



High Thrust-to-Power Annular Engine Technology

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High Thrust-to-Power Annular Engine Technology



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Introduction

Despite more than 50 years of research and development investment in electrostatic (gridded) ion engine technology, and more than 100 engines presently in operation in space on U.S. commercial and NASA spacecraft, these devices were never optimized for Earth orbit transfer operations where maximizing thrust-to-power (F/P_{in}) is the critical metric

This situation arose for several reasons

However, improvements in the ion engine F/P_{in} parameter promise higher performance than any other electric propulsion technology in the 5-kW class, over a broad range of specific impulse



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State of the art ion engines have been operated at high thrust density and high total thrust, at levels approaching other high power devices (e.g. HETs)

These demonstrations however did not involve purposeful modifications to the technology to optimize performance or the F/P_{in} parameter

This is because these engines were intentionally designed for operation at low thrust densities for the purpose of achieving extremely long life times, in support of space science missions



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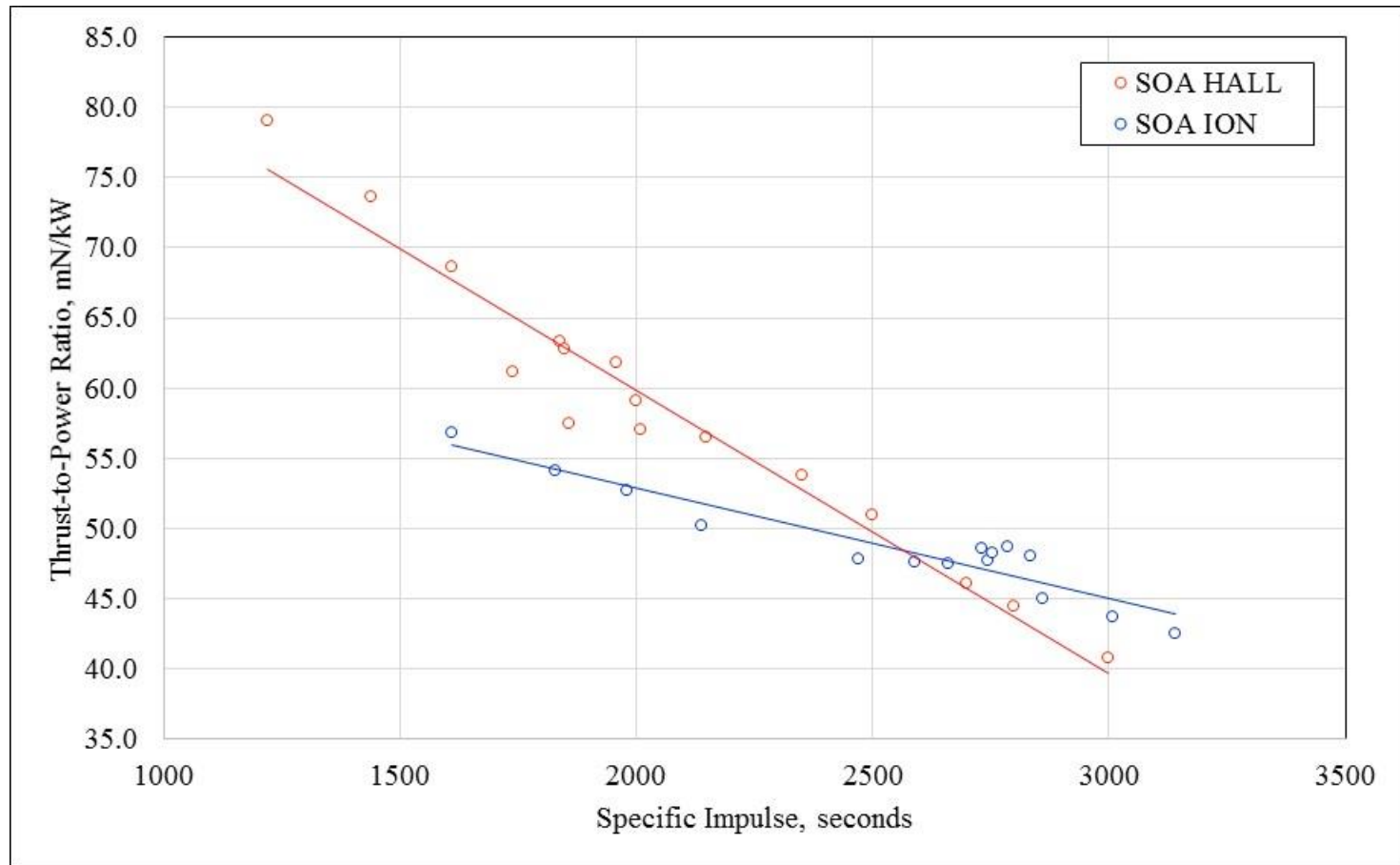
| Engine | Max. F , mN [Thrust Density, N/m ²] | Max. P_{in} , kW [Power Density, kW/m ²] | Peak F/P_{in} (typical), mN/kW | Corresponding Specific Impulse, sec | Reference |
|------------------------|--|---|-------------------------------------|-------------------------------------|----------------|
| 30 cm Divergent | 577 [8.92] | 17.1 [264] | - | 4,380 | AIAA-88-2914 |
| | 301 [4.65] | 8.72 [135] | - | 4,125 | |
| 30 cm Ring-Cusp | - | - | 56.8 | 1,610 | AIAA-92-3203 |
| | - | - | 54.1 | 1,830 | |
| | - | - | 52.7 | 1,980 | |
| | - | - | 50.2 | 2,140 | |
| | - | - | - | - | |
| 40 cm NEXT | 466 [3.71] | 13.6 [134] | - | 4,670 | AIAA-2006-4664 |
| | - | - | 47.5 | 2,660 | |
| | - | - | 47.7 | 2,745 | |
| | - | - | 48.3 | 2,755 | |
| | - | - | 48.0 | 2,835 | |
| | - | - | 48.6 | 2,730 | |
| | - | - | 48.7 | 2,785 | |
| | - | - | 47.8 | 2,470 | AIAA-2013-3891 |
| | - | - | 47.6 | 2,590 | |
| | - | - | 45.0 | 2,860 | |
| | - | - | 43.7 | 3,010 | |
| | - | - | 42.5 | 3,140 | |
| | - | - | - | - | |



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'SOA HALL' include data for both commercial HET (BPT-4000) over its 1,220-2,150 sec Isp range, and the 12.5 kW HET (HERMeS) over its intended 1,850-3,000 sec Isp range



