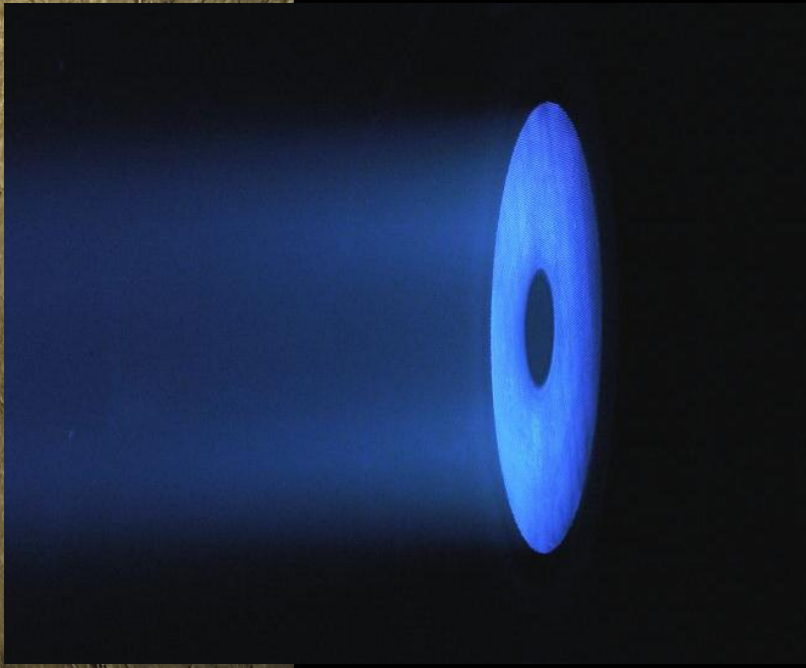
Extending the Performance Capabilities of Electrostatic Ion Engines

Michael J. Patterson

Michael.J.Patterson@nasa.gov

2012 Advanced Space Propulsion Workshop



ACKNOWLEDGEMENTS

This work was supported under the 2012 GRC Center Innovation Fund Program

Sponsored by NASA's **Office of Chief Technologist**

DISCLOSURES

All concepts disclosed in the presentation are Patent-Pending and are filed under both U.S. and International Patent Applications

Assignee – United States Government

Much of the development work for this Concept is being done in partnership with:

The Aerospace Corporation (DoD FFRDC)

University of Michigan

Aerojet Corporation/Redmond Operations

OUTLINE

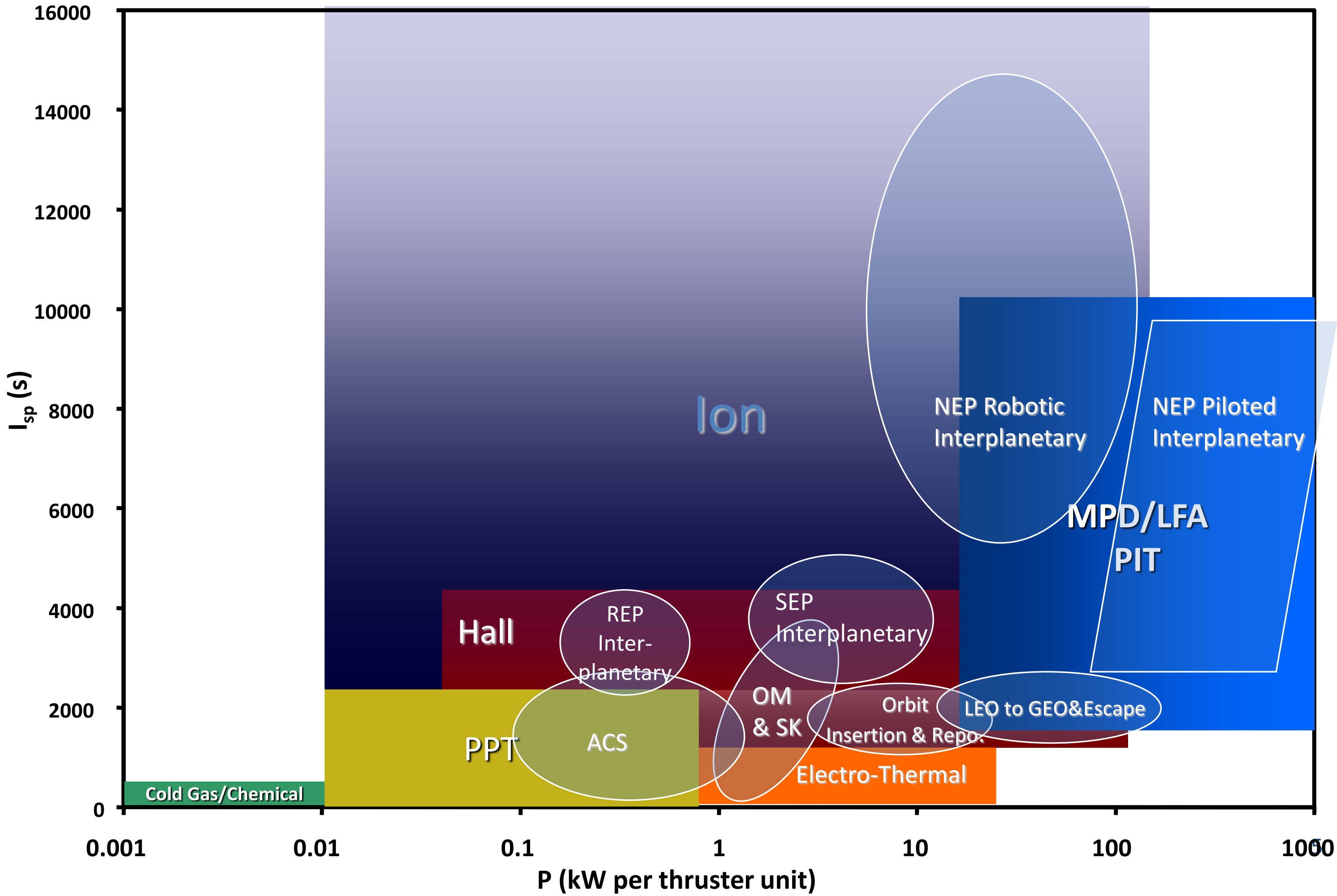
What are the Actual performance characteristics and limitations of SOA Ion Engines?

