Annular Ion Engine: Evolutionary Approach to Achieve Revolutionary Capabilities

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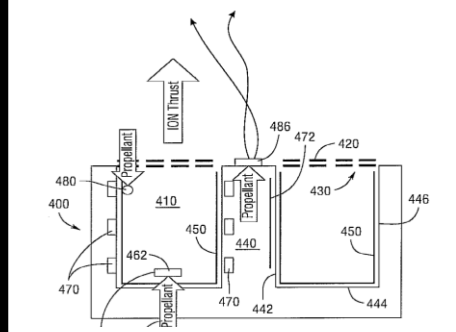
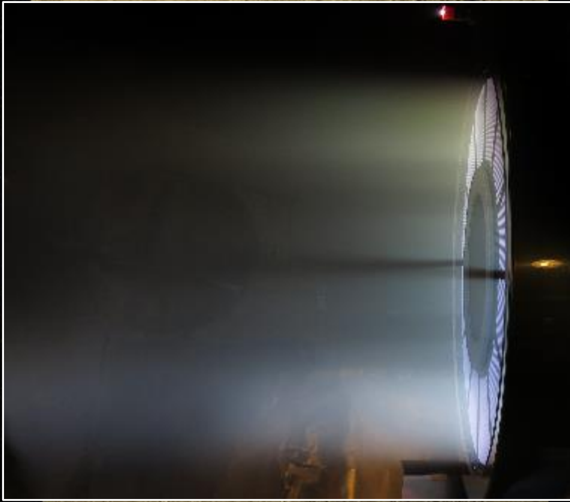
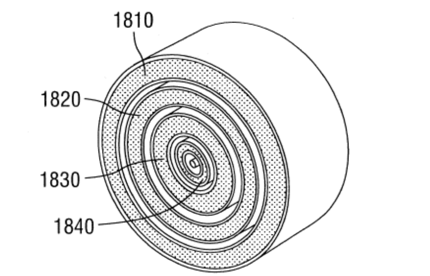
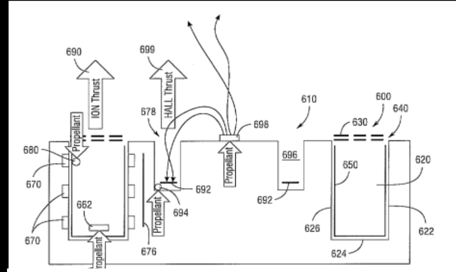


Annular-Geometry Ion-Engine (AGI-Engine, or 'AIE')





Multi-ring Annular-Geometry Ion-Engine (MAGI-Engine)



Dual-Mode Hybrid-Engine (DMH-Engine)

Co-Investigator: The Aerospace Corporation

Outline

1. Concept Description
2. Concept Advantages
3. Applications
4. Technology Development Status
5. Forward Development Plan

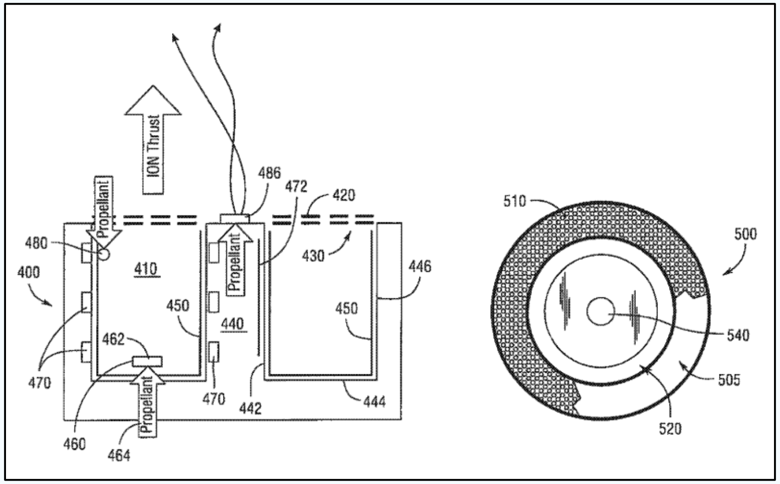
All concepts disclosed in this presentation are covered under U.S. Patent **#8,468,794** ("ELECTRIC PROPULSION APPARATUS", June 25, 2013), U.S. Patent **#9,279,368** ("MULTI-THRUSTER PROPULSION APPARATUS", March 29, 2016), and Patents-Pending filed under both U.S. and International Patent Applications