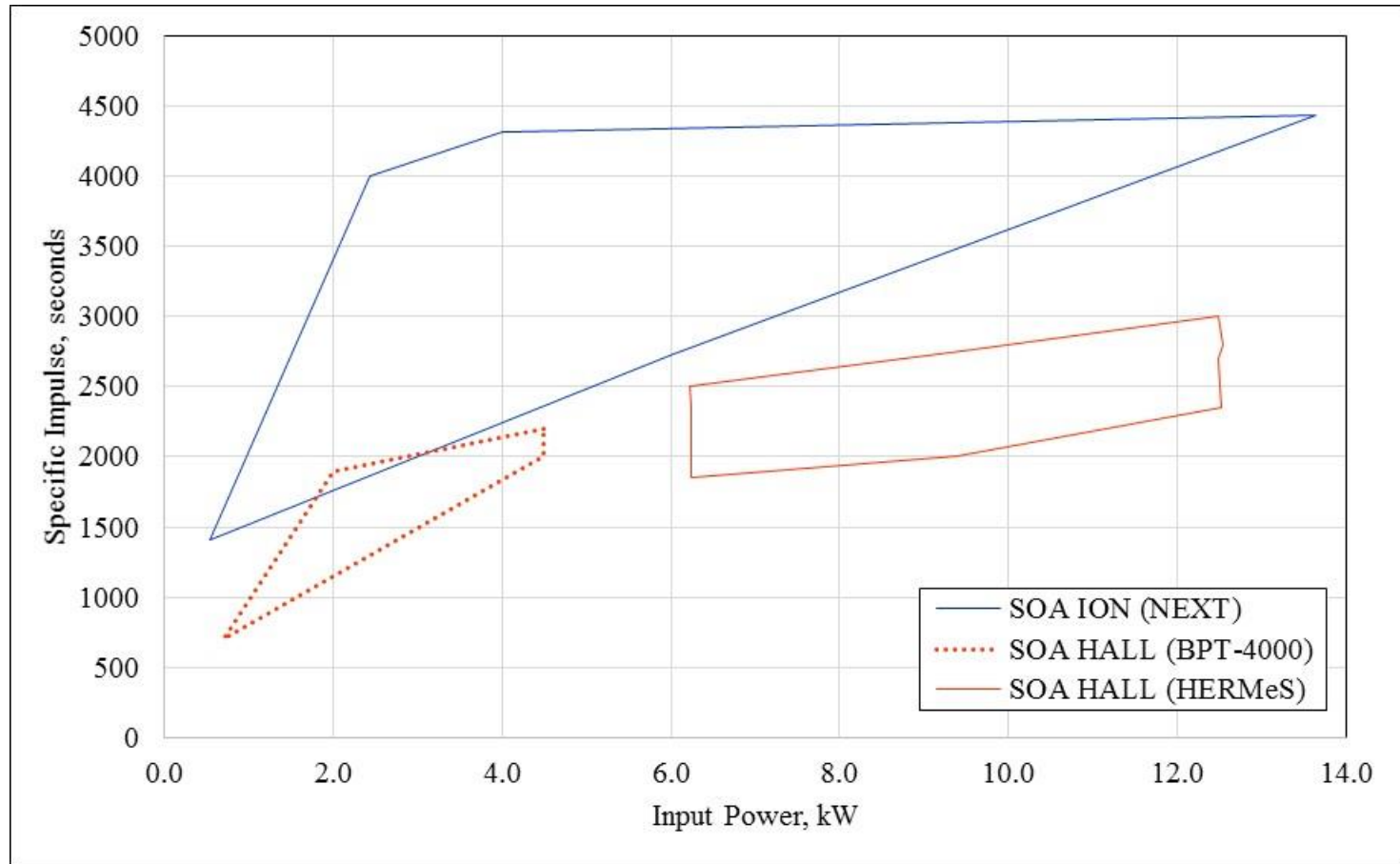
Curve fits of both the SOA HALL and SOA ION data indicate a cross-over in F/P_{in} at about 2,600 seconds Isp, with HETs having superior F/P_{in} below 2,600 seconds, and ion engines having superior F/P_{in} above 2,600 seconds – including at the intended HERMeS operating condition of 3,000 seconds



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Specific Impulse vs. Input Power: SOA ION (NEXT, demonstrated); SOA HALL (BPT-4000, demonstrated, and HERMeS, intended throttle range for SEP TDM).



While NEXT has a larger demonstrated throttling range in both specific impulse and input power, it does so for the most part at a lower F/P_{in} parameter



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For xenon propellant the F/P_{in} ratio reduces to:

$$F / P_{in} = 1.650 \times 10^{-3} \alpha \beta \frac{V_b^{1/2}}{(V_b + \epsilon_i)}$$

Where thrust-to-power ratio is maximized as the thrust-loss correction factors, α and β , approach unity, and the beam voltage, V_b , and the discharge losses, ϵ_i , are minimized

A potential effective means of maximizing ion engine F/P_{in} is by development of the Annular Engine (AE):

- Annular optics allow one to fix the span and span-to-gap ratio to a relatively low value, enabling reduced-dome, or zero-dome (flat) electrodes, thereby increasing β
- Enables higher thrust density operation, yielding higher beam current capacity which will lower the discharge losses, ϵ_i , in addition to enabling higher power operation at lower I_{sp}