What potential advantages might the Next-Generation Electric Propulsion Thruster (Annular Engine) approach provide in extending the performance capabilities of Ion Engines?

What are the likely practical limitations of the Annular Engine concept?

What is the development status of the Annular Engine?

What are the Actual performance characteristics and limitations of SOA Ion Engines?



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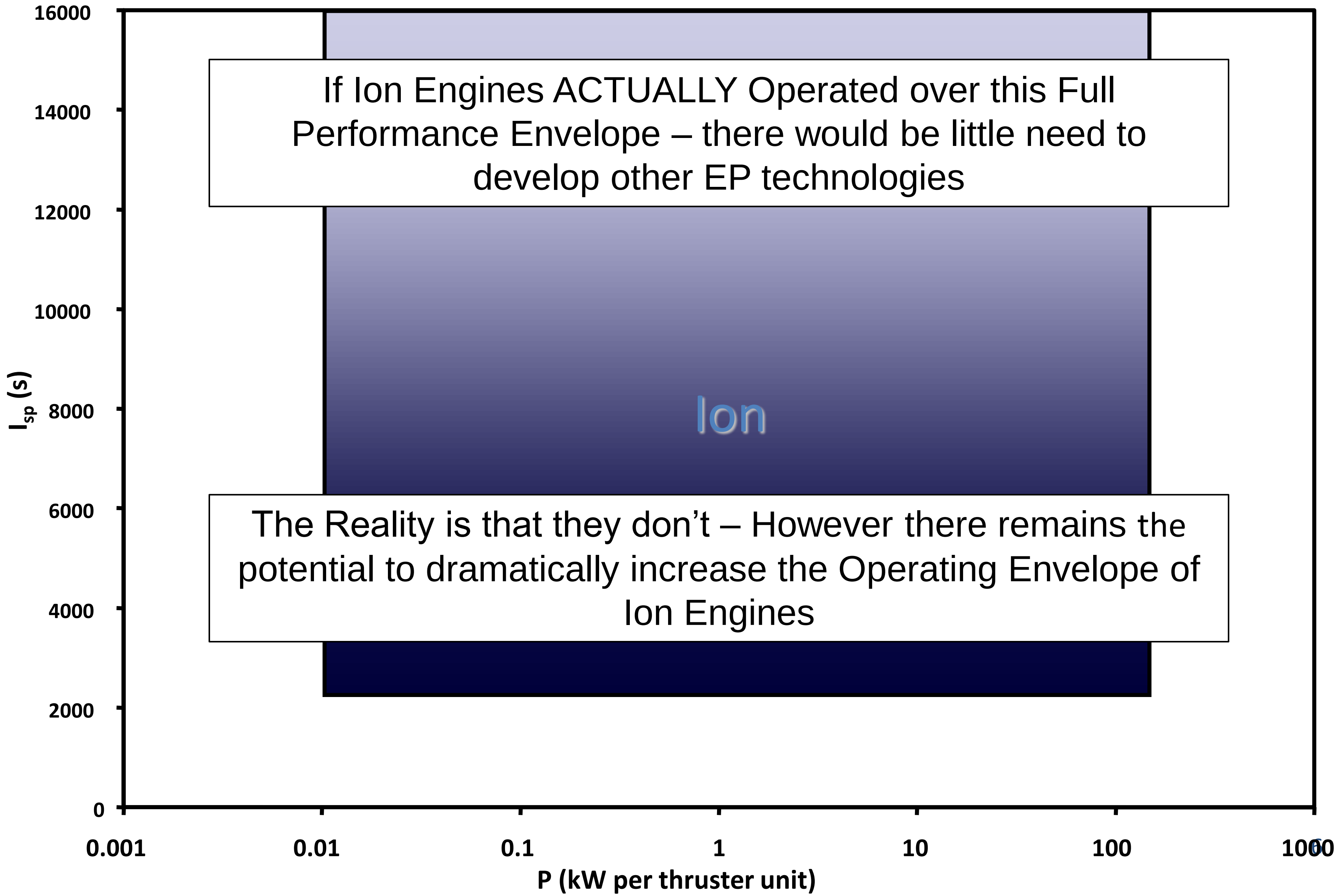