Assignee: United States Government

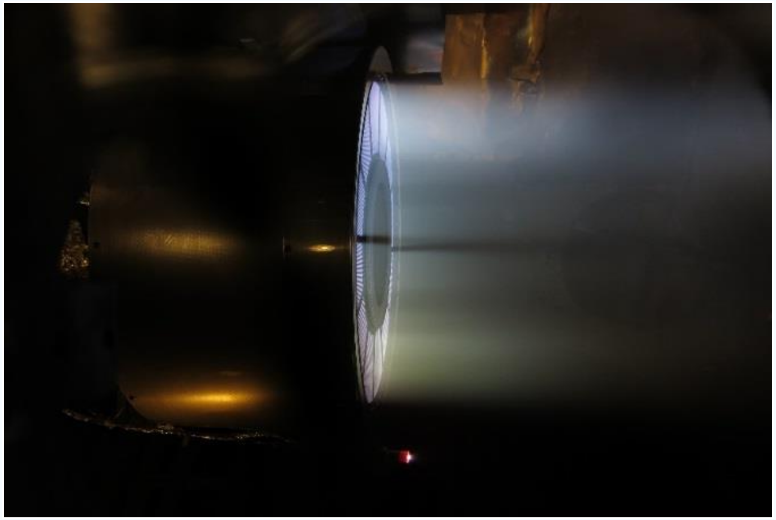
Concept Description

The Annular Ion Engine (AIE) concept consists of an annular discharge chamber, with a set of annular ion optics, potentially configured with a centrally-mounted neutralizer cathode assembly –

It is an evolutionary development with revolutionary capability



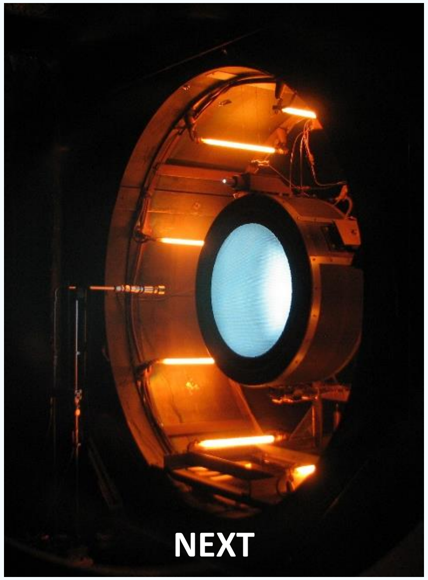
AIE Concept
Cross-Section and Frontal View



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

Concept Description

*From **NEXT** to the **Next-Generation***



State-of-the-Art (SOA) Ion Thruster: NASA's Evolutionary Xenon Thruster (NEXT)

Conventional ion engines are limited in beam diameter to ≤ 45 cm – as it is difficult to mechanically fabricate larger ion optics while maintaining small span-to-gap ratios necessary to achieve high thrust densities. The Annular Ion Engine (AIE) because of its novel design enables fabrication of large area optics with small span-to-gap ratios → yielding high thrust density operation at high power

Concept Advantages

The AIE has significant potential advantages over conventional ion thrusters, and other EP thruster concepts, including:

Higher thrust densities: Annular discharge eliminates source-limited operation, which contributes to higher thrust density (~3X) relative to SOA ion engines

Extensibility to high power: An annular design enables manufacturing very large beam area ion optics with relatively small electrode spans and relatively small span-to-gap ratios. Annular geometry also allows nesting of rings, so that engine diameter scales as the square root of power. Both attributes enable scaling to very high power levels (100's of kW).

