REPORT DOCUMENTATION PAGE

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE 20220522	**2. REPORT TYPE** Briefing Charts	**3. DATES COVERED** **START DATE** 20220503	**END DATE** 20230630

4. TITLE AND SUBTITLE
Propellant Agnostic High Power EP

5a. CONTRACT NUMBER	**5b. GRANT NUMBER**	**5c. PROGRAM ELEMENT NUMBER**
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER** Q2JP

6. AUTHOR(S)
Daniel Eckhardt

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory (AFMC)
AFRL/RQRS
1 Ara Drive
Edwards AFB, CA 93524-7013

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory (AFMC), AFRL/RQR
5 Pollux Drive
Edwards AFB, CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RQ-ED-VG-2022-106

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A: Approved for Public Release; Distribution is Unlimited. PA Clearance Number:AFRL-2022-2220
Clearance Date:11MAY22

13. SUPPLEMENTARY NOTES
For presentation at ICOPS 2022; 22-26 May 2022; Seattle, WA;
The U.S. Government is joint author of the work and has the right to use, modify, reproduce, release, perform, display, or disclose the work.

14. ABSTRACT
Viewgraphs/Briefing Charts

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**C. THIS PAGE** Unclassified	SAR	43

19a. NAME OF RESPONSIBLE PERSON
Daniel Eckhardt

19b. PHONE NUMBER *(Include area code)*
N/A

PREVIOUS EDITION IS OBSOLETE.