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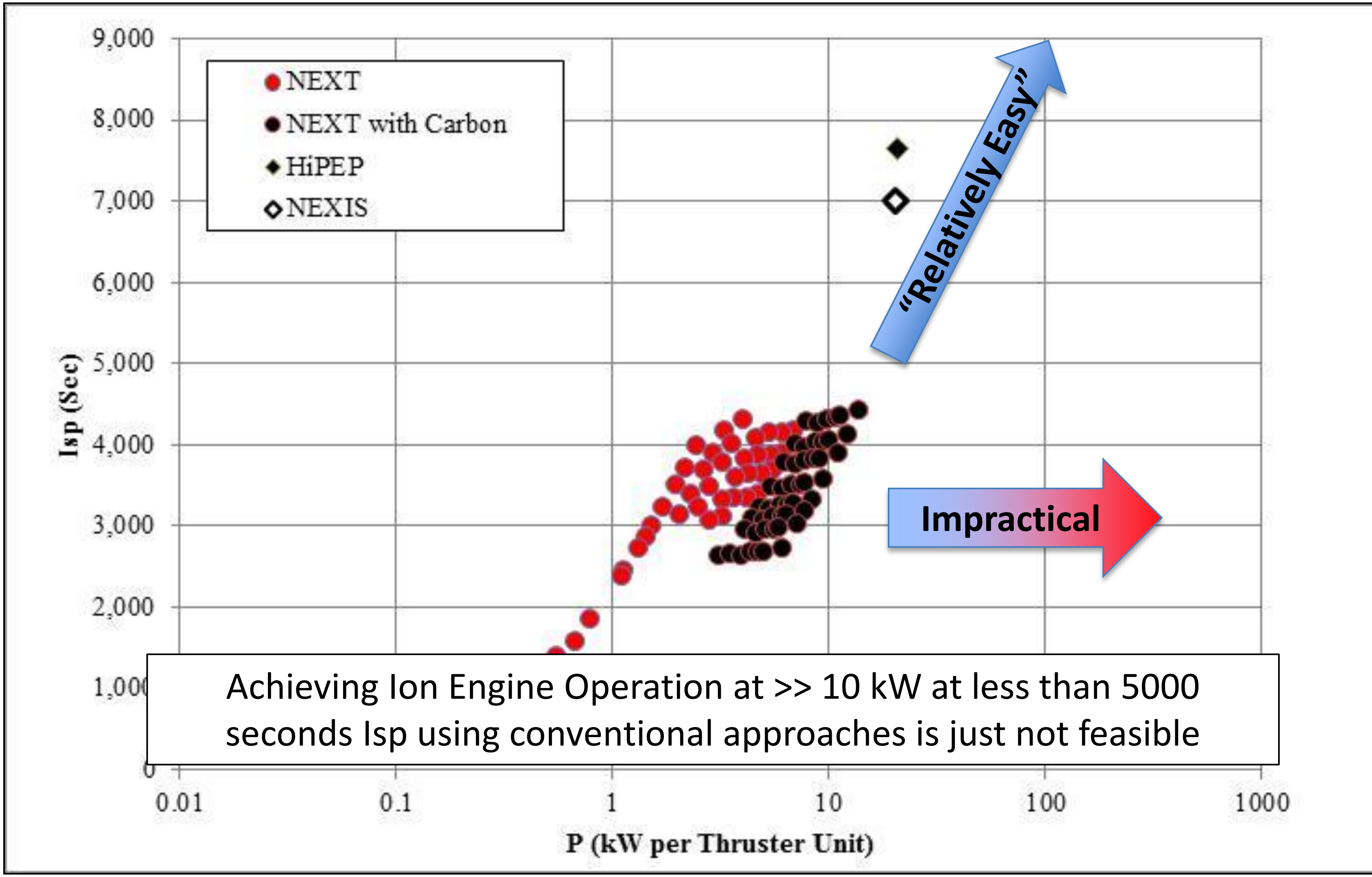


Achieving Ion Engine Operation at >> 10 kW at less than 5000 seconds Isp using conventional approaches is just not feasible

WHAT ARE THE ACTUAL PERFORMANCE CHARACTERISTICS AND LIMITATIONS OF SOA ION ENGINES?

- Achieving Ion Engine Operation at >> 10 kW at less than 5000 seconds Isp using conventional approaches is just not feasible

- This is because to do so requires high-perveance electrode designs – such as those employed on the NSTAR and NEXT thrusters – with Ion Optics Span-to-Gap ratios > 600:1 – which is impractical from a manufacturing and assembly standpoint

What potential advantages might the Annular Engine provide in extending the performance of Ion Engines?

- However Annular-geometry ion optics may allow for scaling of ion thrusters to very high power at ≤ 5,000 sec Isp by enabling very-large beam areas with relatively small electrode spans, and relatively small Span-to-Gap ratios
  - This circumvents the manufacturing, and the mechanical and thermal stability issues inherent with attempting to ever-increase the beam area via increasing the diameter of spherically-domed ion optics used on conventional cylindrical ion thrusters
- The Annular Engine approach allows for a reduction in Span-to-Gap ratio for a given beam area over ion optics of conventional design: typically to ≤ 200:1 ratio

WHAT POTENTIAL ADVANTAGES MIGHT THE ANNULAR ENGINE PROVIDE IN EXTENDING THE PERFORMANCE OF ION ENGINES?

- The annular-shaped discharge chamber of an Annular Engine also increases the effective anode-surface area for electron-collection as compared to a conventional cylindrically-shaped ion thruster of equivalent beam area
  - This may allow the Engine to operate utilizing the full-perveance capability of the ion optics, and not have its maximum input power level limited by the available anode surface area
- The increase in anode surface area may allow the Annular Engine to operate at higher discharge currents and therefore potentially higher beam currents and input power levels than a SOA ion thrusters of equivalent beam area for a given specific impulse: typically a 2-3X increase in power density

What are the likely practical limitations of the Annular Engine concept?

- The Annular Engine approach allows for a dramatic reduction in optics span, and Span-to-Gap ratio for a given beam area over ion optics of conventional design: typically a 4-6X reduction in Span-to-Gap ratios
- **However** there are manufacturing limitations to the fabrication size of Pyrolytic Graphite (PG) material – the leading candidate material for the Engine optics
- Present manufacturing issues limit **individual PG panel sizes to about 66 cm diameter**

  - may be circumvented by combining smaller PG panels

What are the likely practical limitations of the Annular Engine concept?

- Recent tests at GRC of Flat PG annular electrodes of a high-perveance design (NEXT Engine electrostatic configuration) indicate that:
  - Electric field strengths of at least **2400 V/mm**; and
  - Unsupported spans in the active area of at least **14.4 cm** are feasible without significant electrostatic deflection
- The combination therefore of the maximum single panel diameter of 66 cm and a span of 14.4 cm would yield a maximum area for a single-panel annular electrode of **2333 cm^2** – approximately **2.3X the beam area of the NEXT Engine**

WHAT ARE THE LIKELY PRACTICAL LIMITATIONS OF THE ANNULAR ENGINE CONCEPT?