Improved Efficiencies and F/P: Annular-geometry ion optics of small span can employ flat electrodes, yielding improved efficiencies by eliminating off-axis beam vectoring associated with spherically-domed ion optics electrodes used on cylindrical thrusters

Enhanced life time: Relatively-simple physical design of the electrodes circumvents manufacturing issues, allowing the practical implementation of carbon and the life time enhancements of this material

Concept Advantages

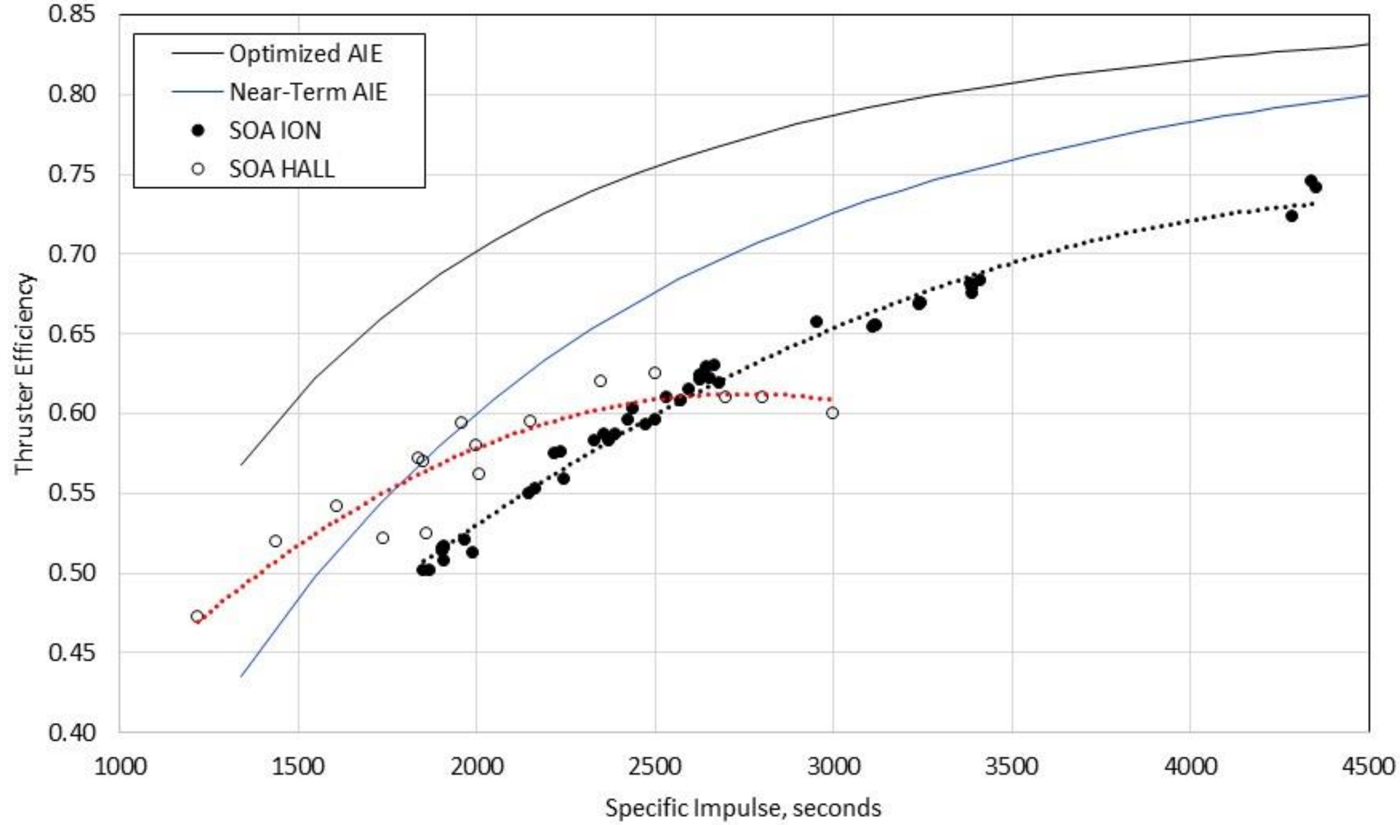
SOA Ion thruster technology, and AIE performance goals:

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

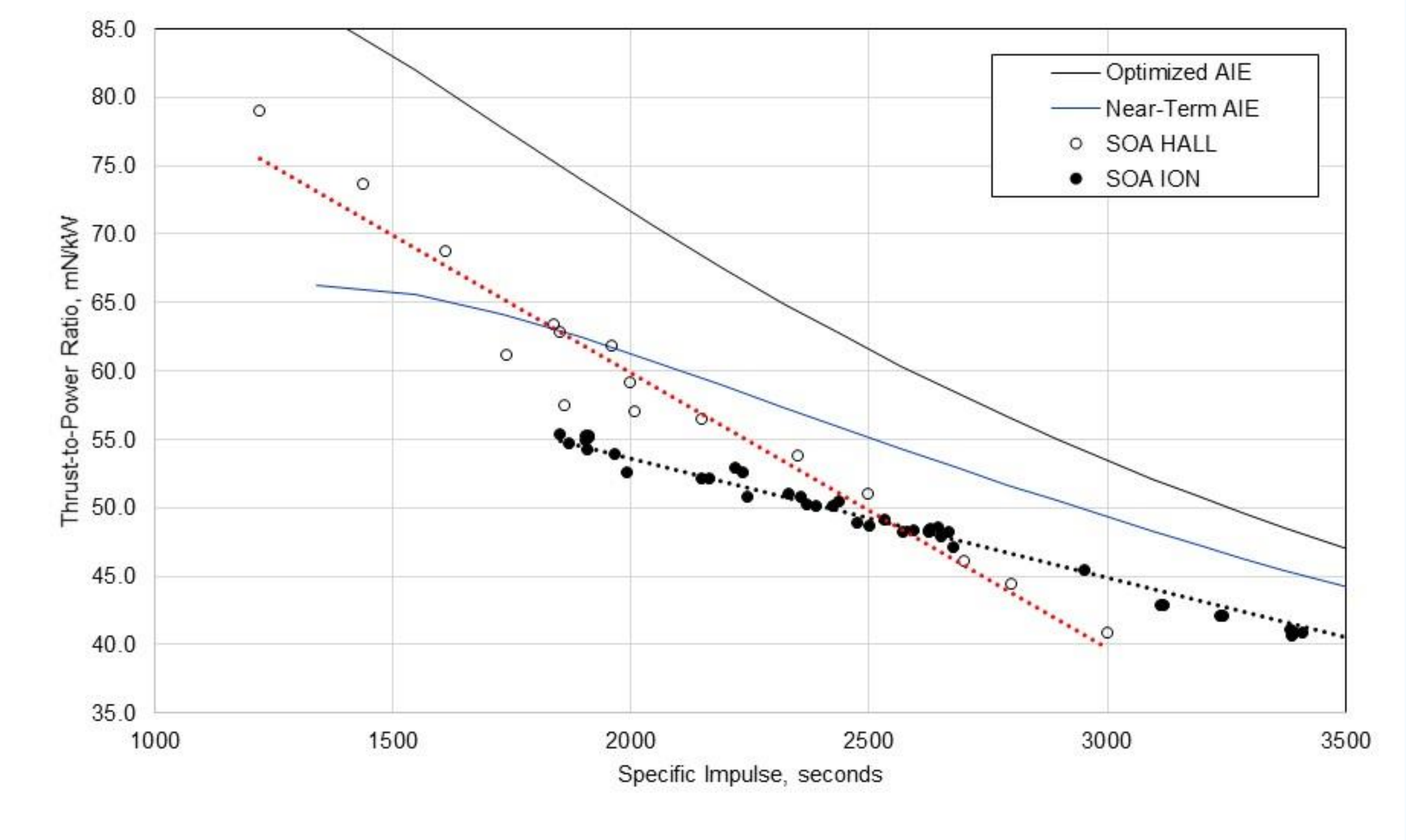
SOA ion technology is representative of the performance capabilities of NASA's high-fidelity NEXT ion thruster, which has superior demonstrated F/P, and efficiency, as compared to all other EP technology options above about 2600 seconds Isp

