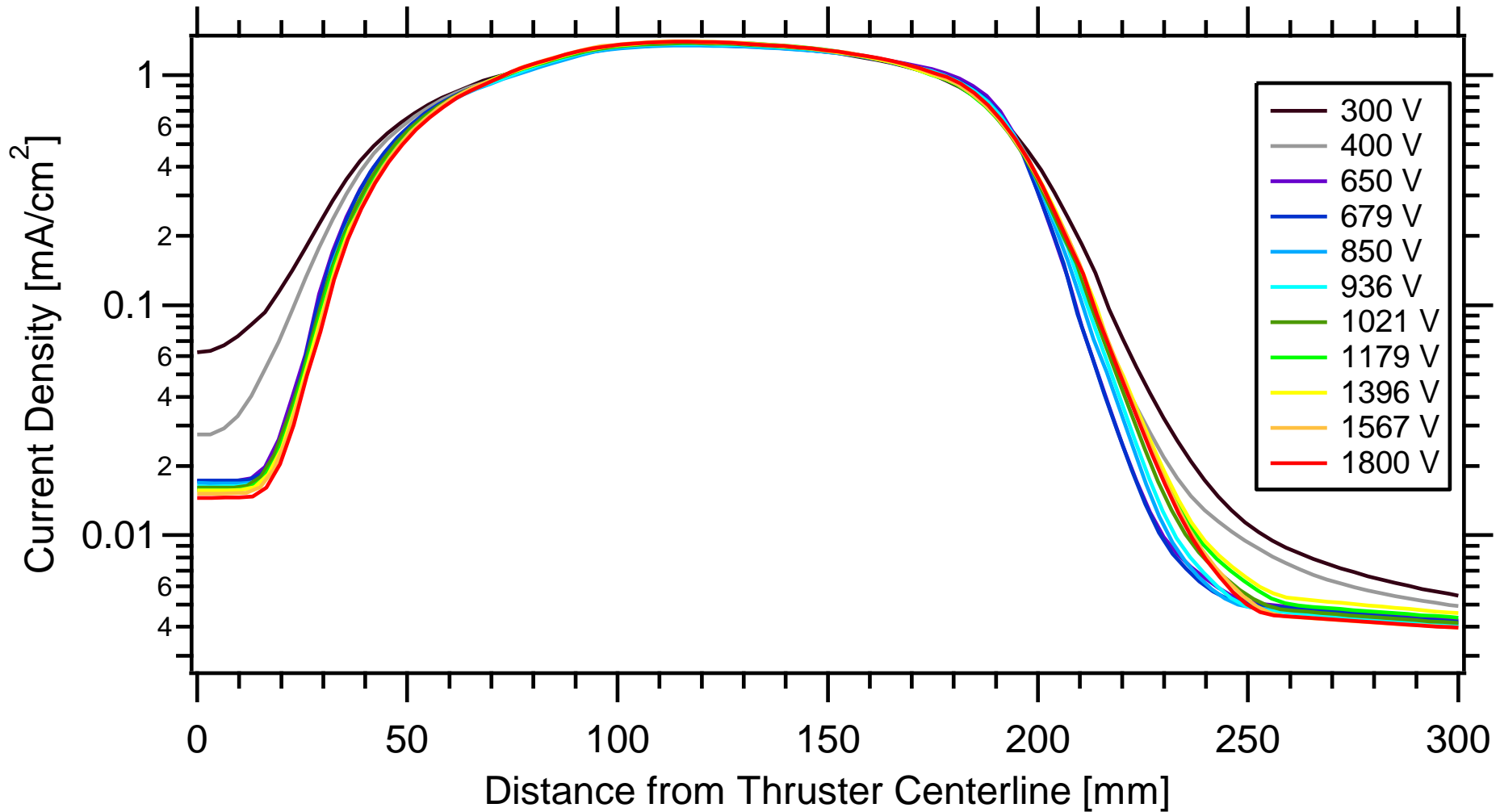


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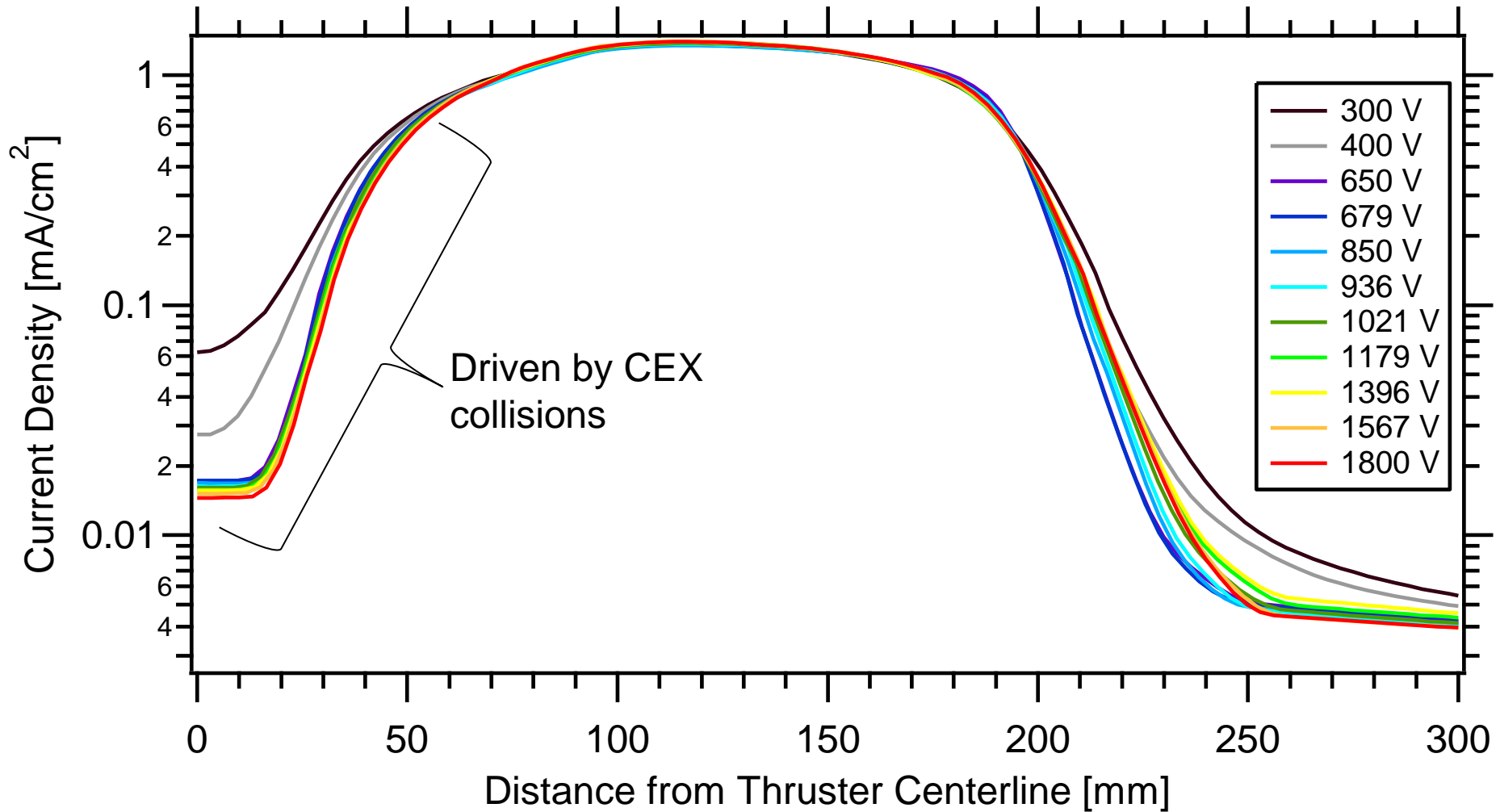
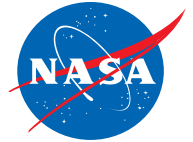


- Initial rise likely due to two sides of beam coming together and merging in the center
- Decay is due to geometric expansion once merging has occurred
- Low density, low potential zone expected along thruster centerline – attracts CEX ions to center, but how they move and what their effect is on the current density is presently unknown