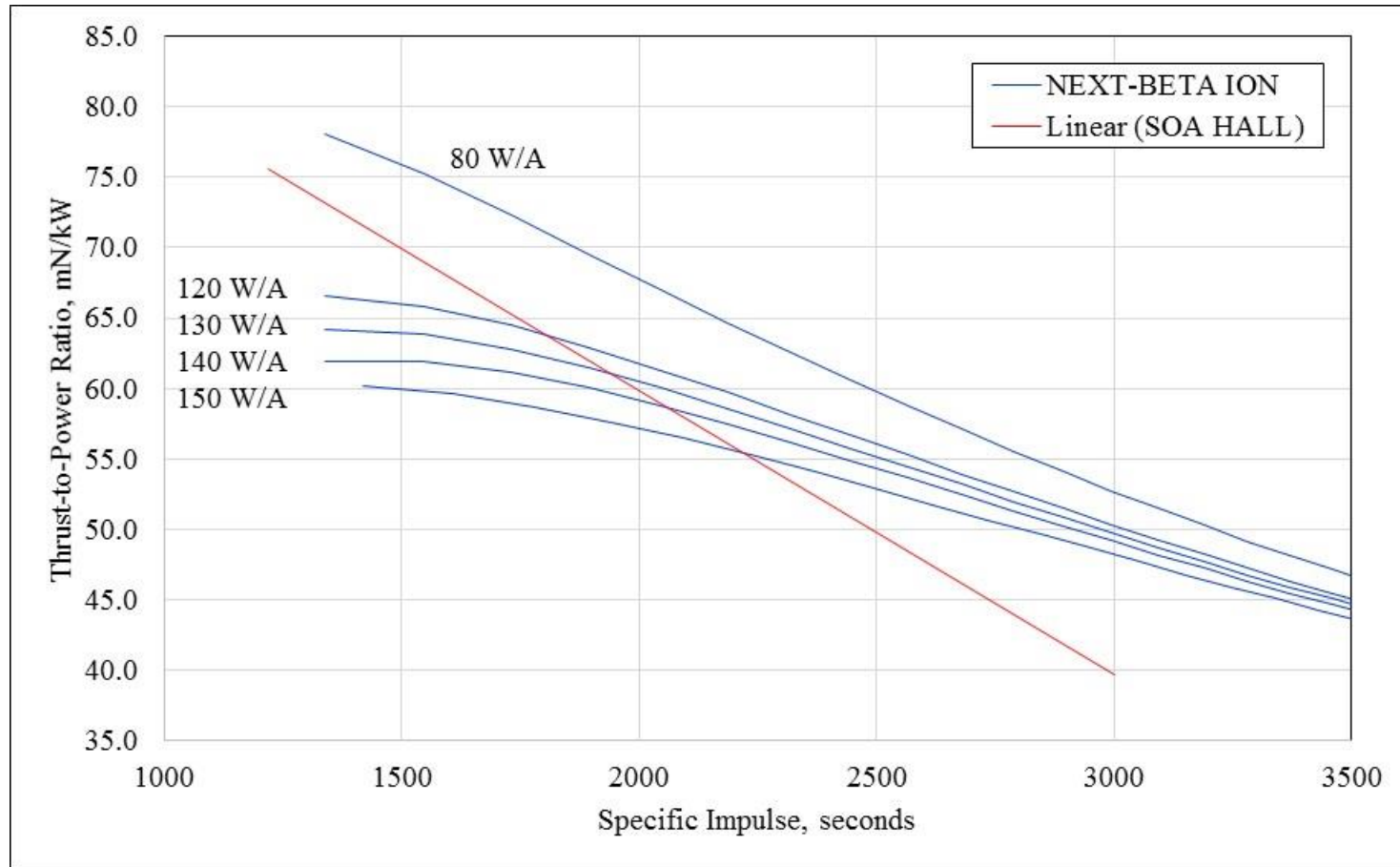
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Curve fit of the SOA HALL data

Projections of ('conventional') ion engine performance are given for a range of discharge losses, ϵ_i , from 80-150 W/A

The thrust-loss correction factors α and β for these projections are equivalent to those documented for the NEXT ion engine



With minor magnetic circuit modifications and higher current density, lower discharge losses should be readily obtainable; at least to 150 W/A. At 150 W/A, the cross-over point where F/P_{in} for ion engines exceeds that for HETs is reduced from 2,600 seconds (for SOA engines) to about 2,300 seconds I_{sp} – with further improvements in ϵ_i lowering the cross-over further



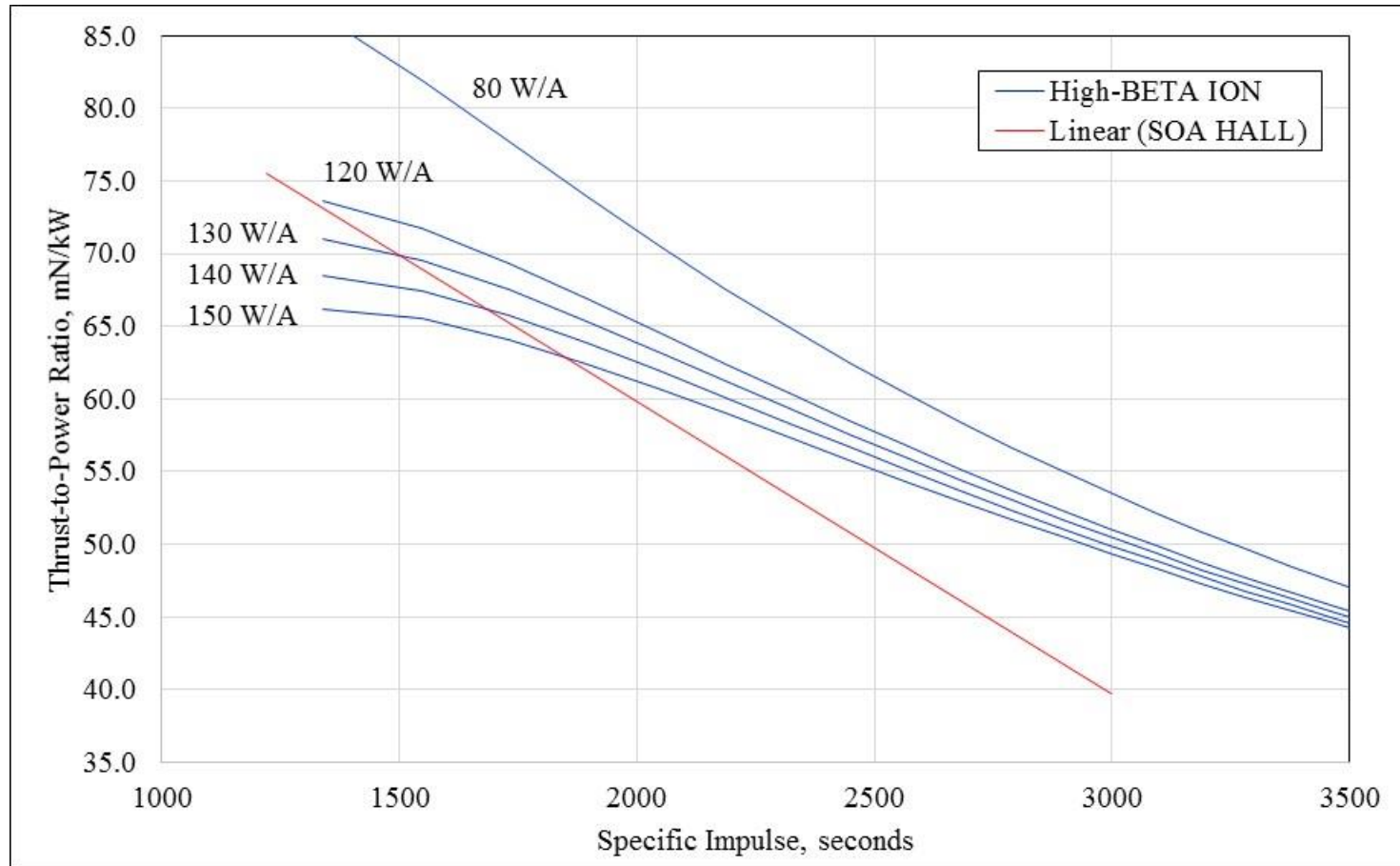
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Curve fit of the SOA HALL data