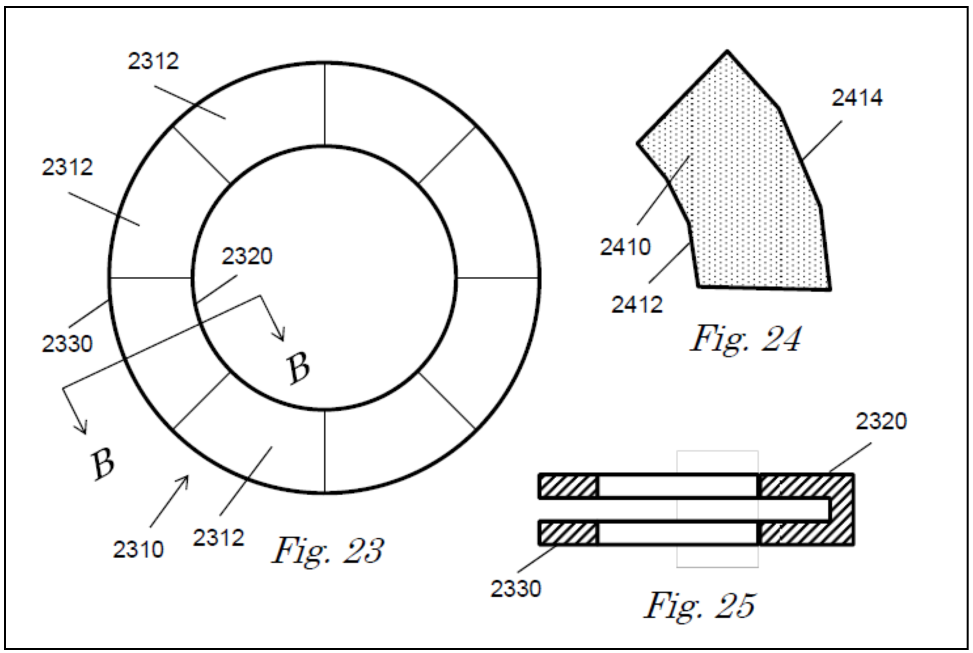
- Nesting a NEXT Engine within the interior of this Annular Engine would yield a total beam area of **3350 cm^2 – or about 3.3X the beam area of the NEXT Engine**
- At the maximum power density demonstrated with the NEXT Engine an Annular Engine/NEXT Engine hybrid could yield a **peak power level of approximately 58.4 kW at 4670 seconds Isp** using this **SINGLE PANEL CONSTRUCTION TECHNIQUE**

WHAT ARE THE LIKELY PRACTICAL LIMITATIONS OF THE ANNULAR ENGINE CONCEPT?

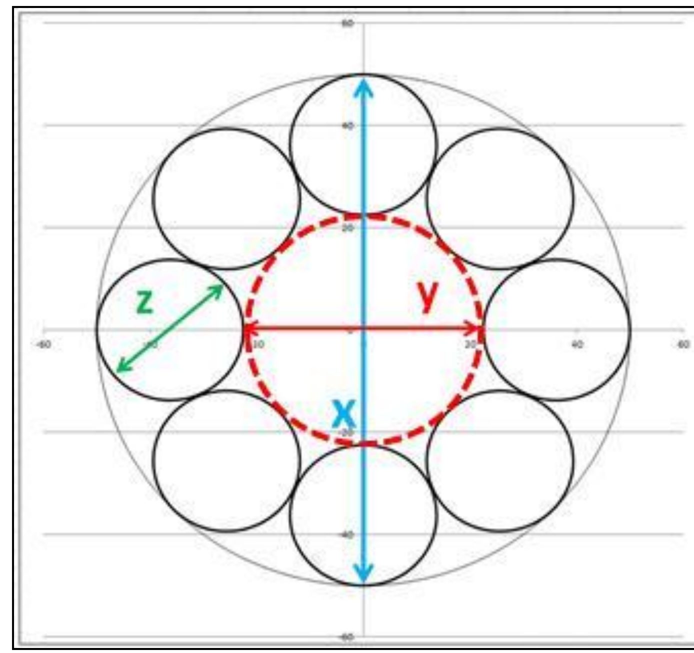
- One means of circumventing the present manufacturing size limitations associated with fabricating PG panels for annular ion optics is to implement ***Segmented*** or ***Unitized*** electrodes to limit the required size of individual panels
- The individual panels would then be clustered together and mechanically secured to a framework on the discharge chamber to create an annulus (annulus maintained for nesting)

WHAT ARE THE LIKELY PRACTICAL LIMITATIONS OF THE ANNULAR ENGINE CONCEPT?