STANDARD FORM 298 (REV. 5/2020)
Prescribed by ANSI Std. Z39.18

U.S. AIR FORCE

USSF

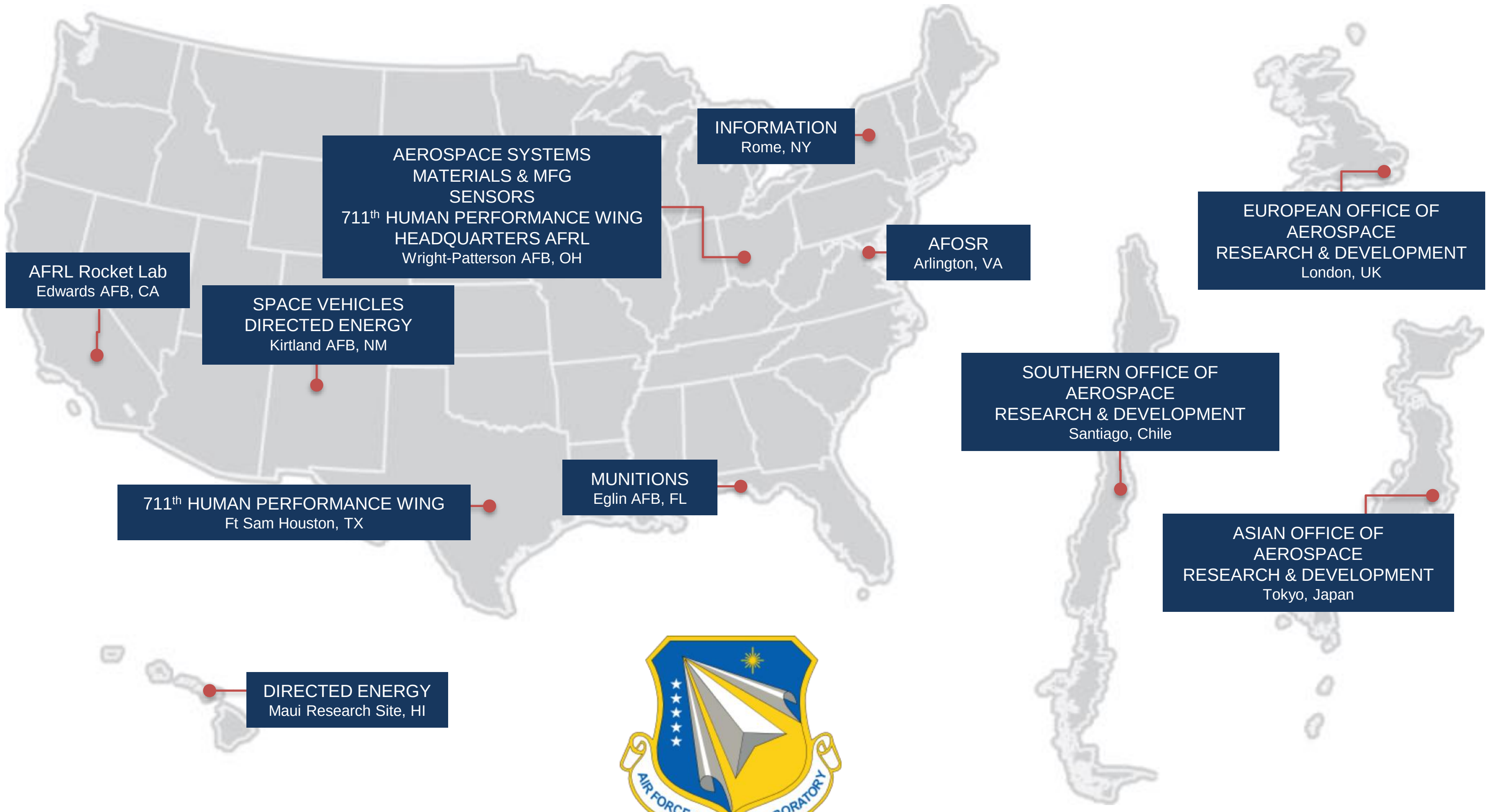
AFRL

Propellant Agnostic High Power EP

Dan Eckhardt

AFRL/USSF

AFRL Geographic Footprint



INFORMATION
Rome, NY

AEROSPACE SYSTEMS
MATERIALS & MFG
SENSORS
711th HUMAN PERFORMANCE WING
HEADQUARTERS AFRL
Wright-Patterson AFB, OH

AFRL Rocket Lab
Edwards AFB, CA

SPACE VEHICLES
DIRECTED ENERGY
Kirtland AFB, NM

AFOSR