Projections of ion engine performance are given for a range of discharge losses, ϵ_j , from 80-150 W/A

The thrust-loss correction factor β assume 0.998, consistent with the beam divergence documented previously for flat annular ion optics



In this instance, minor improvements in magnetic circuit design in combination with flat ion optics should drive the cross-over point where the F/P_{in} parameter for ion engines exceeds that for HETs from 2,600 seconds down to about 1,800 seconds I_{sp}



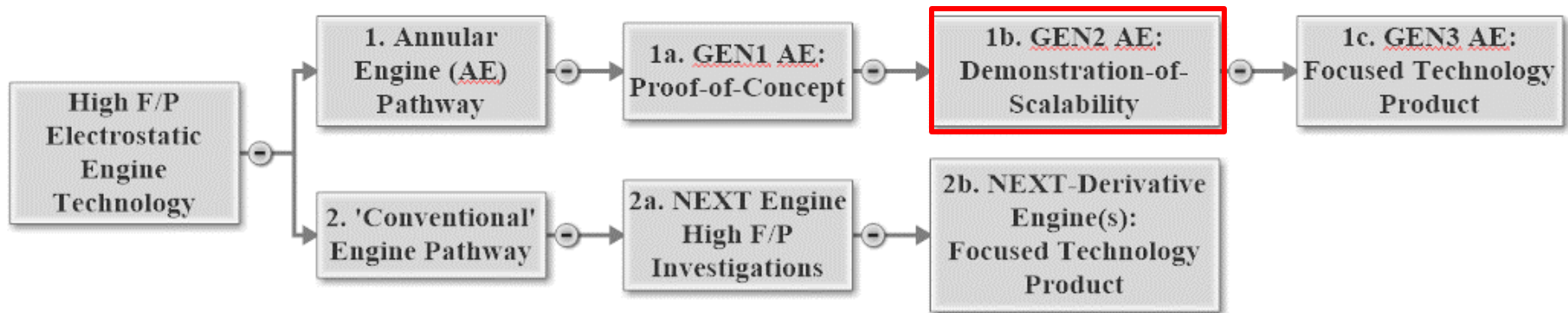
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High Thrust-to-Power Development Plan

Two ion engine design paths may provide near-term opportunities for demonstration of high thrust-to-power ratio, and high thrust density operation:

1. Continued development of the AE concept [*extensible pathway to higher power*]; and
2. Demonstration of a (conventional) cylindrical-geometry ion engine derived from the NEXT ion thruster, but incorporating advanced-design ion optics to increase β and a magnetic circuit intended to reduce ϵ_i and inhibit source-limited operation [*nearer-term technology product*]





GEN2 Annular Engine Development

Design and Performance Expectations

To meet the objective of demonstrating scalability of the AE concept to high power – including scalability of the annular discharge chamber and ion optics – requires the fabrication of a full-scale AE

‘GEN2’ AE was designed to be sufficiently large to operate in the ~10’s of kW power range, and to assess whether or not the azimuthal and radial discharge and beam uniformity demonstrated with the ~40 cm diameter GEN1 AE could be maintained using a single-cathode design

The larger size would also provide the opportunity to address manufacturing, assembly, and test issues associated with larger-area PG electrodes



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GEN2 also scaled to ensure that there would be sufficient anode surface area to enable operation closer to the Child-Langmuir limit than is the case for conventional ion thrusters, while maintaining relatively-low discharge losses

The interior diameter of the annulus was also sized to limit the optics span to a value comparable to that demonstrated with the GEN1 AE, approximately 14.4 cm diameter in the active area

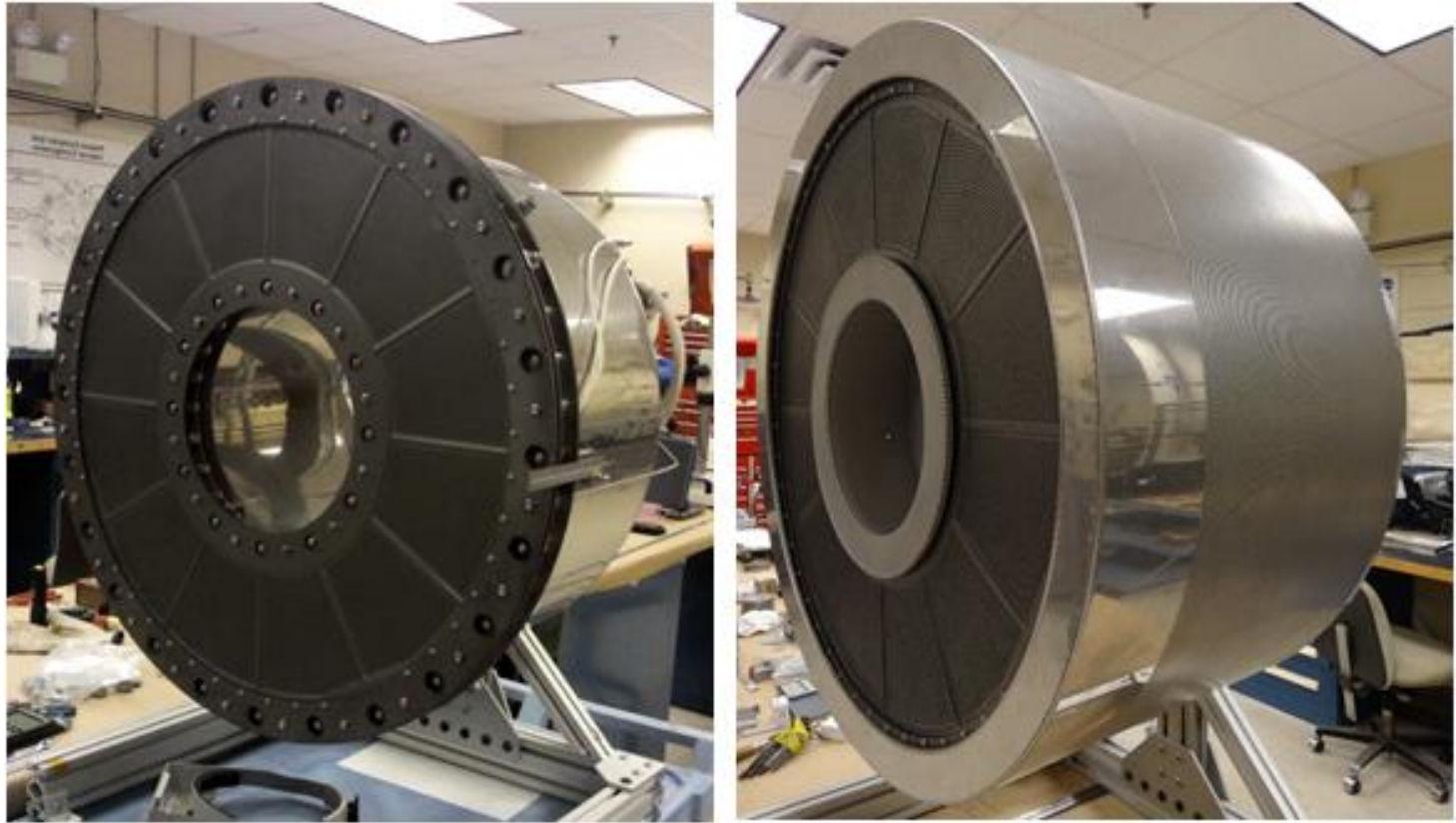
The AE has beam dimensions of approximately 65 cm O.D. and 36 cm I.D., yielding a total (annular) beam area $> 2X$ that of the NEXT ion thruster, with an anode area of approximately $4X$ that of the NEXT thruster