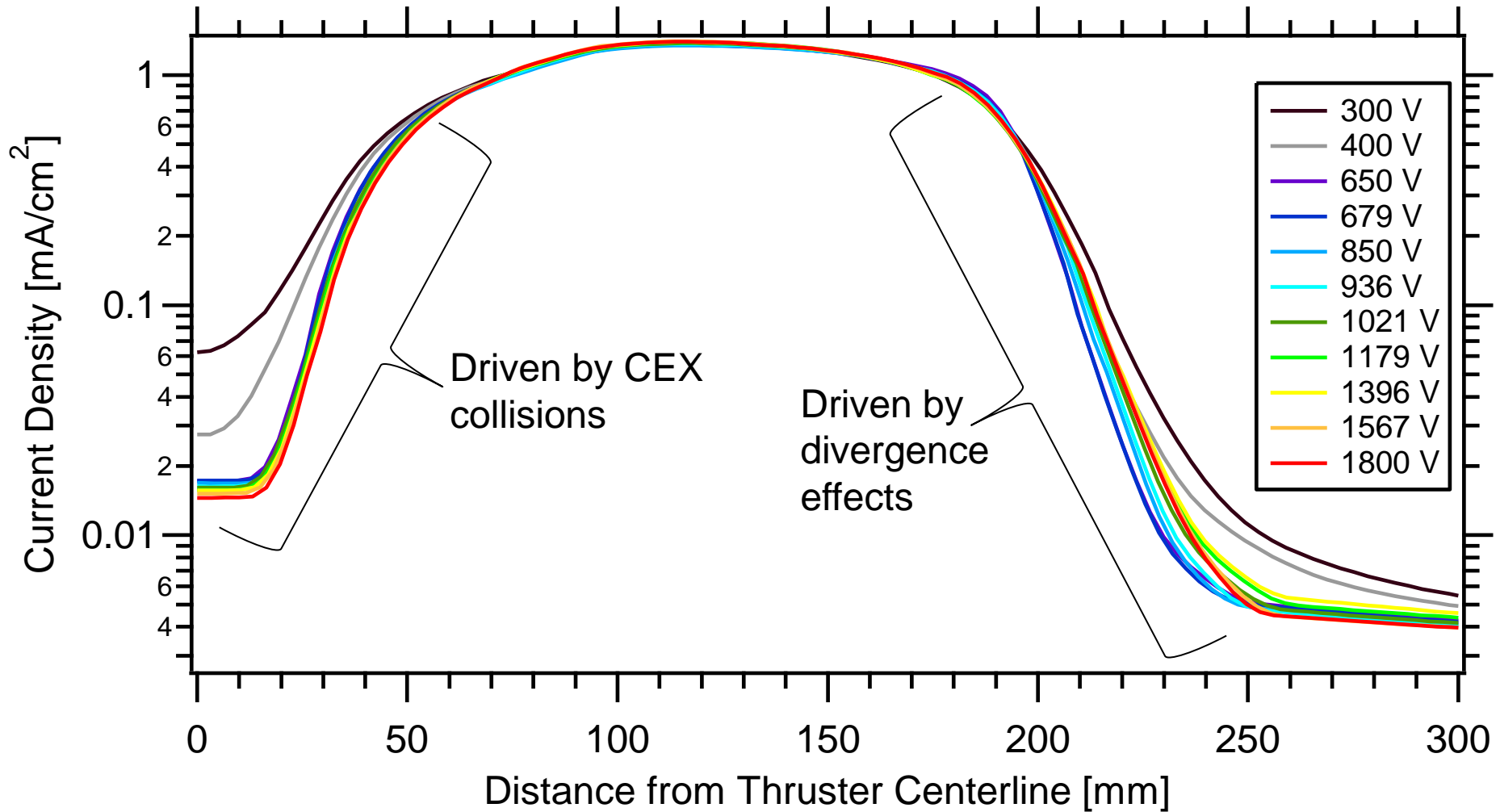
Profiles at Constant $I_b = 1.20$ A



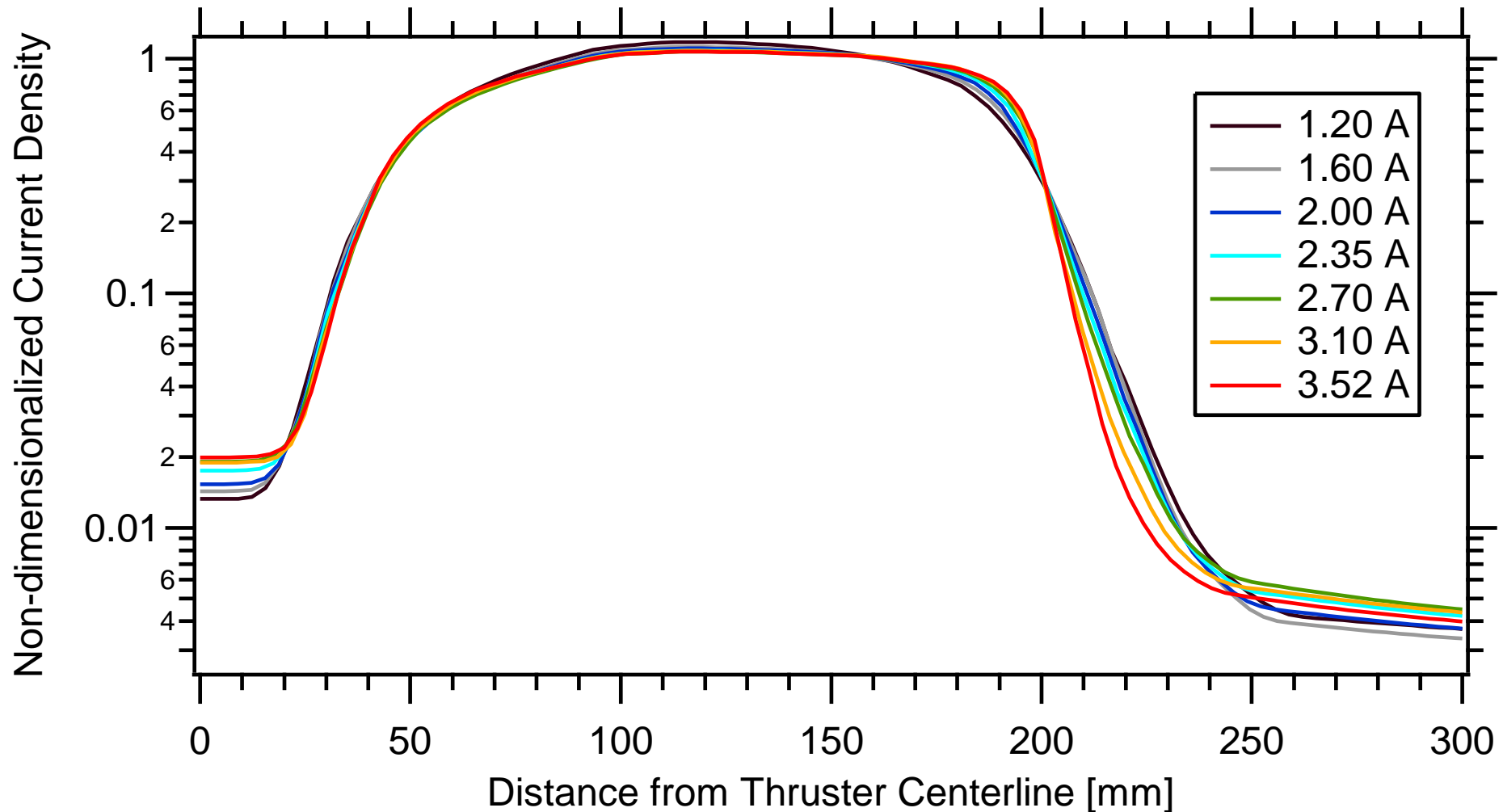
Profiles at Constant $I_b = 1.20$ A



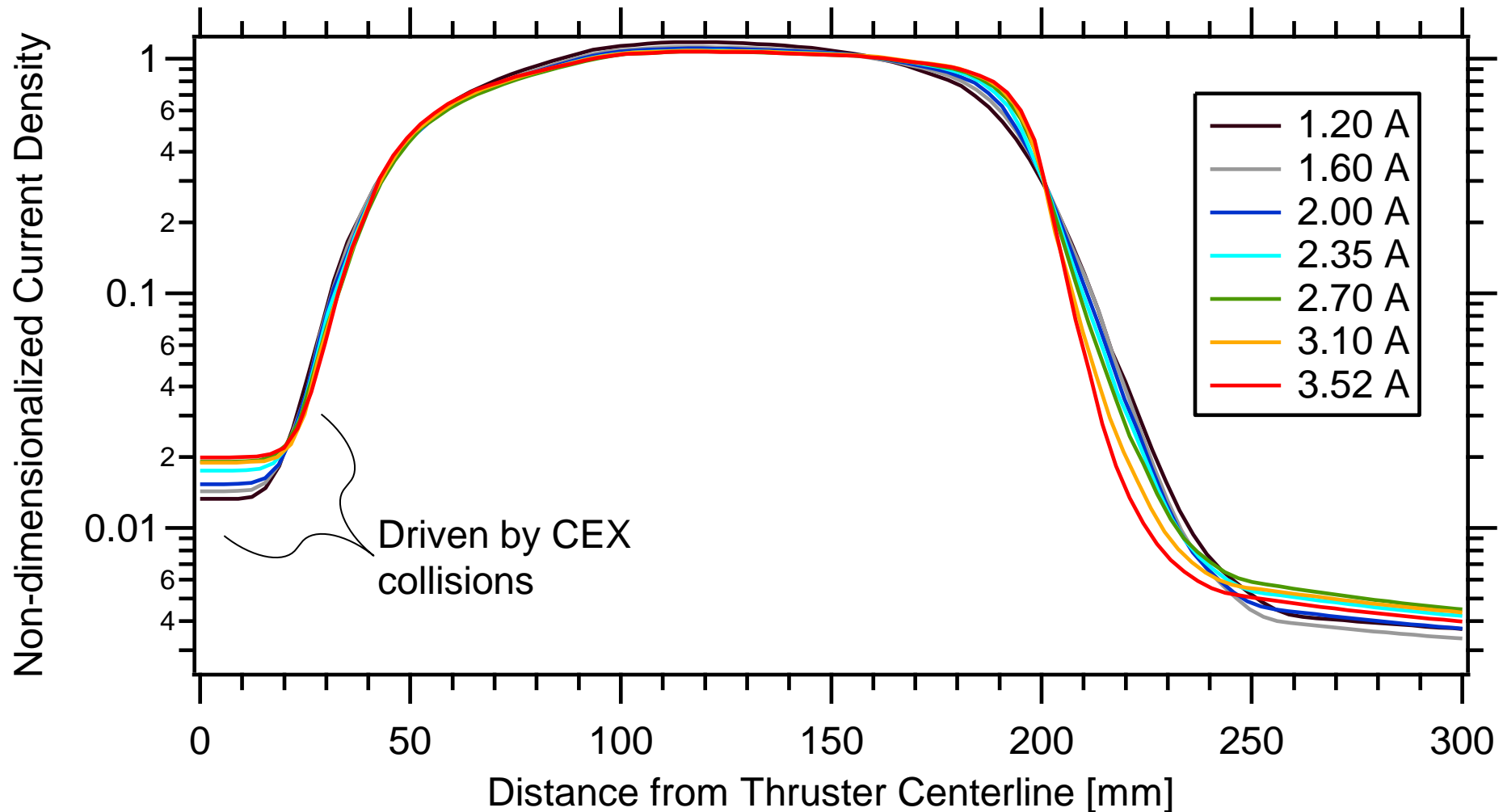
Profiles at Constant $I_b = 1.20$ A



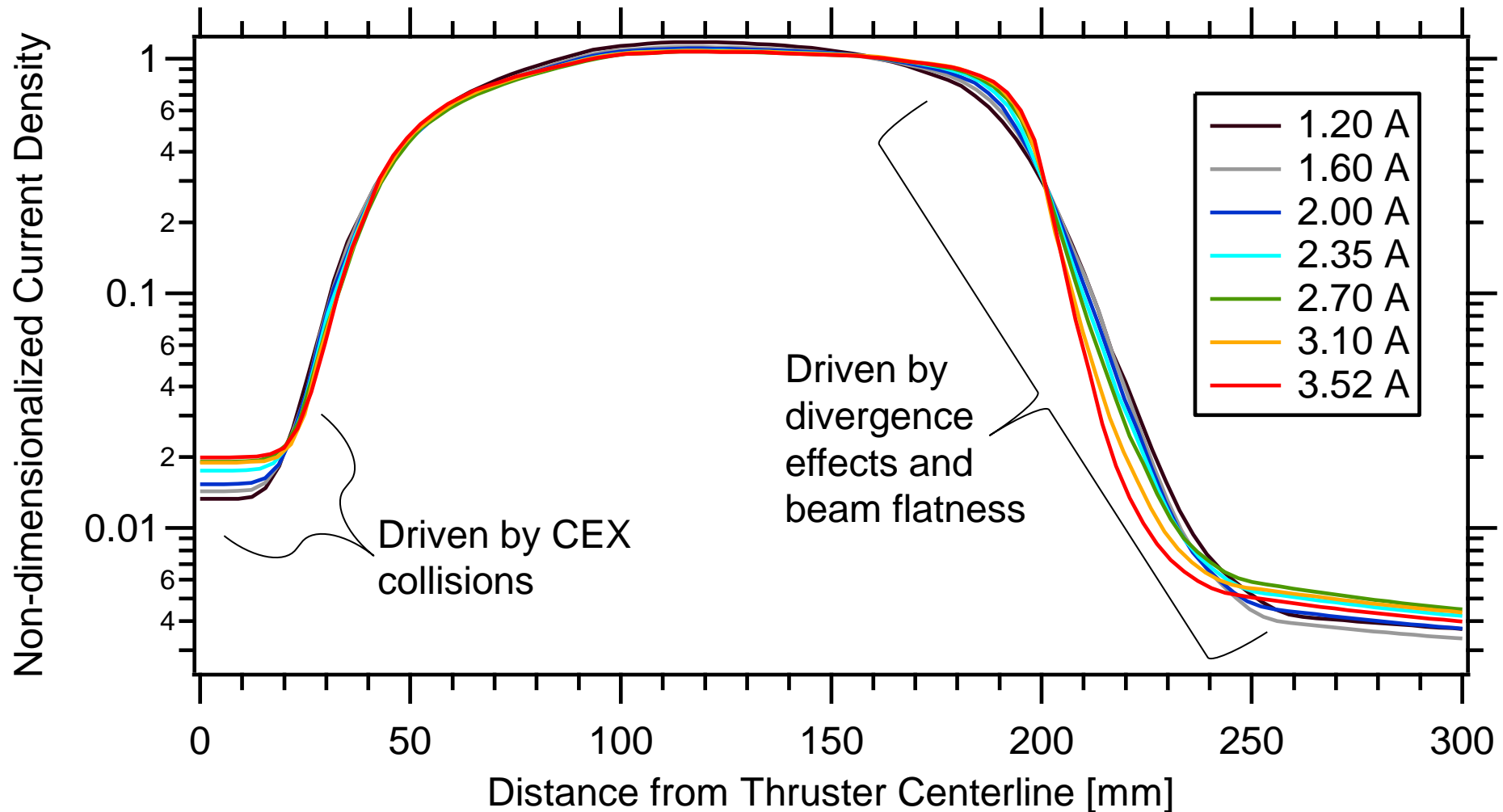
Profiles at Constant $V_b = 1179$ V



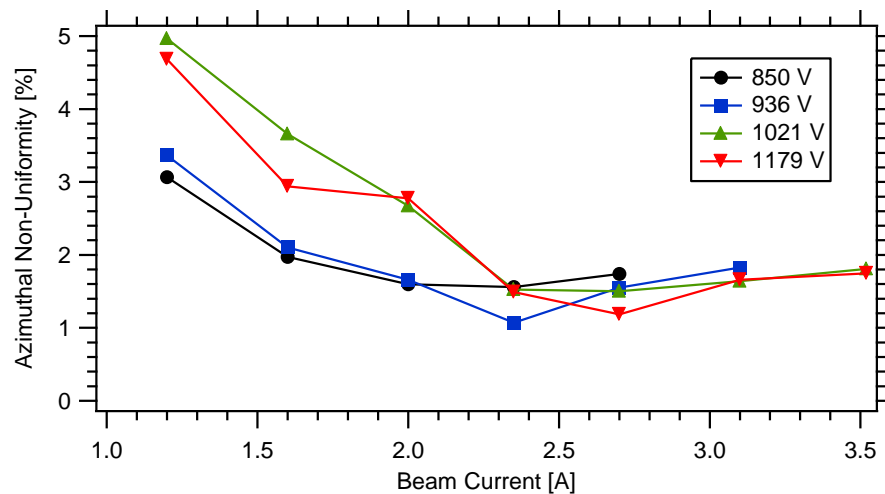
Profiles at Constant $V_b = 1179$ V



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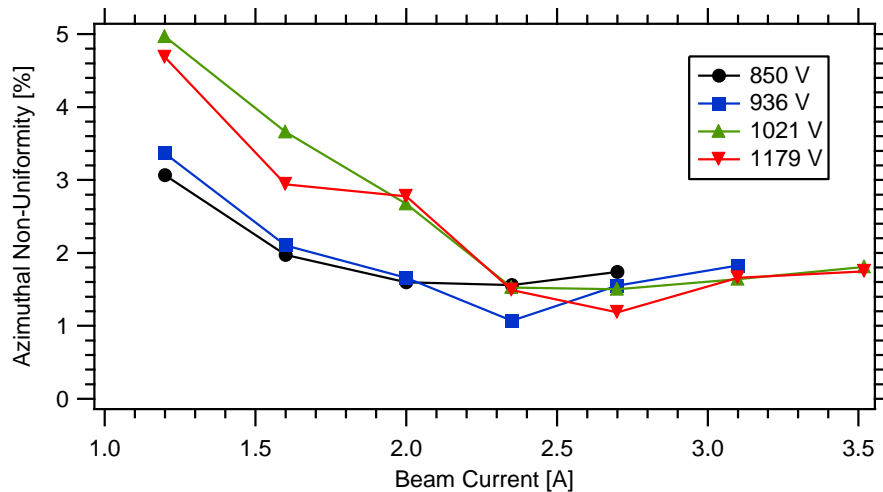
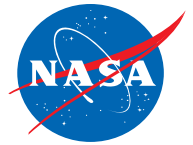


Calculated Non-Uniformity – Phase 2