Arlington, VA

EUROPEAN OFFICE OF AEROSPACE RESEARCH & DEVELOPMENT
London, UK

SOUTHERN OFFICE OF AEROSPACE RESEARCH & DEVELOPMENT
Santiago, Chile

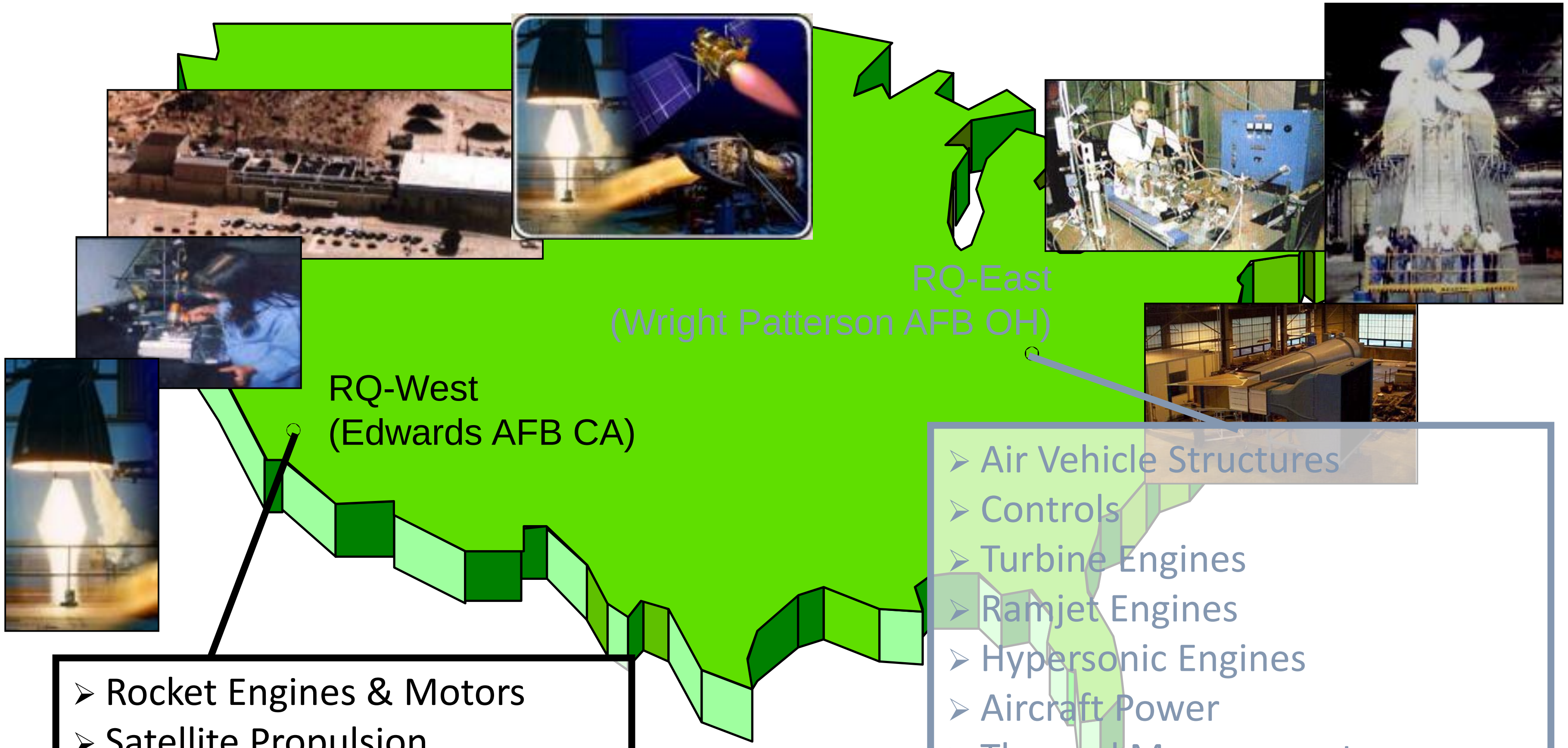
MUNITIONS
Eglin AFB, FL

711th HUMAN PERFORMANCE WING
Ft Sam Houston, TX

ASIAN OFFICE OF AEROSPACE RESEARCH & DEVELOPMENT
Tokyo, Japan

DIRECTED ENERGY
Maui Research Site, HI

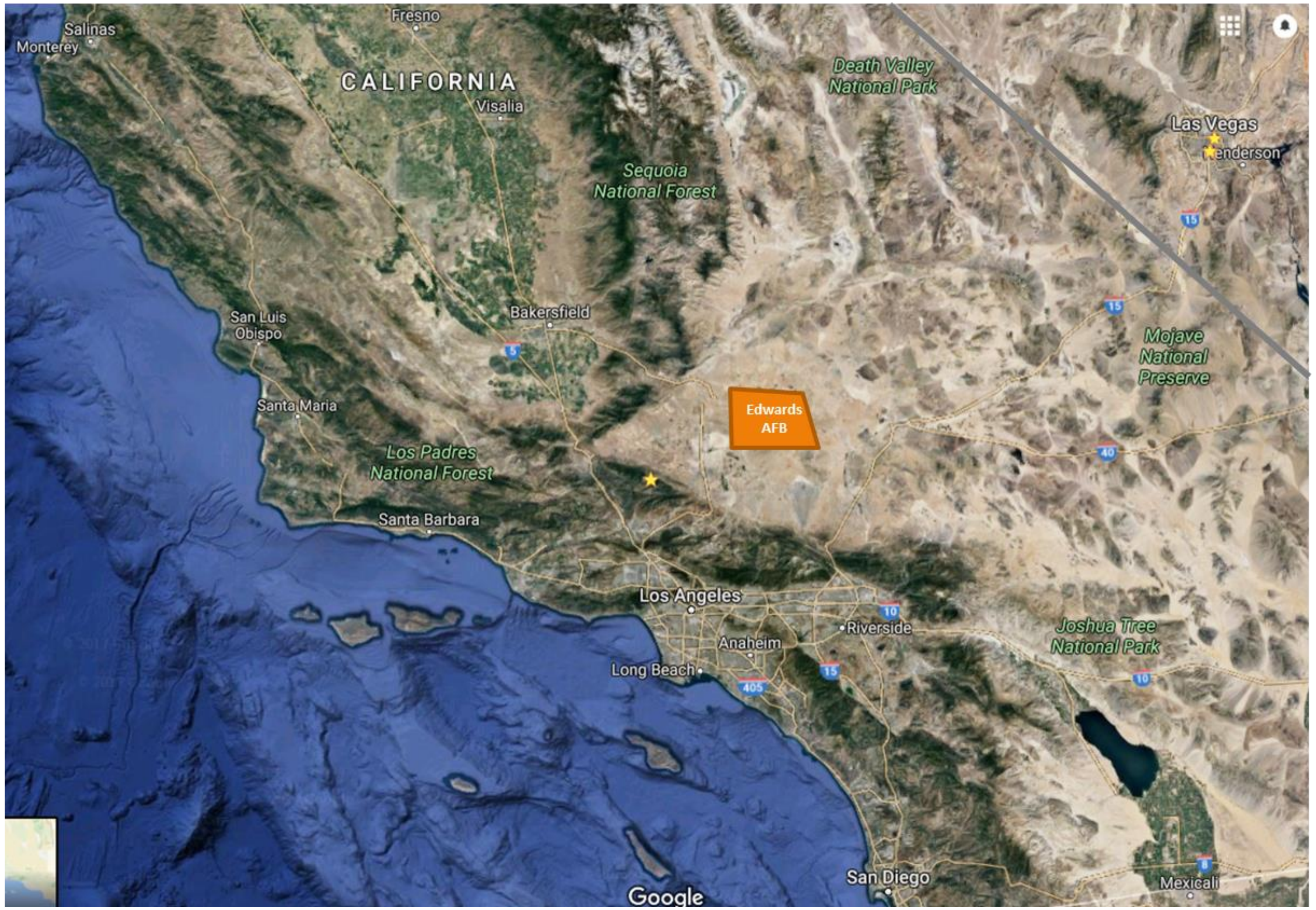
AFRL/RQ - *Aerospace Systems Directorate*