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The exterior dimensions for the laboratory-model GEN2 AE are approximately 76 cm diameter x 39 cm length, with a mass of approximately 34 kg



Images of GEN2 (65 cm dia.) Annular Engine hardware, left-to-right: pyrolytic graphite electrodes, with carbon-carbon stiffener ring, ion optics assembly integrated with discharge chamber; engine with plasma screen, sans neutralizer cathode assembly.



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The ion optics electrodes were machined at NASA from substrate nucleated PG panels

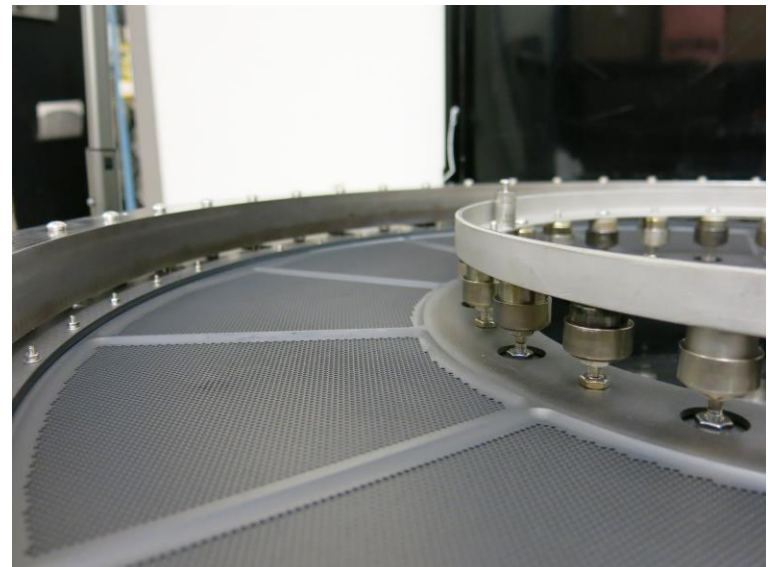
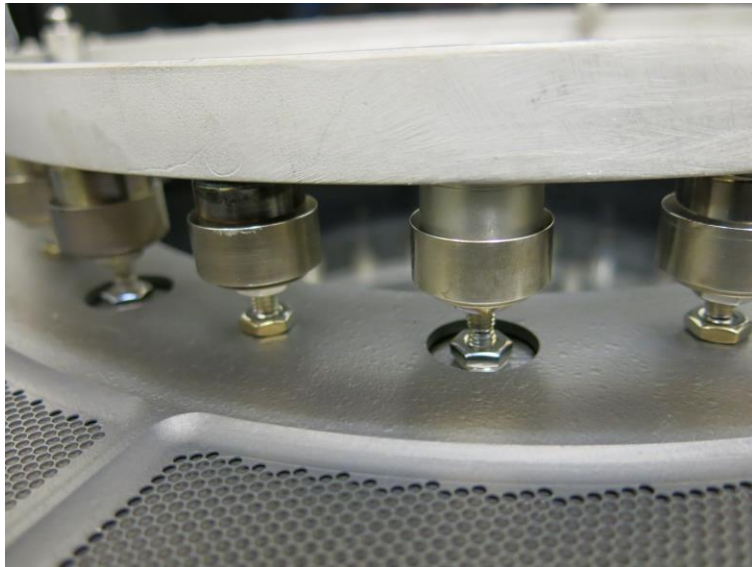
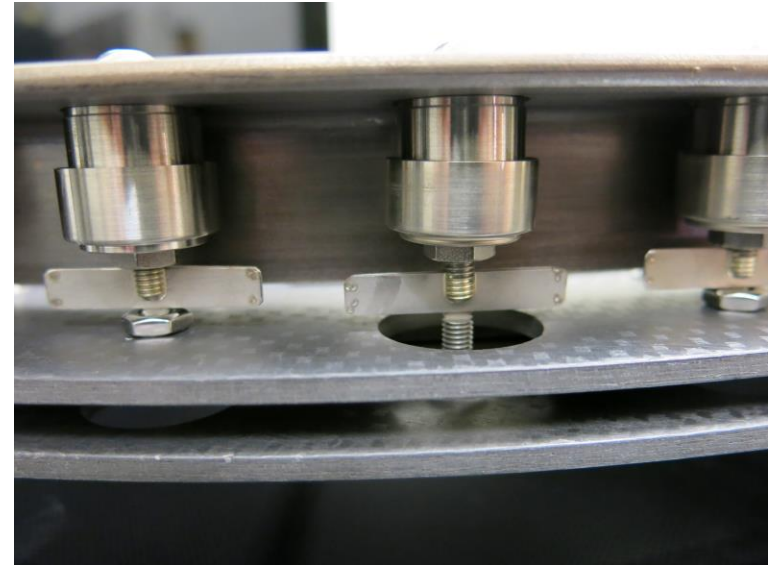
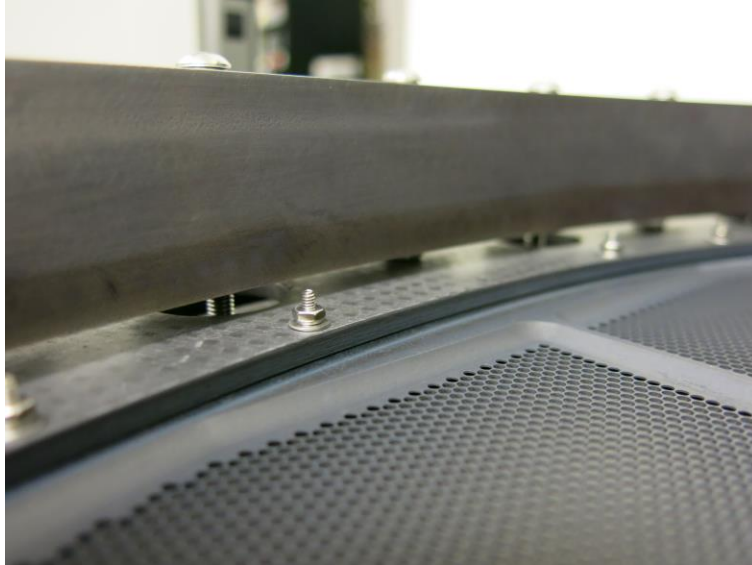
Each of the 2 electrodes contains 45,356 apertures, and were completed with 100% yield and zero defects