Concept Advantages



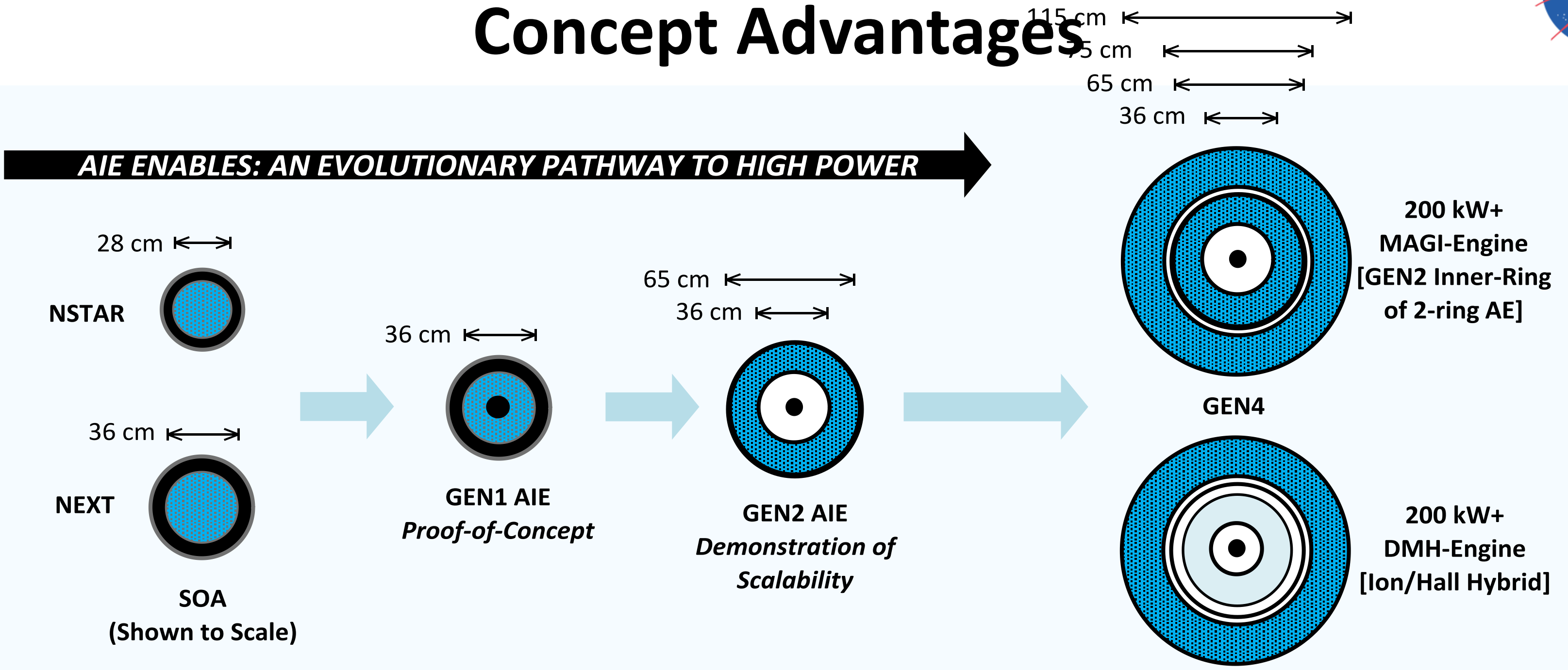
- Hall thruster and Ion Thrusters represent the highest performance EP thruster options in the U.S. inventory
- The AIE has the potential to achieve excellent performance over entire range of Isp operation needed for future NASA, Commercial, and National Security Space applications