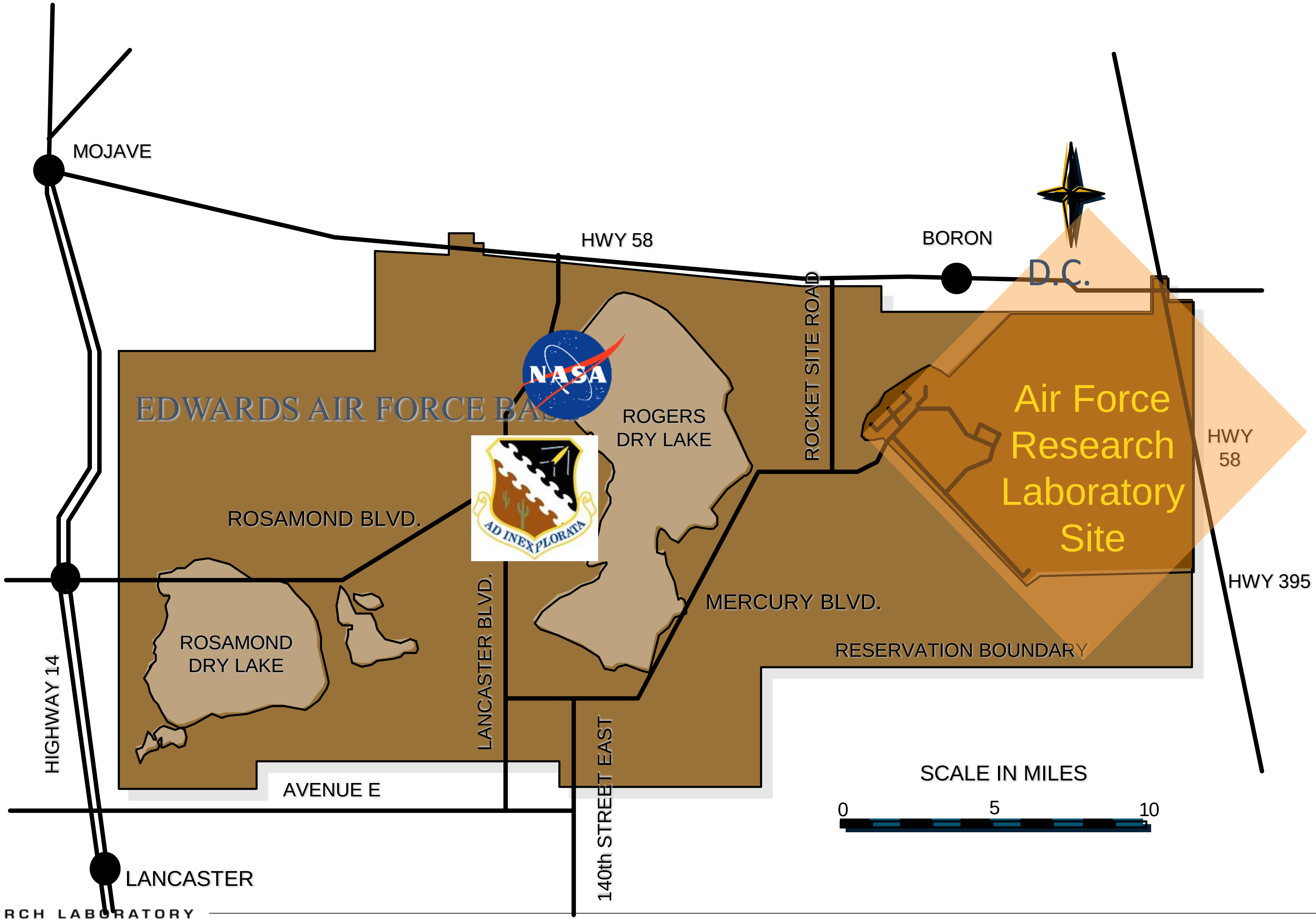
- Rocket Engines & Motors
- Satellite Propulsion
- Advanced Propulsion
- Fuels and Propellants
- System Analysis

- Air Vehicle Structures
- Controls
- Turbine Engines
- Ramjet Engines
- Hypersonic Engines
- Aircraft Power
- Thermal Management
- Fuels and Propellants
- System Analysis