Upon inspection, the electrode geometry conformance-to-design exceeded that obtained with SOA conventional metal electrodes with apertures created using a photo-chemical etching process

The electrodes are flat, but incorporate radial ribs of thicker unperforated base material to increase the overall electrode stiffness, and are secured to mounting rings fabricated from carbon fiber-reinforced carbon ('carbon-carbon'). The mounting scheme for the electrodes incorporates flexures which allow for radial-motion under thermal load.



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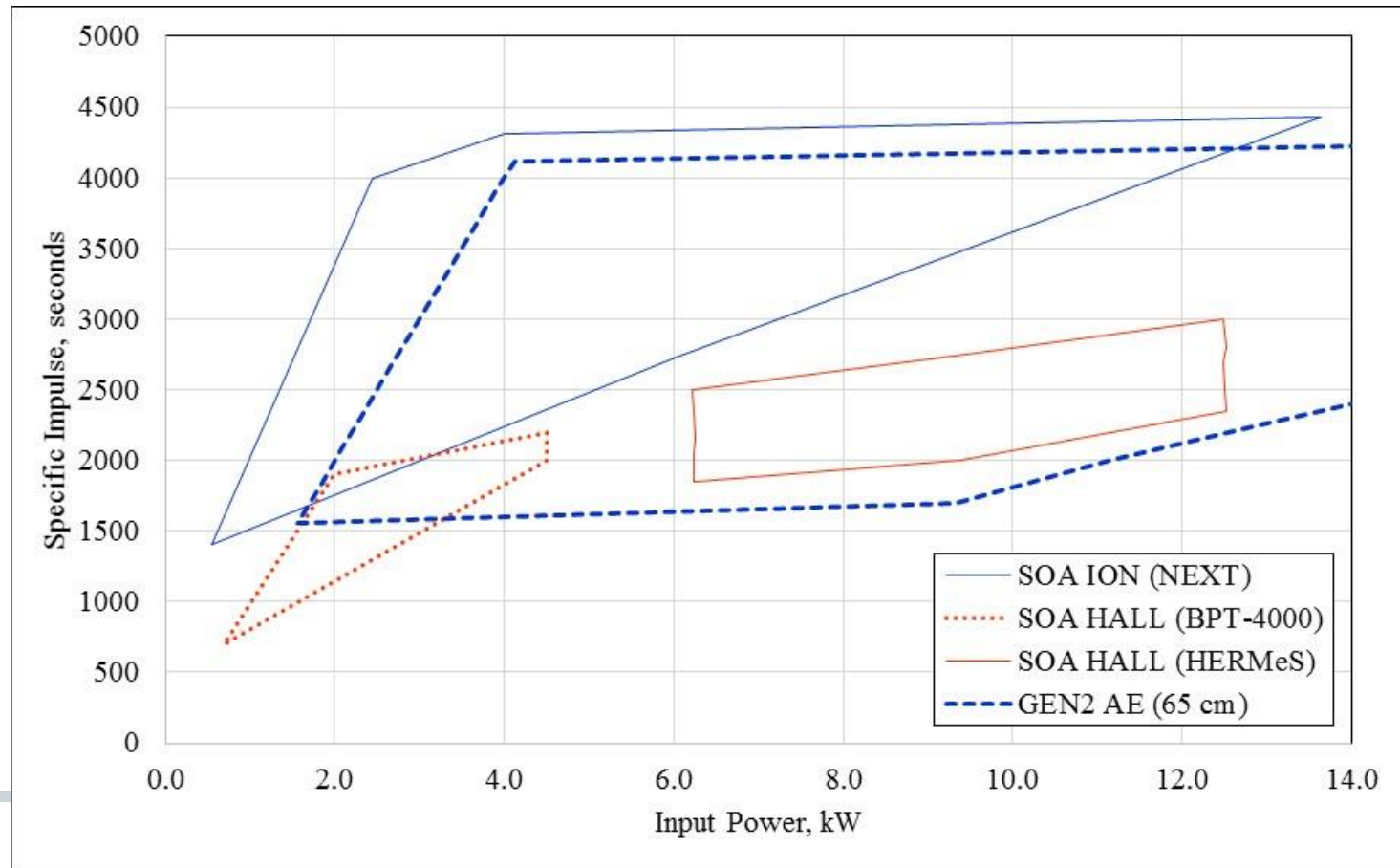


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While the GEN2 AE is a laboratory-model experimental test article to evaluate scalability of the annular concept, and not a design solution to a specific propulsion application, it is of interest to note what the performance of such an AE size and configuration might yield

GEN2 AE: α equal to NEXT; β modestly improved from that documented for the NEXT ion engine, varying from about 0.993 at high I_{sp} down to about 0.933 at low I_{sp} ; discharge losses, ϵ_i , were conservatively assumed to be 200 W/A; and a perveance per-unit-area and total maximum voltage equivalent to that of the NEXT were assumed





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GEN2 Annular Engine Development

