

ANNULAR ION ENGINE CONCEPT AND DEVELOPMENT STATUS

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ABSTRACT:

The Annular Ion Engine (AIE) concept represents an evolutionary development in gridded ion thruster technology with the potential for delivering revolutionary capabilities. It has this potential because the AIE concept: (a) enables scaling of ion thruster technology to high power at specific impulse (I_{sp}) values of interest for near-term mission applications, ≤ 5000 sec; and (b) it enables an increase in both thrust density and thrust-to-power (F/P) ratio exceeding conventional ion thrusters and other electric propulsion (EP) technology options, thereby yielding the highest performance over a broad range in I_{sp} .

The AIE concept represents a natural progression of gridded ion thruster technology beyond the capabilities embodied by NASA's Evolutionary Xenon Thruster (NEXT) [1]. The AIE would be appropriate for: (a) applications which require power levels exceeding NEXT's capabilities (up to about 14 kW [2]), with scalability potentially to 100's of kW; and/or (b) applications which require F/P conditions exceeding NEXT's capabilities.

This publication synthesizes the technology development status of the AIE and a potential forward-path for further concept maturation.

1. CONCEPT DESCRIPTION

All concepts disclosed in the publication are covered under U.S. Patent #8,468,794 ("Electric Propulsion Apparatus", June 25, 2013), U.S. Patent #9,279,368 ("Multi-Thruster Propulsion Apparatus", March 29, 2016), and Patents-Pending filed under both U.S. and International Patent Applications. Assignee: United State Government.

The AIE concept consists of an annular discharge chamber, with a set of annular ion optics, potentially configured with a centrally-mounted

neutralizer cathode assembly. This concept is illustrated in Fig. 1. Fig. 2 shows a second-generation ('GEN2') full-scale AIE under test with beam extraction [3].

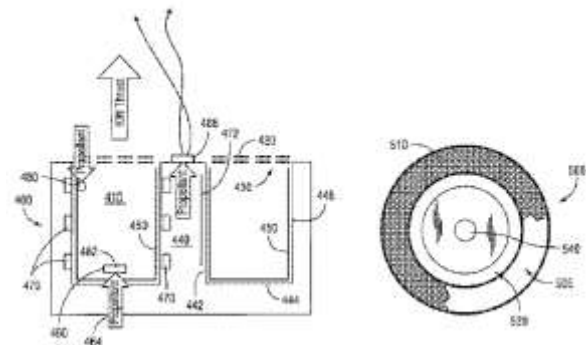


Figure 1. AIE Concept in Cross-Section and Frontal View



Figure 2. Full-Scale GEN2 AIE in Test; 65 cm outside Beam Diameter

2. CONCEPT ADVANTAGES

The AIE has significant potential advantages over conventional ion thrusters, and other EP thruster concepts [4]. Attributes and technical descriptions of the AIE are listed in Tab. 1, and include: very high thrust density; extensibility to high power; improved efficiencies and F/P; enhanced life time; and improved packaging over State-of-the-Art (SOA) EP thrusters.

Table 1. AIE Concept Attributes and Descriptions

Concept Attribute	Technical Description
3X Increase in Thrust Density	The annular discharge chamber increases the effective anode surface area for electron collection as compared to a conventional cylindrically-shaped ion thruster of equivalent beam area. This enables operation at higher discharge currents and therefore high beam currents yielding an increase in thrust density (up to 3X) and enabling near full-perveance capability of the optics. An annular-geometry flat electrode may enable further electrostatic refinements yielding higher-perveance designs with even higher thrust densities.
>10X Increase in Power	Instead of spanning a large discharge chamber diameter, an annular design enables a very large beam area with relatively small electrode spans and relatively small span-to-gap ratios. This mitigates the manufacturing, mechanical, and thermal challenges of large span spherically-domed conventional ion optics, typically limited to about 600:1 span-to-gap.
Improved Efficiencies	Annular-geometry ion optics of small span may have sufficiently-high natural frequency to implement flat electrodes. Flat electrodes will inherently yield improved efficiencies by eliminating off-axis beam vectoring associated with spherically-domed ion optics electrodes used on cylindrical thrusters; ~3-4 percentage point increase in efficiency across the I_{sp} range.
10X Increase in Life	Because of the relatively-simple physical design of the electrodes the present manufacturing limitations with carbon are circumvented, thereby allowing the practical implementation of carbon and the life time enhancements of this material.
Improved Packaging	The annular discharge chamber design allows central mounting of the neutralizer within the annulus, and the potential to incorporate multiple annular discharges packaged into concentric rings, thereby reducing the outer profile of the engine. This would also allow for a shared gimbal platform.