Edwards AFB


Fresno
Salinas
Monterey
CALIFORNIA
Visalia
Death Valley National Park
Las Vegas
Henderson
Sequoia National Forest
Bakersfield
San Luis Obispo
Mojave National Preserve
Edwards AFB
Santa Maria
Los Padres National Forest
Santa Barbara
Los Angeles
Riverside
Anaheim
Long Beach
Joshua Tree National Park
San Diego
Mexicali
Google

AFRL Rocket Lab



Site Overview

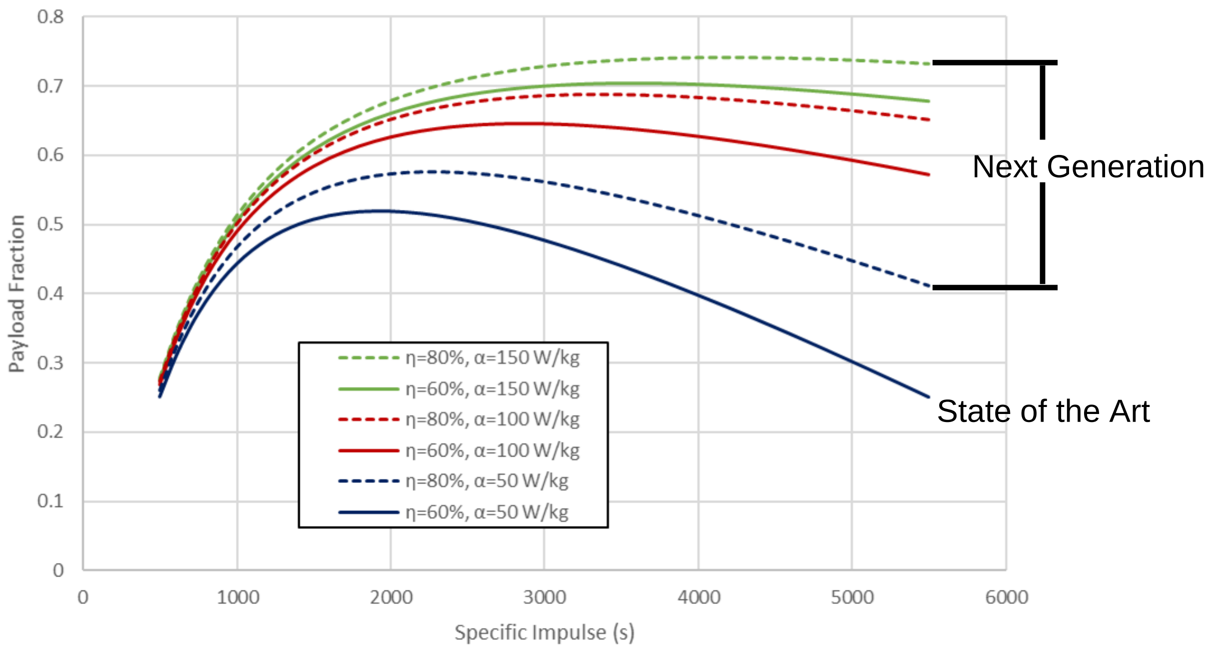
- Over 450 personnel on-site
  - Civil service, military, contractors

65 square miles

- 135 buildings
- 19 liquid engine stands
- 13 solid rocket motors stands

Next-Gen EP Thrusters: Expands operational envelop of USSSF fleet

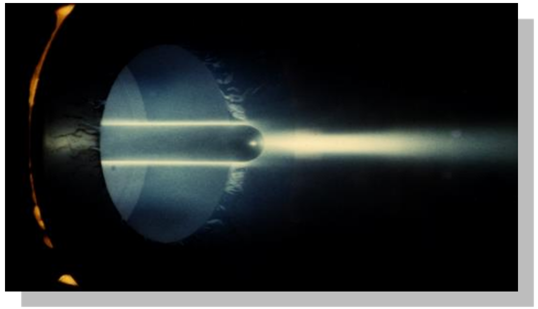
- Next-generation are expected to operate at higher density and temperature (increased power and efficiency)
- Investment into these technologies can build resilience against future technology surprises by adversaries
- Predictive forward modeling capability can shed valuable a-priori insights into performance of these devices before an extensive (and expensive) experimental campaign and help guide designers.