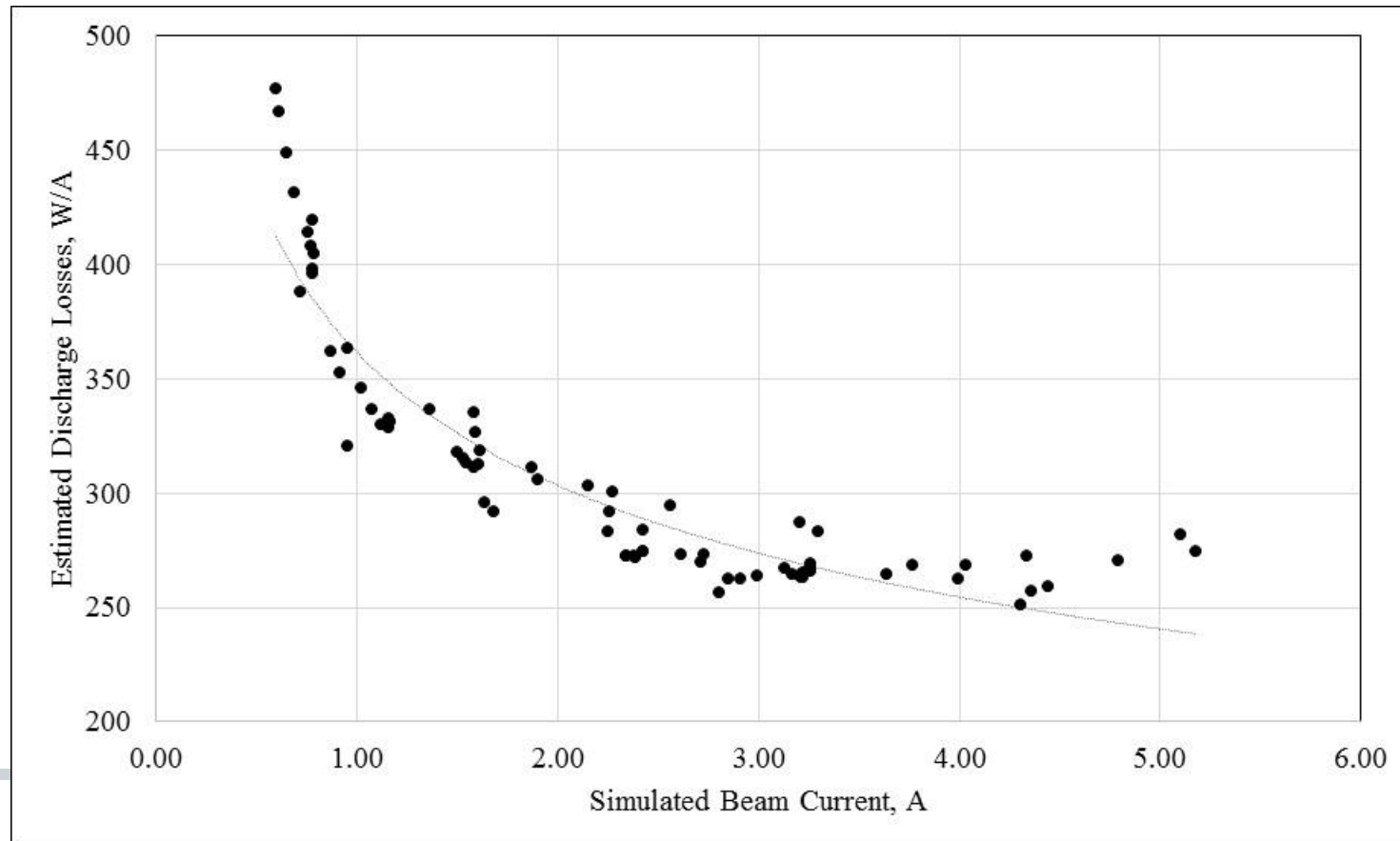
Discharge Chamber Tests

AIAA-2015-3721: *“Characterization of discharge uniformity and performance via stimulated beam extraction of a 65 cm annular ion engine”*

Extremely-stable discharge operation over a broad range in discharge currents

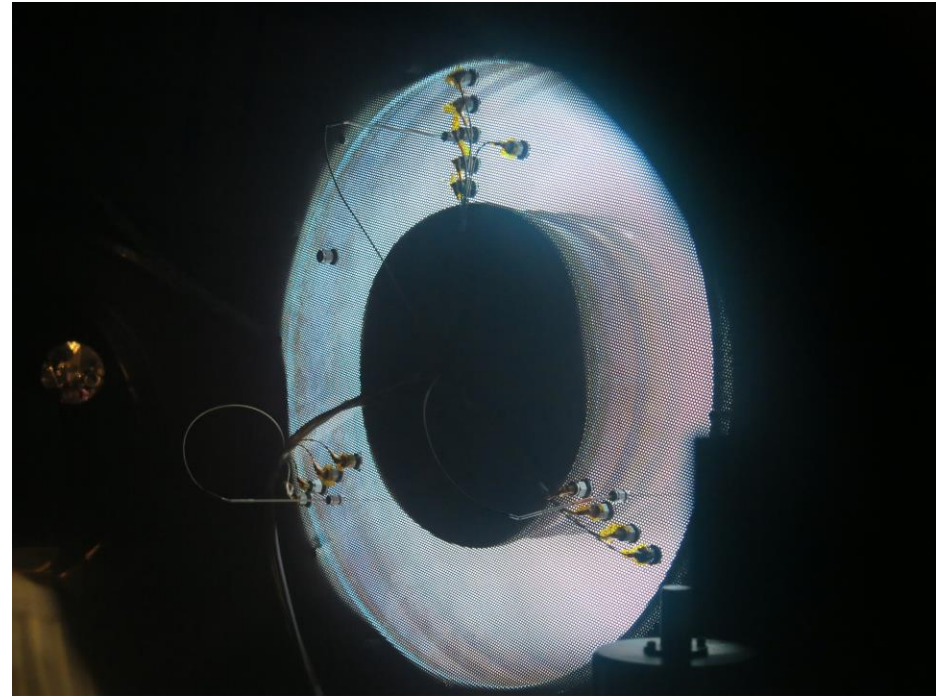
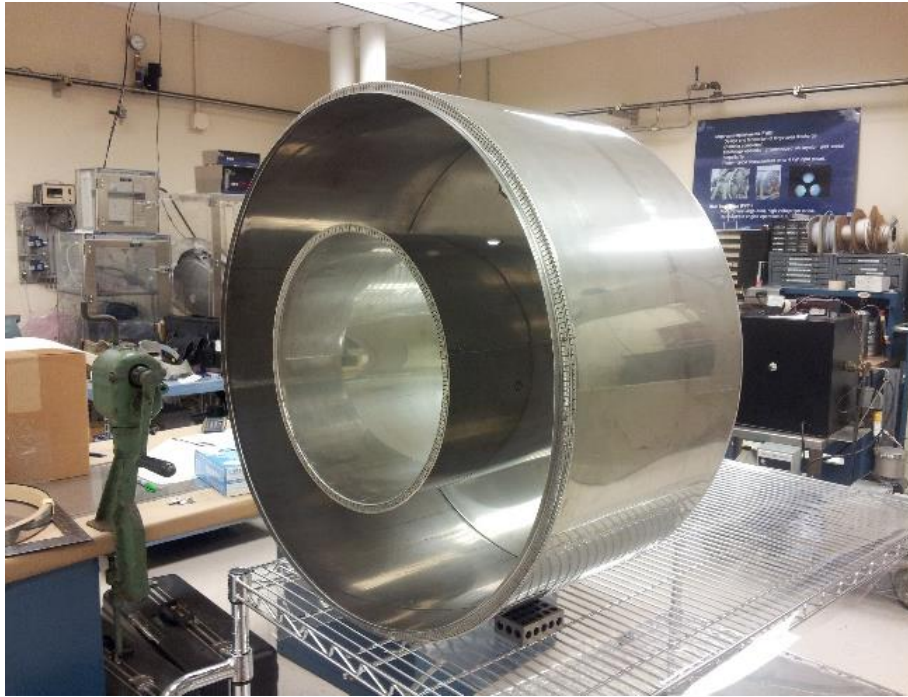
Uniform plasmas in the radial and azimuthal directions

Estimated discharge losses decrease with increasing beam current, asymptotically reaching about 250 W/A; while not as efficient as desired the results are satisfactory for the initial magnetic circuit iteration





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Images of GEN2 (65 cm dia.) Annular Engine hardware, from left-to-right: annular discharge chamber, sans magnetics, undergoing assembly; annular discharge chamber in vacuum undergoing simulated beam extraction tests, with high-transparency grid-plate and embedded probes on downstream end of discharge chamber.