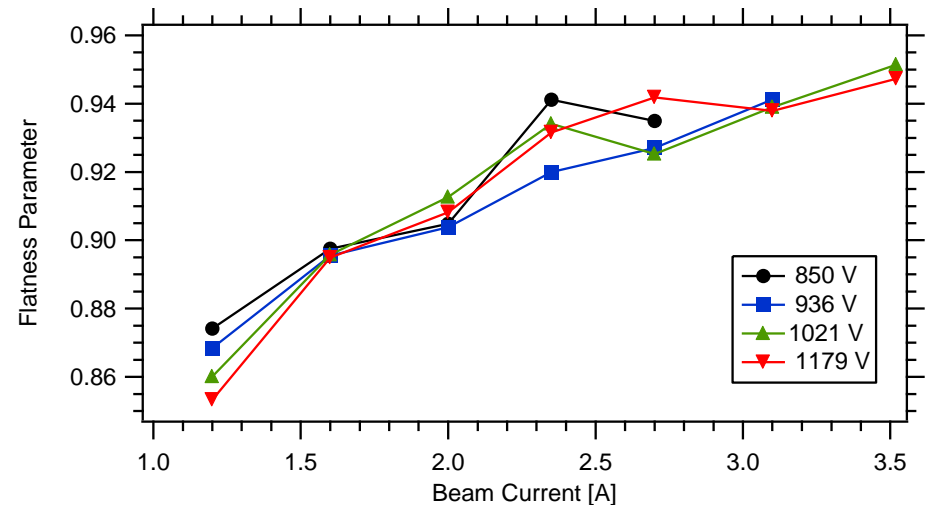
- Azimuthal uniformity calculated using four clocked positions at the radial location of the discharge cathode
- Non-uniformity shown to decrease with increasing beam current, with uniformity between 1-2% at the higher currents
- All measured non-uniformities were $\leq 5\%$

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- Non-uniformity shown to decrease with increasing beam current, with uniformity between 1-2% at the higher currents
- All measured non-uniformities were $\leq 5\%$