Payload fraction, m_{pay}/m_0, for different specific power, α, and propulsion efficiency, η, for a 90 day, ~6km/s constant thrust transfer [J. Koo, AAS 19-087]

Realistic options for High Power EP

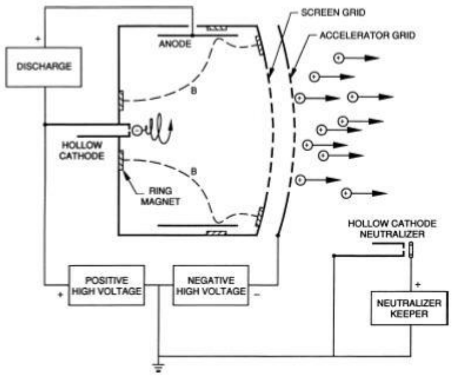
- Electrothermal
  - Electrical heating and nozzle expansion accelerates the propellant
    - Resistojets (commercially available)
    - Arcjets (commercially available)
- Electrostatic
  - Electric field accelerates an ionized propellant
    - Hall thrusters (commercial & development)
    - Ion engines (commercial & development)
  - Electrospray directly accelerates ionic liquid
- Electromagnetic
  - *jxB* force accelerates an ionized propellant
    - MagnetoPlasmaDynamic thruster(MPD) (laboratory)
    - Pulsed Inductive Thruster (PIT) (laboratory)
    - Pulsed Plasma Thrusters (PPTs) (commercially available)



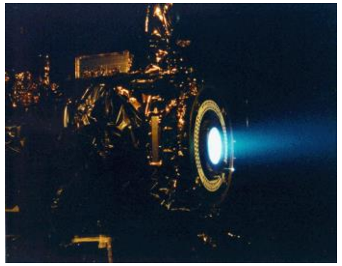
Electrostatic EP

Propellant is ionized and subsequently accelerated through the application of large electric fields

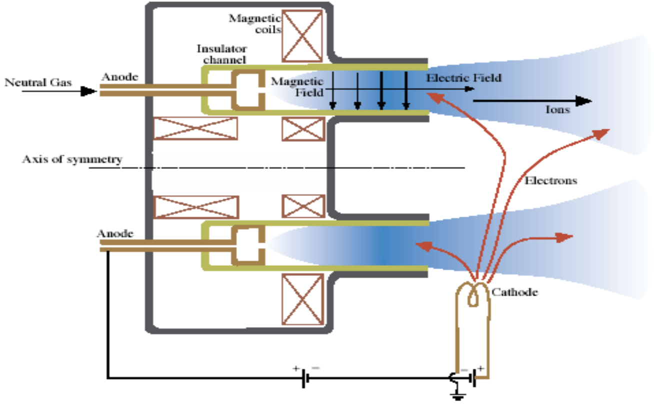
<u>Ion Engine:</u> Applies large potential between two closely spaced grids