EXAMPLES OF MULTI-PANEL CONSTRUCTION TECHNIQUE



Segmented Pie-Wedged Electrodes arranged in an annular geometry

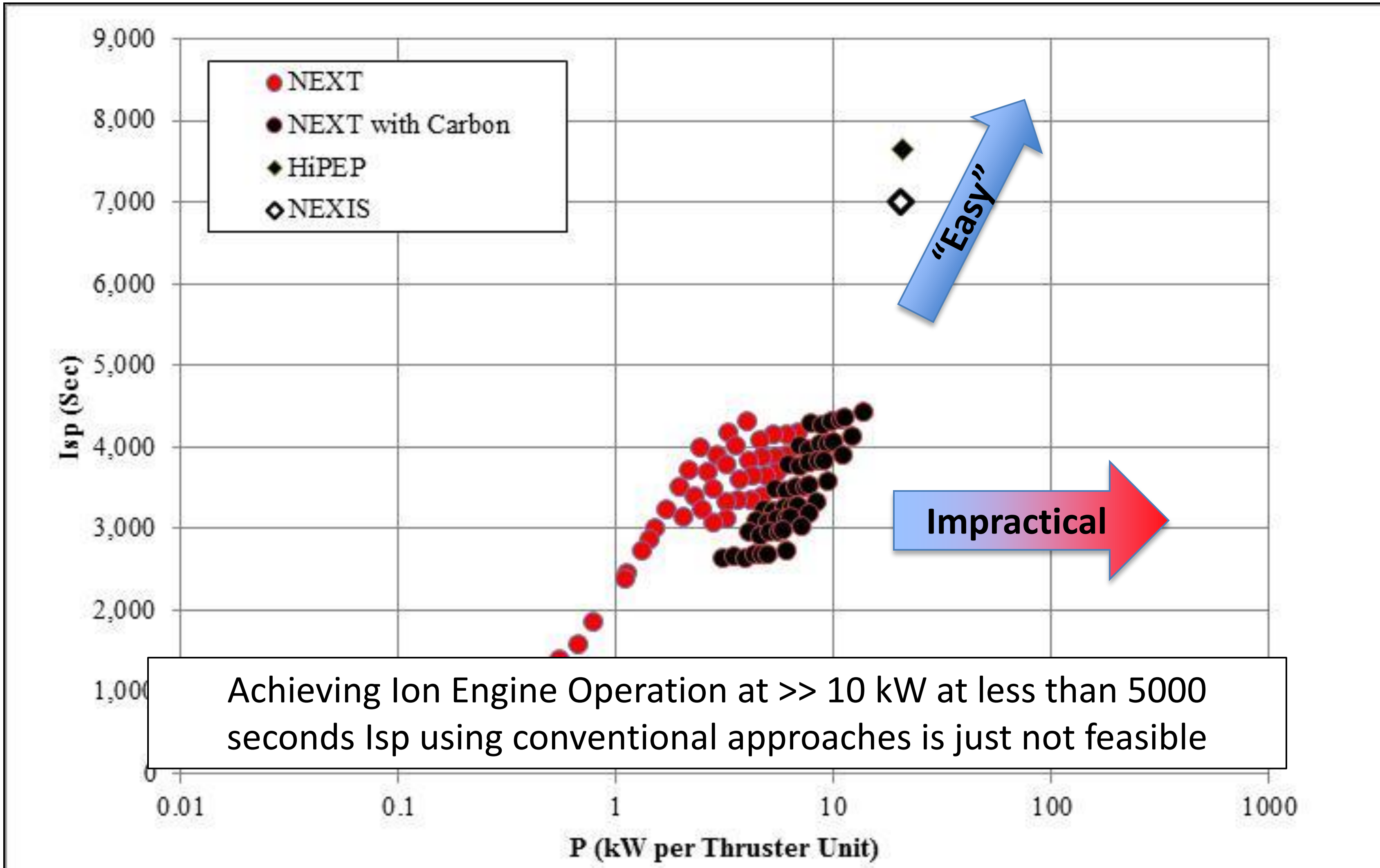


Unitized Circular Electrodes arranged in an annular geometry

WHAT ARE THE LIKELY PRACTICAL LIMITATIONS OF THE ANNULAR ENGINE CONCEPT?

- By applying this **MULTI-PANEL CONSTRUCTION TECHNIQUE** the maximum size of the Annular Engine which could be built is only limited by considerations associated with spacecraft integration – 1.5 meters in diameter or greater may be practical
- A Multi-ring (nested) Annular Geometry Ion-Engine (MAGI-Engine) constructed of 4 rings with a constant span of 17 cm and with the outer-most ring having an outside diameter of approximately 1.5 m could potentially achieve input power levels exceeding **0.10 MW at about 1,800 seconds Isp, and > 0.30 MW processed above about 4,000 seconds Isp**

WHAT ARE THE LIKELY PRACTICAL LIMITATIONS OF THE ANNULAR ENGINE CONCEPT?



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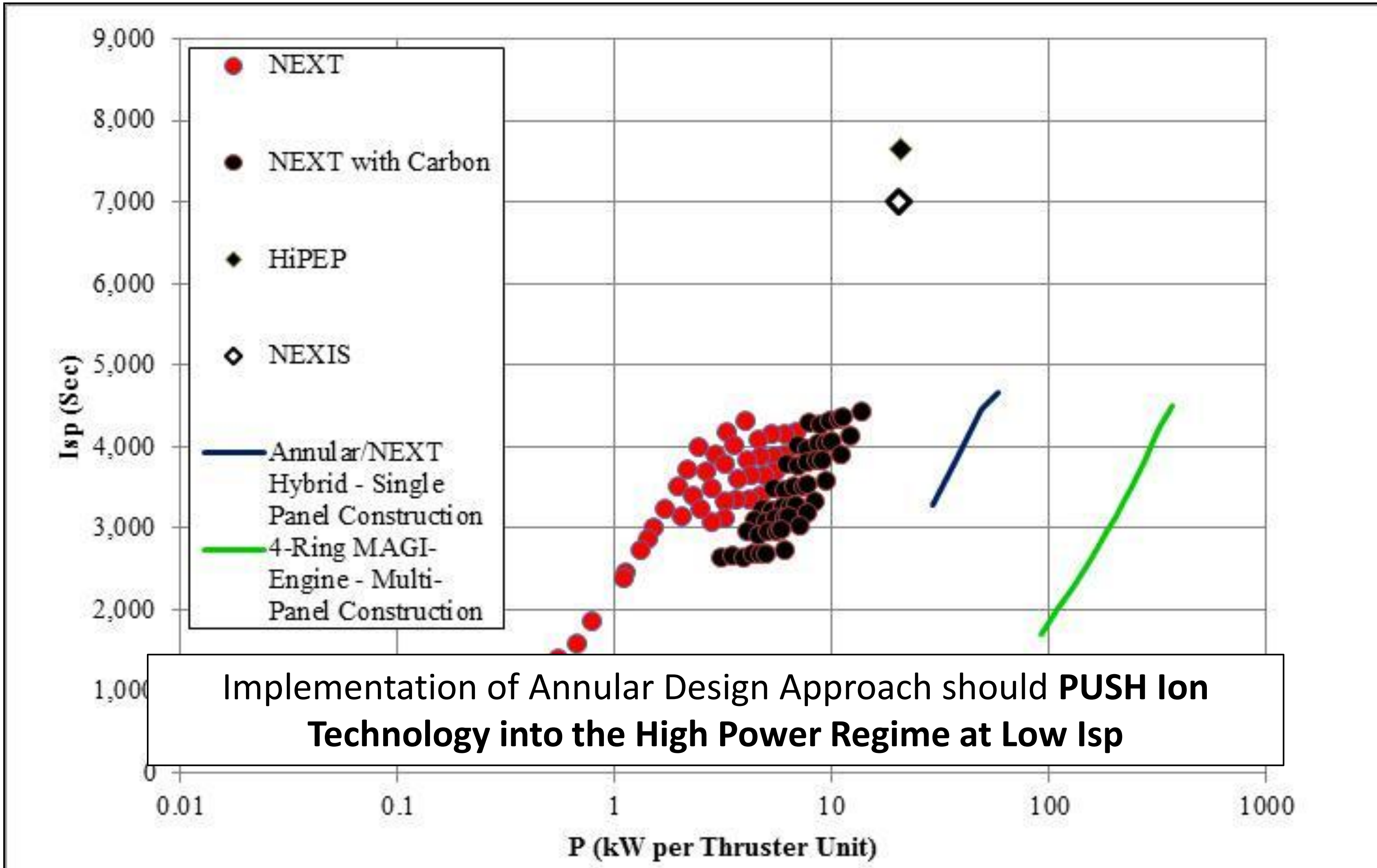
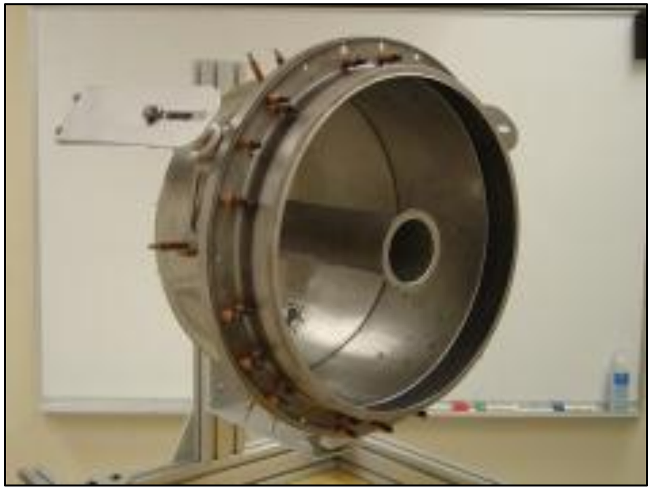
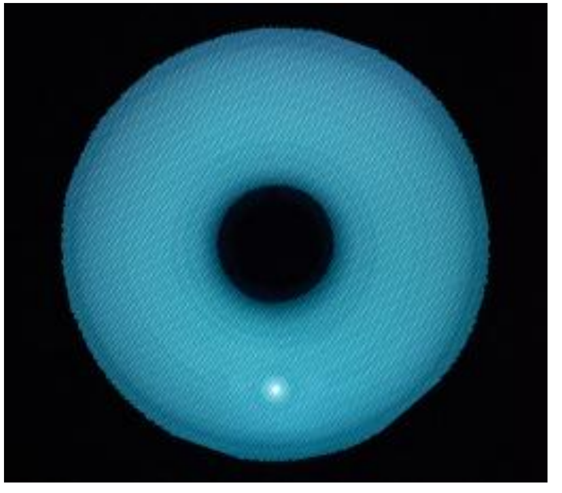