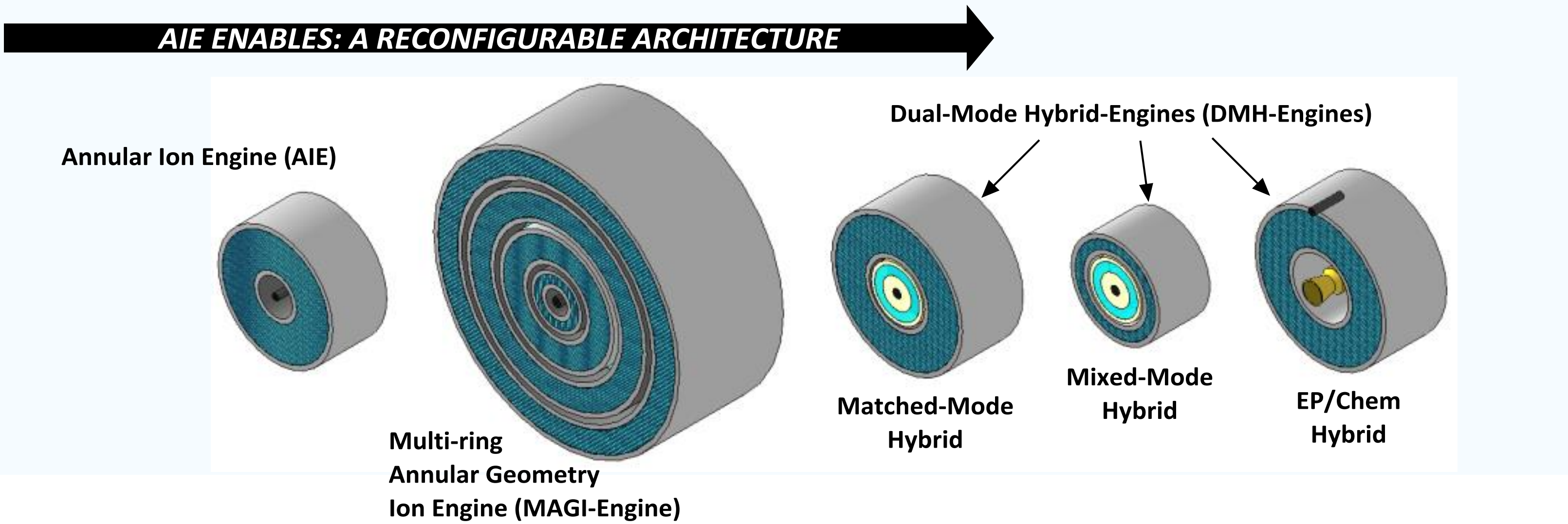
Concept Advantages



AIE could achieve higher Thrust/Power over the entire Isp range. Near-term potential to lower the cross-over point for Hall/Ion performance from 2,600 secs to 1,800 secs.

Concept Advantages





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 can leverage the substantial resources made-to-date in the development of NEXT

Earth Orbital – High F/P EP

If the AIE performance projections can be realized, this technology option would be a superior solution to existing Ion and Hall systems presently employed on Commercial Space and National Security Space assets in Earth orbit:

- 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

Applications

Planetary – High Power EP

The AIE has significant potential for application to **NASA Science Missions** –

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 by:

- Executing missions requiring longer thruster life;
- 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

Applications

Planetary – High Power EP

The AIE could play a major role in support of **NASA Human architectures** 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:

- The near-lossless acceleration mechanism ensures electrical efficiencies in excess of 90%; an important consideration relative to thruster and system thermal management when processing high power
- 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

Technology Development Status

Despite limited resources significant progress has been made to date in the development of the AIE concept since conception in 2011, including *demonstration of proof-of-concept*, and *demonstration of scalability* –

<u>2011</u>: **A sub-scale AIE discharge chamber (40 cm outside dia.) was designed, fabricated, and tested**. Highly-uniform azimuthal and radial discharge plasma were observed at all conditions using a single hollow cathode design;

<u>2012:</u> The sub-scale first-generation ('GEN1') AIE was completed, and successfully tested using conventional ion optics. <u>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.</u> Flat carbon annular ion optics electrodes were successfully manufactured.

<u>2013</u>: **The sub-scaled AIE was successfully operated with flat carbon ion optics electrodes.** <u>Extremely-high beam collimation was documented; a thrust-loss correction factor of 0.997, the highest ever demonstration for an ion thruster.</u>

<u>2014:</u> A full-scale second-generation ('GEN2') AIE discharge chamber (65 cm outside dia.) was designed, fabricated, and tested. Full-scale flat carbon annular ion optics electrodes were successfully manufactured. <u>The finished pyrolytic graphite electrodes achieved all the required dimensional tolerances, with zero defects</u>.

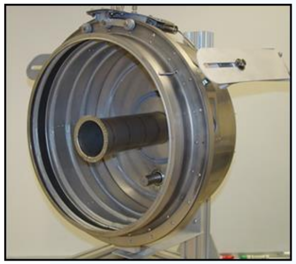
<u>2015:</u> The GEN2 AIE assembly was completed. The ion optics assembly, fabricated from pyrolytic graphite electrodes and a carbon fiber-reinforced carbon mounting system, <u>are the largest-area high-perveance design ever manufactured.</u> Preliminary tests with beam extraction were conducted, and several minor optics and discharge chamber design modifications were identified.