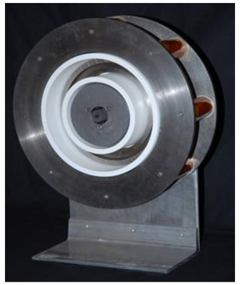
Specific Impulse: 3000 s – 5000 s

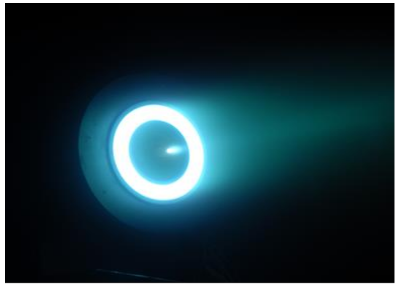


<u>Hall Thruster:</u> Magnetic field traps electrons forming electrostatic field

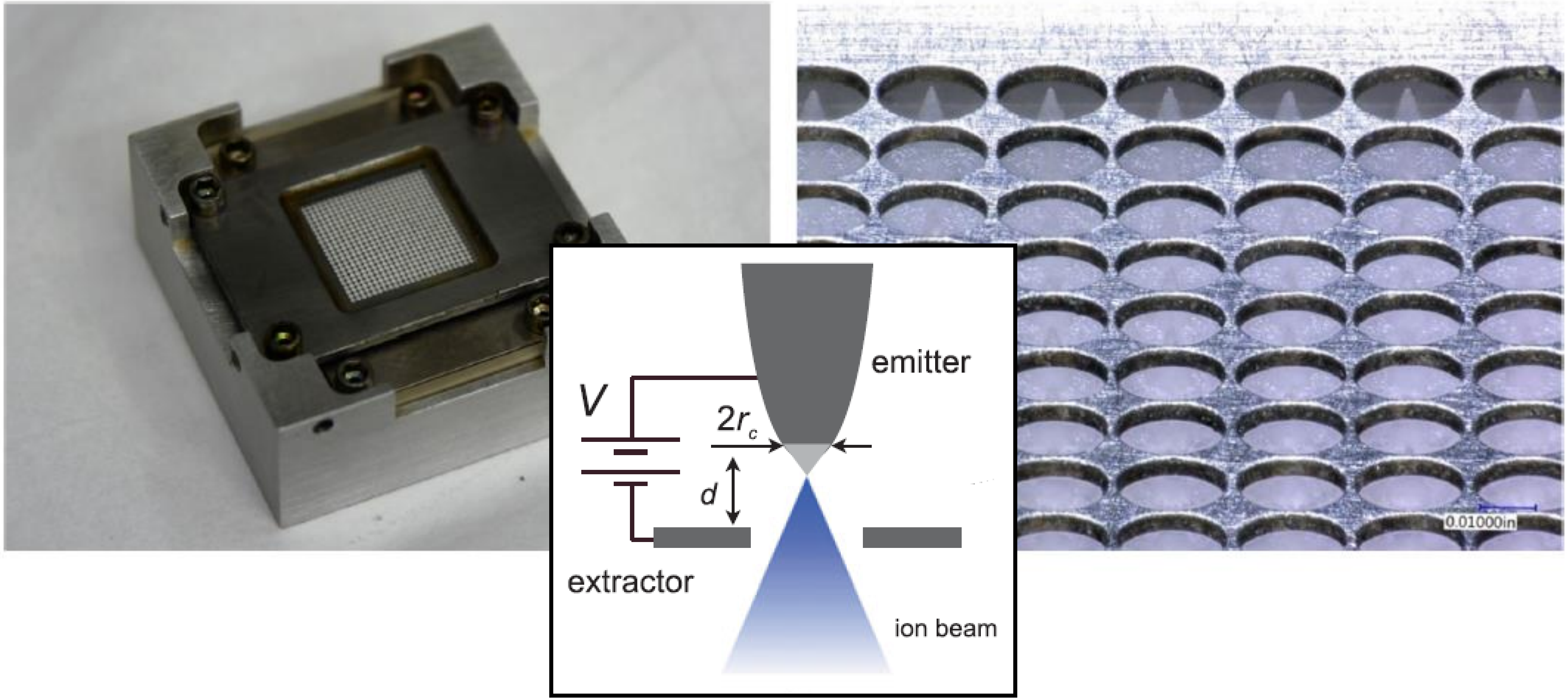


Specific Impulse: 1000 s – 3000 s





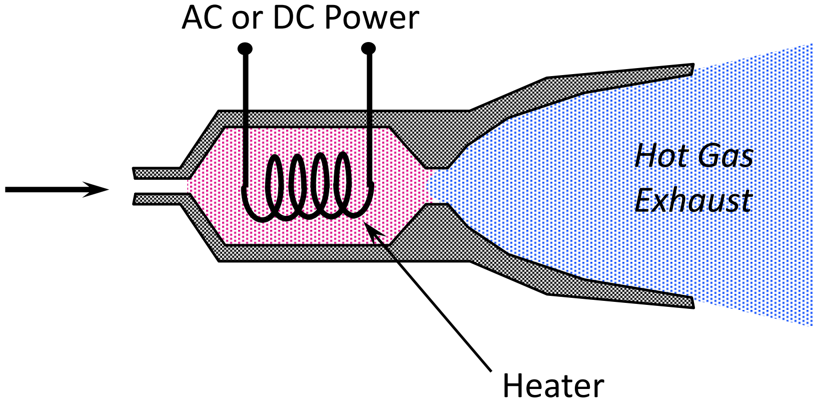
Electrosprays (another Electrostatic)



Electrothermal EP

Propellant is heated by a resistive element, by an arc, or by EM radiation (RF, µwaves) and expanded out a nozzle

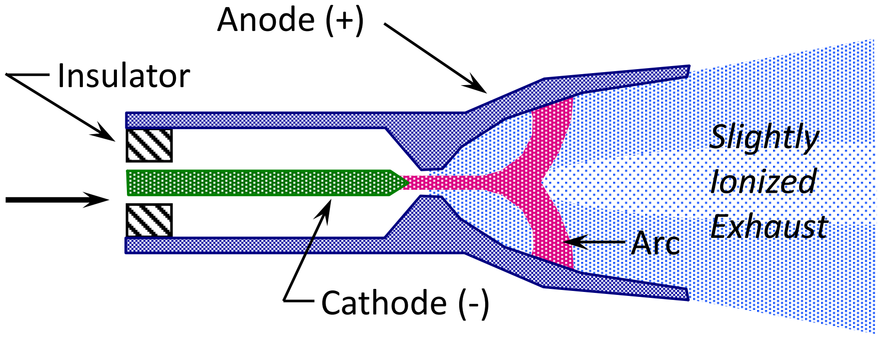
Resistojet



Hydrogen, Ammonia, or Decomposed Hydrazine

300 s (hydrazine)
600 s (hydrogen)