The capabilities of SOA ion thruster technology, and the performance goals for the development of

the AIE are enumerated in Tab. 2. SOA ion technology is reflective of the performance capabilities of NASA's high-fidelity NEXT ion thruster, which has superior demonstrated F/P, and efficiency, as compared to all other EP technology options above about 2600 seconds specific impulse (Isp) [3].

Table 2. Ion Thruster Capabilities and AIE Goals

Figure of Merit	Capabilities	
	SOA ION	AIE Goal
F/P (Eff.)	>ALL Other EP Options @ >2600 sec Isp	>ALL Other EP Options over Entire Isp Range
Power	7 kW*	4-300 kW
Thrust Density	2 N/m ²	>8 N/m ²

*NEXT qualified to 7 kW, but demonstrated capability to 14 kW

Below 2600 seconds, Hall-Effect Thrusters [HETs], as embodied by the commercial HET (BPT-4000) [5], and the 12.5 kW HET (Hall Effect Rocket with Magnetic Shielding, or HERMeS) under co-development by NASA and JPL for the Solar Electric Propulsion Technology Demonstration Mission (SEP TDM) project [6] have superior performance as compared to all other EP technology options, including conventional ion thrusters (where potential thrust-losses due to cant-angle requirements for HET's larger beam divergence are ignored). Fig. 3 quantifies the SOA HET [5, 6] and SOA Ion [3] F/P ratio as a function of Isp. These two technologies represent the highest performance EP thruster options in the U.S. inventory.

The AIE, with improved thrust and electrical efficiencies associated with flat electrodes and increased thrust densities, has the potential to increase SOA Ion efficiencies and F/P over the entire Isp operational range. This would drive down the performance cross-over point between Ion and HETs below 2600 seconds, thereby and yielding superior performance over the entire Isp range [3]. Fig. 3 also includes projected performance for the AIE: a Near-Term ('minimum') performance curve assuming reduced thrust losses via implementation of flat ion optics, but with comparable discharge electrical efficiency to the NEXT thruster; and an Optimized ('maximum') performance curve which assumes both reduced thrust losses and superior discharge electrical efficiencies as compared to the NEXT thruster. As indicated, the threshold curve drives down the Isp

cross-over point to about 1800 seconds, and the goal curve yields a superior efficiency over the entire Isp range. Fig. 4 re-plots the data and projections from Fig. 3, displaying thruster efficiency vs. specific impulse.

With respect to Tab. 2, the AIE concept also enables the fabrication of high perveance large-area ion optics, which in turn increases the power handling capability per engine, doing so at specific impulse levels of interest (≤ 5000 sec., typ.). AIE designs capable of processing 100's of kW should be feasible [7].

In addition, the AIE should allow for operation at substantially higher thrust densities than SOA ion thrusters; to 8 N/m^2 or greater. This is because the annular discharge chamber allows increases the effective anode surface area for electron collection as compared to a conventional cylindrically-shaped ion thruster of equivalent beam area. This should enable operation at higher discharge currents and therefore high beam currents yielding an increase in thrust density, and if properly implemented, enabling ion optics operation at or near the Child-Langmuir limit [8].

3. APPLICATIONS

The AIE represents a natural progression of gridded ion technology beyond that embodied by NEXT ion propulsion system (IPS), and its development to higher Technology Readiness Level (TRL) can leverage the substantial resources made-to-date in the development of NEXT.