Implementation of Annular Design Approach should **PUSH Ion Technology into the High Power Regime at Low Isp**

What is the development status of the Annular Engine?

- To date most of the development tasks associated with demonstration of the feasibility of the Annular Engine have been completed – as presented at JPC2012 – on a subscale Engine





- What remains is demonstration of Engine scalability

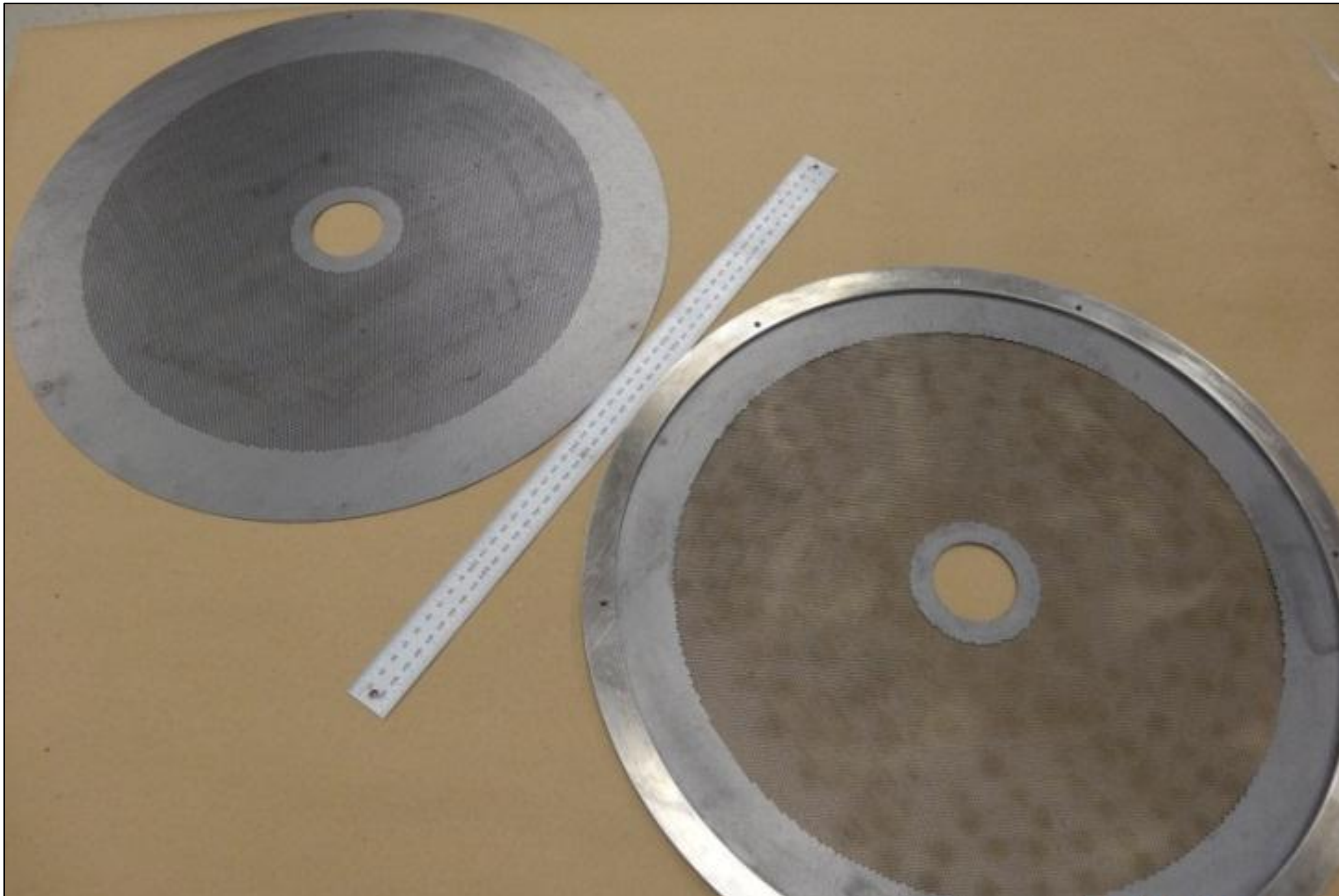
What is the development status of the Annular Engine?