GEN2 Annular Engine Development

Operation with Beam Extraction

At this time only a very-modest level of testing of the full engine with beam extraction has been completed

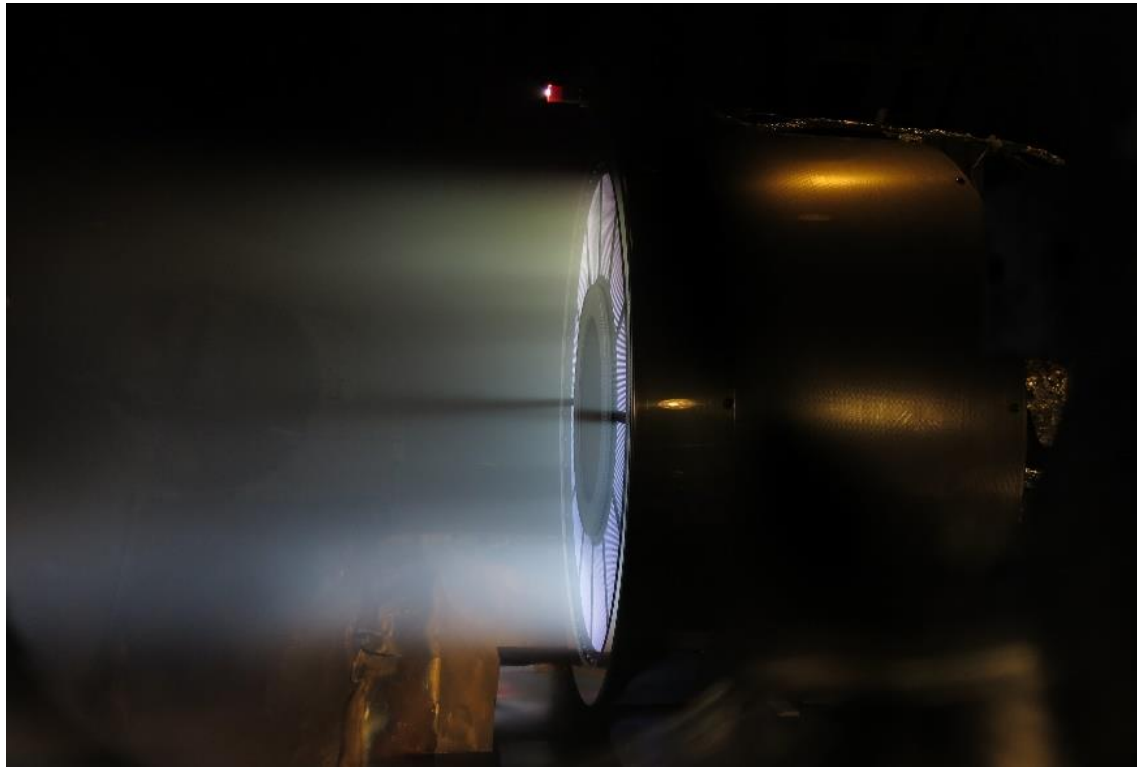
However, the ion optics electrostatic design was validated to a degree, and successful ion beam extraction was demonstrated

Some anomalous behavior of the accelerator electrode impingement current (or, drain current) was noted, including both its magnitude (high, ~1-2+% of the beam current) and its sensitivity to discharge parameters and applied accelerator electrode potential; 3 mechanisms were identified as potential causes for the high accelerator current

Engine modifications are presently being implemented and GEN2 will undergo additional testing in August 2015



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Images of 65 cm dia. Annular Engine beam extraction tests, left-to-right: side-view showing beam propagation; head-on view of engine. Neutralizer cathode assembly is at 12-o'clock position (left image) and is cropped (right image) due to beam target surface in camera field-of-view.



Forward Work

Objective: Demonstrate and evaluate electrostatic (gridded ion) engine technology for operation at high F/P_{in} (4-12+ kW) – combining:

1. High β demonstrated with AE flat optics
2. Low ϵ_i demonstrated with Ring-Cusp magnetic circuit
3. High beam current densities demonstrated with Divergent-Field magnetic circuit

Near-Term: Validate flat pyrolytic graphite-based AE as a high F/P_{in} device over wide envelope

1. Rework & retest GEN2 AE consistency with Goal 1
2. Rework GEN1 AE optics and magnetic circuit. Fully-characterize performance of GEN1 AE. Document maximum F/P_{in} characteristics.
3. Fully-characterize performance of GEN2 AE. Document maximum F/P_{in} characteristics



Forward Work

Mid-Term:

Optimize ion engine technology for high F/P_{in}

1. Design, fabricate, and performance characterize GEN3 AE as a focused technology product with 4-12+ kW target operating range
2. Define, fabricate, test NEXT-Derivative 40 cm engine concept(s) (2). Document maximum F/P_{in} characteristics



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Summary

- Despite more than 50 years of research and development in ion engine technology these devices were never optimized for Earth orbit transfer operations where maximizing thrust-to-power is the critical metric
- Improvements in the ion engine F/P_{in} parameter may yield higher performance than other EP technology options in the 4-12+ kW power range, over the broadest obtainable range in specific impulse
- A potential means of maximizing ion engine F/P_{in} is by development of the Annular Engine; a combination of reduced discharge and thrust losses has the potential to lower the cross-over point where ion engines exceed the F/P_{in} of SOA Hall thrusters from 2,600 seconds down to below 1,800 seconds I_{sp}



Summary

- A 65 cm 'GEN2' AE was built to demonstrate scalability of the concept
- Discharge chamber tests were successfully concluded, with excellent discharge stability over a broad discharge current range, yielding good plasma uniformity
- Manufacturing of large-area high-perveance-design carbon ion optics were subsequently completed, integrated with the AE discharge chamber, and beam extraction testing of the AE has been initiated