Significant number of thruster components are the same (identical, or similar) for both the NEXT thruster and the AIE, including: wiring; magnetics; discharge chamber materials; discharge and neutralizer cathodes; high voltage propellant

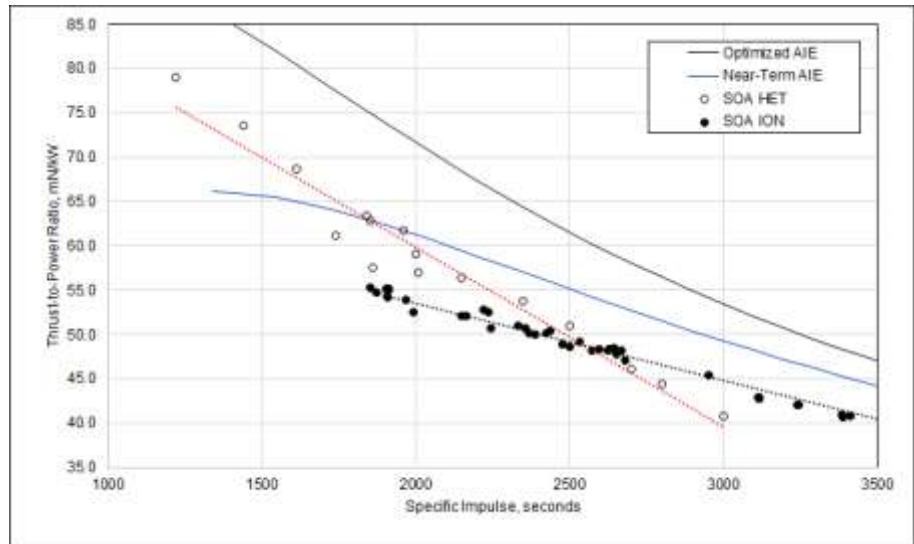


Figure 3. Thrust-to-Power ratio vs. Specific Impulse for SOA HET (BPT-4000 and HERMeS HETs), as well as SOA ION. Curve fits of data for both technologies indicate a cross-over in F/P at about 2600 seconds. Also plotted are 'Near-Term' and 'Optimized' AIE projected F/P.

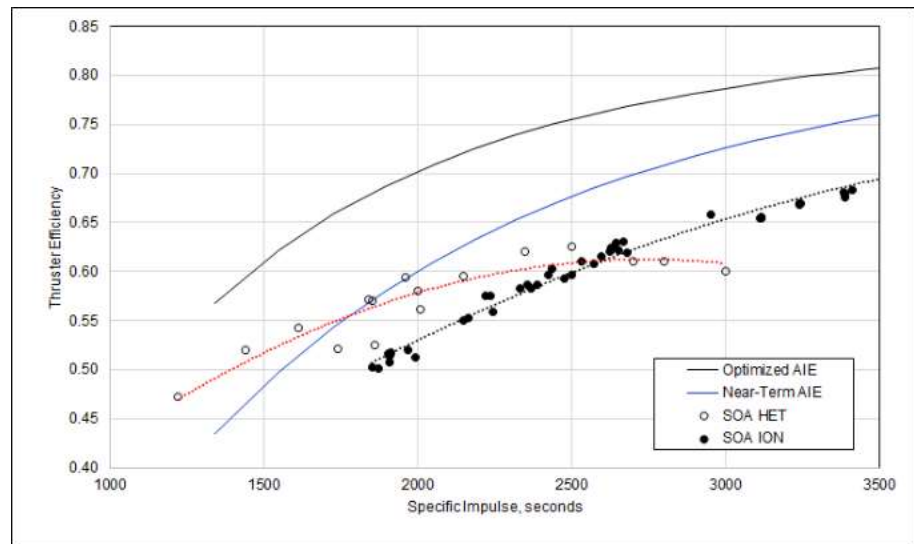


Figure 4. Thruster Efficiency vs. Specific Impulse for SOA HET and SOA ION. Also plotted are 'Near-Term' and 'Optimized' AIE projected efficiencies.

isolation, and high voltage insulators; etc. In addition, depending upon the maximum input power for the AIE, the low voltage power modules (discharge cathode and neutralizer cathode heaters, discharge) and high voltage accelerator power supply modules employed in the NEXT Power Processor Unit (PPU) could be used as-is, or the topologies for the modules (e.g., discharge) could be scaled as required for higher power.