Development Task	Status	Comment
#1. Demonstrate Stable Annular Discharge Operation	**Demonstrated**	JPC2012
#2. Demonstrate Uniform Annular Plasma Densities	**Demonstrated**	JPC2012
#3. Demonstrate Low (< 400 W/A) Discharge Losses	**Demonstrated**	JPC2012: ~200 W/A
#4. Demonstrate Uniform Beam Current Density	**Demonstrated**	JPC2012
#5. Demonstrate Feasibility of Annular Ion Optics at Sub-Scale	**Demonstrated**	Operation with Beam Extraction: JPC2013
#6. Demonstrate Scalability of Annular Discharge-and-Ion Optics	**To Be Demonstrated**	> 36 cm Beam Diameter
#7. Demonstrate Higher Supportable Discharge Currents than SOA	**Partially Demonstrated**	> 30 Amperes for 40 cm Ø Discharge
#8. Demonstrate Higher Beam Current Densities than SOA	**To Be Demonstrated**	> 4 mA/cm^2 average
#9. Demonstrate Carbon-Based Annular Ion Optics	**Demonstrated**	Pyrolytic Graphite: IEPC2013
#10. Demonstrate Feasibility of Flat Annular Ion Optics	**Demonstrated**	Improved Performance & Reduced Fabrication Cost: IEPC2013

What is the development status of the Annular Engine?

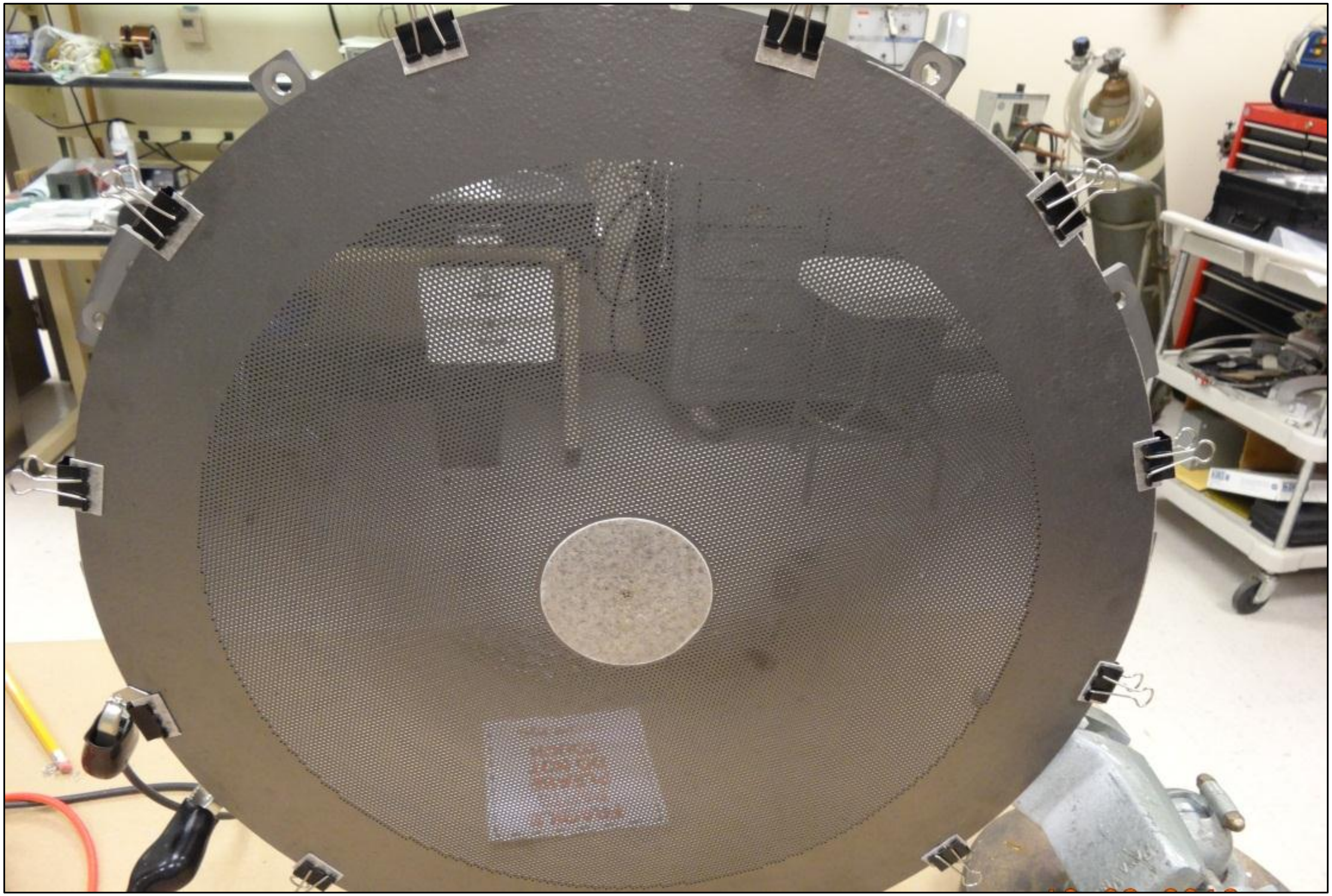
- What has been completed since last reporting is the successful fabrication and testing of Flat Annular Ion optics manufactured from PG
- **Why Flat?** → To improve Engine performance by eliminating the off-axis beam vectoring associated with spherically-domed ion optics electrodes used on cylindrical thrusters, and to simplify the manufacturing process
- **Why PG?** → To take advantage of the life enhancement enabled by Carbon, and its low CTE

What is the development status of the Annular Engine?