Technology Development Status

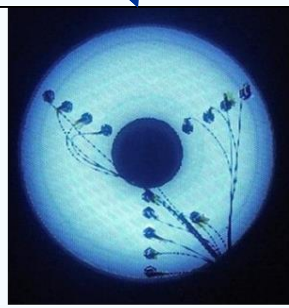
Highly-uniform azimuthal and radial discharge plasmas were observed at all conditions using a single hollow cathode design – within 10% of the mean

Extremely-high beam flatness documented (0.85-0.95, highest ever demonstrated; AIAA-2012-4186), with operation up to 6.3 kW

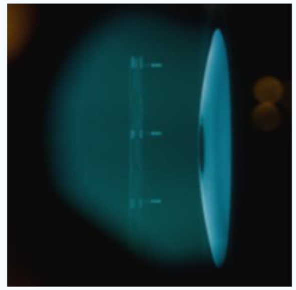
Extremely-high thrust loss divergence correction factor (0.997) documented for the flat PG electrodes (AIAA-2013-3892)



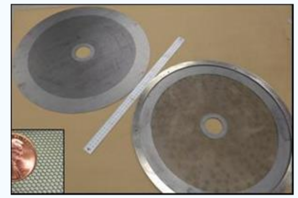
Sub-Scale Discharge Design and Fabrication
FY11



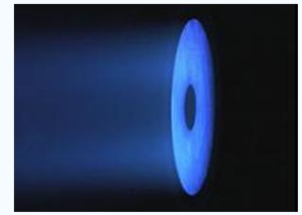
Sub-Scale Discharge Operation Under Simulated Beam Extraction
FY11



Operation with Beam Extraction Using Conventional Ion Optics
FY12



Successful Fabrication of Sub-Scale Flat Carbon Annular Ion Optics
FY12



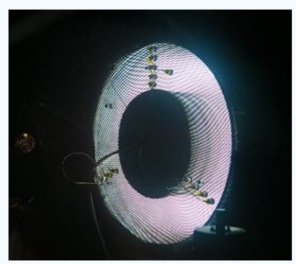
Successful Demonstration of Sub-Scale Annular Engine Operation with Flat Carbon Annular Ion Optics
FY13

Successful Fabrication of Second-Generation Sub-Scale Flat Carbon Annular Ion Optics
FY14

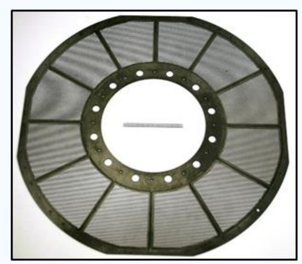
GEN1 AE PROGRESSION
Proof-of-Concept

GEN2 AE PROGRESSION
Demonstration of Scalability

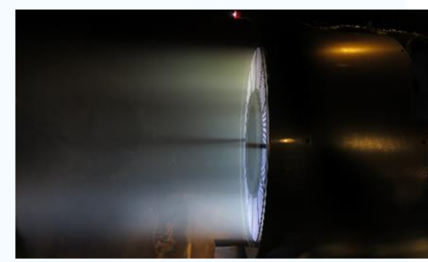
Full-Scale Discharge Design and Fabrication
FY14



Full-Scale Discharge Operation Under Simulated Beam Extraction
FY14



Successful Fabrication of Full-Scale Flat Carbon Annular Ion Optics
FY14



Full-Scale Annular Engine Assembly and High-Power Test
FY15

Highly-uniform azimuthal and radial discharge plasmas were observed at all conditions using a single hollow cathode design – within 10% of the mean

The finished pyrolytic graphite electrodes achieved all the required dimensional tolerances, 100% manufacturing yield with zero aperture defects

Forward Development Plan

In 2016:

- Design upgrades to the GEN1 AIE ion optics were identified and 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:

- 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

Summary

- The AIE concept has the potential to revolutionize the implementation of electric propulsion (EP) – delivering the highest performance technology option – while employing an approach based on well-understood physics and heritage of ion thrusters

- It is ‘Home-Grown’ NASA IP: patent awarded; patents pending

- Technology has potential at ~20 kW power levels for NASA Science Missions (*What’s next after NEXT?*) and non-NASA Earth-orbital applications (National Security Space, Commercial). It is also well suited for HEO applications being scalable to 300 kW and greater.

- Leverages NASA’s ion technology investments of ~$100M over last decade

- Very modest resources are required to advance the AIE concept technology readiness level, while yielding multiple product pathways supporting NASA , National Security Space, and Commercial applications

Questions?