The beam power supply in the NEXT PPU, which processes the bulk of the input power, was intentionally designed to be scaled via the addition

of modules as required to process the maximum beam current. This would be the approach for the AIE PPU.

The complexity of the AIE PPU would be driven by the intended application. In applications requiring either high F/P, or high power, one can envision a reduced input voltage range into the PPU (reduced from the NEXT PPU requirement of 80-160 V), and possibly two, or a few, throttle set-points (as opposed to NEXT's 70+ conditions).

3.1. Earth Orbital – High F/P EP

If the performance projections as reflected in Figs.3 and 4 can be realized by the AIE concept, this technology option could be a superior solution to existing Ion and HET systems presently employed on Commercial Space (CS) and National Security Space (NSS) assets in Earth orbital (EO). A bi-modal system in which the AIE is operated at high power, high F/P, low Isp, for orbit transfer, and then operated at reduced power, high Isp for stationkeeping – operating at maximum input power levels in the range of 10-20 kW per string – may be a desirable, low technology risk, pathway.

3.2. Planetary – High Power EP

The AIE has significant potential for application to NASA science missions, via the Science Mission Directorate (SMD) – who have supported, and continue to support the maturation and transition-to-flight of the NEXT IPS. While science missions may be less sensitive to gains in F/P, and in the near-term may not benefit from significant increases in power handling capability (beyond more than 10-20 kW per string) – improvements in propellant throughput, via the practical application of carbon ion optics which the AIE approach affords, could all-but-eliminate the anticipated first-failure mode of the ion thrusters, yielding ~10X increases in life time. This capability could be leveraged in several ways: by execution of missions requiring longer thruster life; by reducing the number of thruster-PPU strings necessary to process the required propellant; reducing or eliminating the application of redundant strings; and reducing the duration of life validation testing.

The AIE also could play a major role for application in support of Human architectures, via NASA's Human Exploration and Operations Mission Directorate (HEOMD), as a candidate propulsion option for 150 kW and 300 kW class Solar Electric Propulsion (SEP) vehicles. The AIE potential to extend ion thruster operation to 100's of kW, doing

so at specific impulse values of interest – at superior levels of efficiency relative to other technology options – makes it an attractive option.

Additionally, the near-lossless acceleration mechanism associated with gridded ion thrusters ensures electrical efficiencies in excess of 90%; an important consideration relative to thruster and system thermal management when processing high power. Also as the power-to-mass ratio of SEP vehicles continues to increase with technology progression, the mission-optimal specific impulse will continue to trend upward. Adaptation of ion thruster technology to an upwardly-trending optimal specific impulse is an inherent advantage of the technology.

4. TECHNOLOGY DEVELOPMENT STATUS

Despite limited resources significant progress has been made to date in the development of the AIE concept since conception in 2011 [9], including demonstration of proof-of-concept, and demonstration of scalability (reference Fig. 5):

- In 2011 a sub-scale AIE discharge chamber (40 cm outside dia.) was designed, fabricated, and tested under conditions simulating beam extraction. Highly-uniform (within 10% of the mean) azimuthal and radial discharge plasma were observed at all conditions using a single hollow cathode design;
- In 2012 the sub-scale AIE ('GEN1') was completed, and successfully tested with beam extraction using conventional ion optics. Extremely-high beam flatness was documented with operation up to 6.3 kW; 0.85-0.95, *the highest ever demonstrated for an ion thruster* [10]. Additionally flat carbon annular ion optics electrodes were successfully manufactured.
- In 2013 the sub-scaled AIE was successfully operated with flat carbon ion optics electrodes. Extremely-high beam collimation was documented; a thrust-loss correction factor of 0.997, *the highest ever demonstration for an ion thruster* [11].
- In 2014 a full-scale second-generation ('GEN2') AIE discharge chamber (65 cm outside dia.) was designed, fabricated, and tested under conditions simulating beam extraction. As with the smaller sub-scale AIE, highly-uniform (within 10% of the mean) azimuthal and radial discharge plasma were observed at all conditions using a single hollow cathode design. Additionally, full-scale flat carbon annular ion optics electrodes were