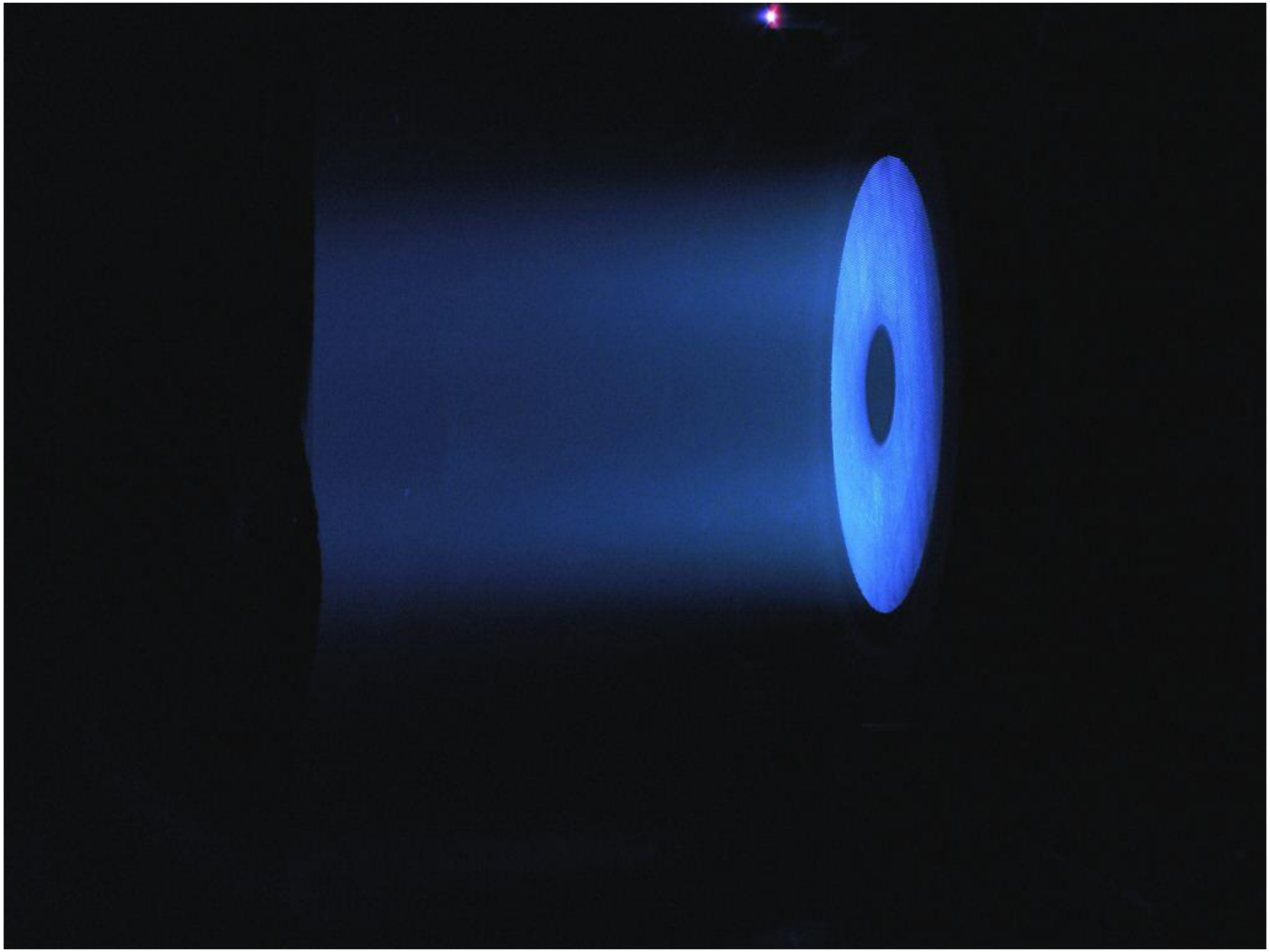
Large-Diameter Flat Pyrolytic Graphite Electrodes
~23,000 matched thru-holes

WHAT IS THE DEVELOPMENT STATUS OF THE ANNULAR ENGINE?



Electrostatic Testing of Pyrolytic Graphite Ion Optics Assembly

WHAT IS THE DEVELOPMENT STATUS OF THE ANNULAR ENGINE?



Annular Engine with Flat PG Ion Optics under Beam-Extraction Testing at The Aerospace Corporation

SUMMARY

- SOA Ion thrusters are limited to about 10-15 kW at < 5,000 seconds Isp due to limitations in the ability to scale high-perveance ion optics to large areas
- The Annular Engine approach may allow for a practical means of dramatically increasing the input power capability of ion thruster technology at low Isp by limiting the required maximum Span-to-Gap ratio of the ion optics
- Ion optics manufactured from Single-Panel PG may restrict the maximum Engine size to about 66 cm diameter – however this size Engine may achieve > 50 kW at sub-5000 seconds
- Using a Multi-Panel PG optics design may allow for unrestricted Engine size, enabling > 0.10 MW operation at 1,800 seconds and above

SUMMARY

- Progress has been made in the development of the Annular Engine – including the successful fabrication and testing of Flat PG Annular ion optics
- Results will be presented at the JPC2013 and IEPC2013

NEXT-GENERATION ELECTRIC PROPULSION THRUSTERS