- Flatness parameter calculated as ratio of average beam current density to peak measured current density
- Flatness seen to increase with increasing beam current, indicating a higher degree of radial uniformity
- All measured flatness parameters were between 0.85 and 0.95



Conclusions



- Fourteen button probes and three Faraday probes were used to measure the current density of the discharge during simulated beam extraction and the plume during true beam extraction to characterize and quantify potential non-uniformities in a breadboard AGI-Engine
- Discharge measurements show variations under most conditions limited to $\pm 10\%$ of the mean current density, while variations in the plume 30 mm from the ion optics were limited to $\pm 5\%$ of the mean current density at all 40 operating conditions tested. Uniformity typically increased with increasing discharge/beam currents
- Azimuthal uniformity in the discharge appeared to be sensitive to the main plenum mass flow rate, with excessive neutral densities increasing the differences between the plasma near the cathode and away from it at a given discharge current
- Current density along cathode and “non-cathode” centerlines were found to decay exponentially with downstream distance, with profiles along thruster centerline exhibiting a humped structure likely driven by beam merging and CEX ions
- The current density close to thruster centerline appears to be driven by charge-exchange effects, while the current density falloff on the outer edge of the plume is primarily driven by beam divergence
- The breadboard AGI-Engine has shown a high degree of plasma uniformity over a wide range of conditions despite the use of a single discharge cathode at an asymmetric location



Questions?