successfully manufactured. The finished pyrolytic graphite electrodes achieved all the required dimensional tolerances, with zero defects.

- In 2015 the GEN2 AIE assembly was completed, including the high-fidelity annular ion optics. Preliminary tests with beam extraction were conducted, and several minor optics and discharge chamber design modifications were identified.

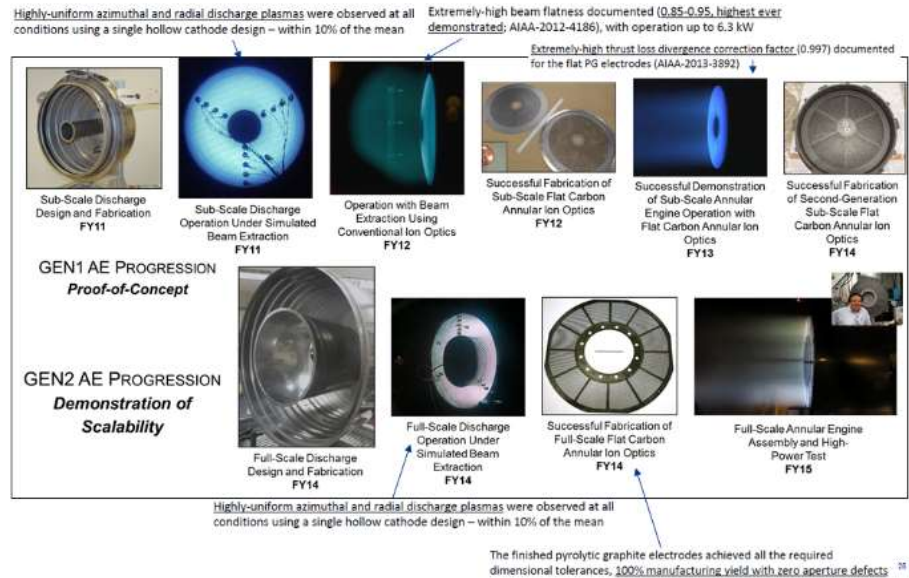


Figure 5. AIE Technology Development Status

As of 2016:

- Design upgrades to the GEN1 AIE ion optics were identified. Also an engineering task was initiated to complete the design of a higher-fidelity GEN1 AIE that would be operationally compatible with ~4-20 kW input power levels at high F/P.
- Several design modifications to the GEN2 AIE ion optics and discharge chamber assemblies were completed, and the AIE prepared for testing. This is with the intention of demonstrating high power operation; up to 60 kW.

Forward work – including retesting of the GEN1 and GEN2 AIE hardware – is predicated on securing additional resources.

5. FORWARD DEVELOPMENT PLAN

For the foreseeable future – and as is the case for nearly all EP technologies with application for primary propulsion – the mission opportunities for the AIE are likely ~10X greater and ~100X greater for NSS and CS missions as compared to NASA missions, based on NASA’s low mission rate. Despite these opportunities, the in-space propulsion investment resources within NASA appear constrained to the development of technologies which have specific and direct application to the anticipated/planned NASA mission set. To the degree these technologies also have non-NASA applications, leveraged resources are sought.

As such, and unless the technology is adopted for further development by non-NASA U.S. customers,

the NASA development path for the AIE concept will be supported to the degree it is aligned with the anticipated NASA mission set. The potential for ‘off-ramp’ products within these development activities which may have performance capabilities more-directly supportive of the non-NASA customers is possible.

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