Arcjet



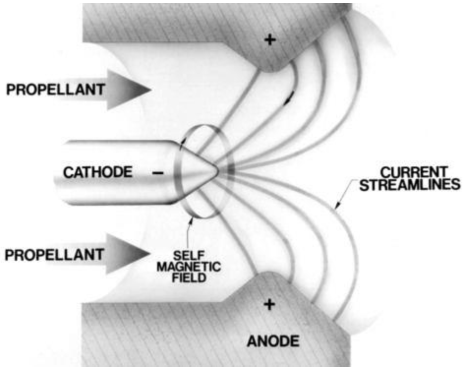
Hydrogen, Ammonia, or Decomposed Hydrazine

500-600 s (hydrazine)
1,000 s (hydrogen)

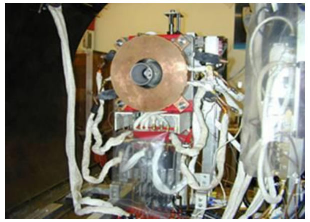
Electromagnetic EP

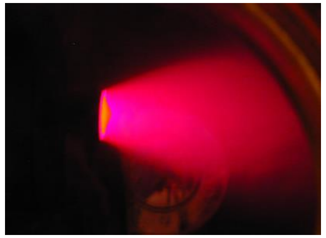
Propellant is accelerated through the interaction of plasma currents and magnetic fields → Lorentz Force *jxB*

MPD: Large steady-state current ionizes propellant and interacts with self B-field

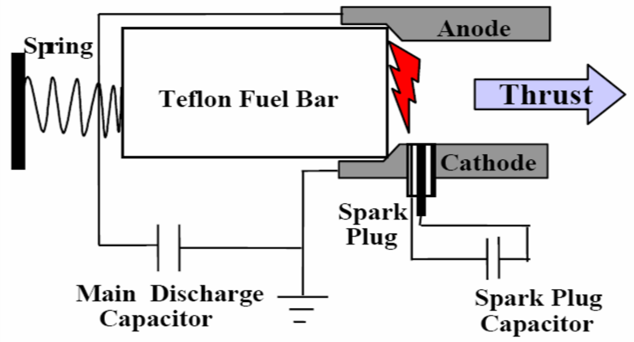


Specific Impulse: 2000 s – 6000 s

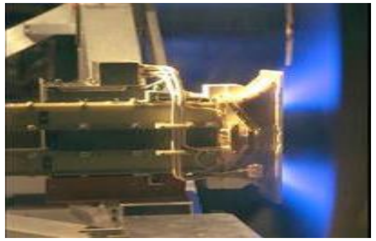




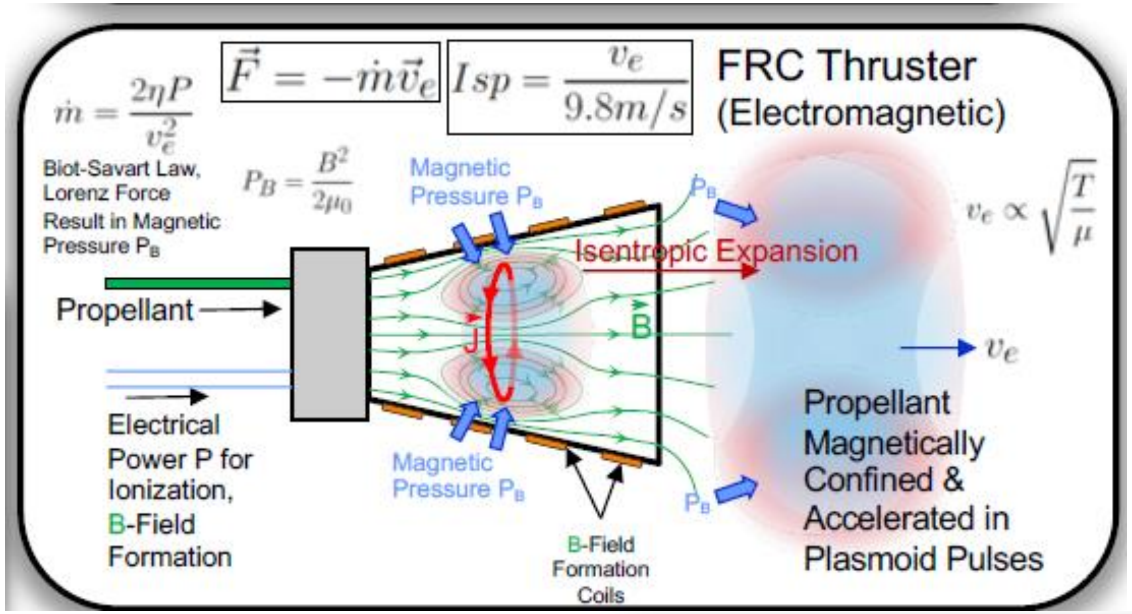
PPT: High current arc ablates solid propellant and interacts with induced B-field

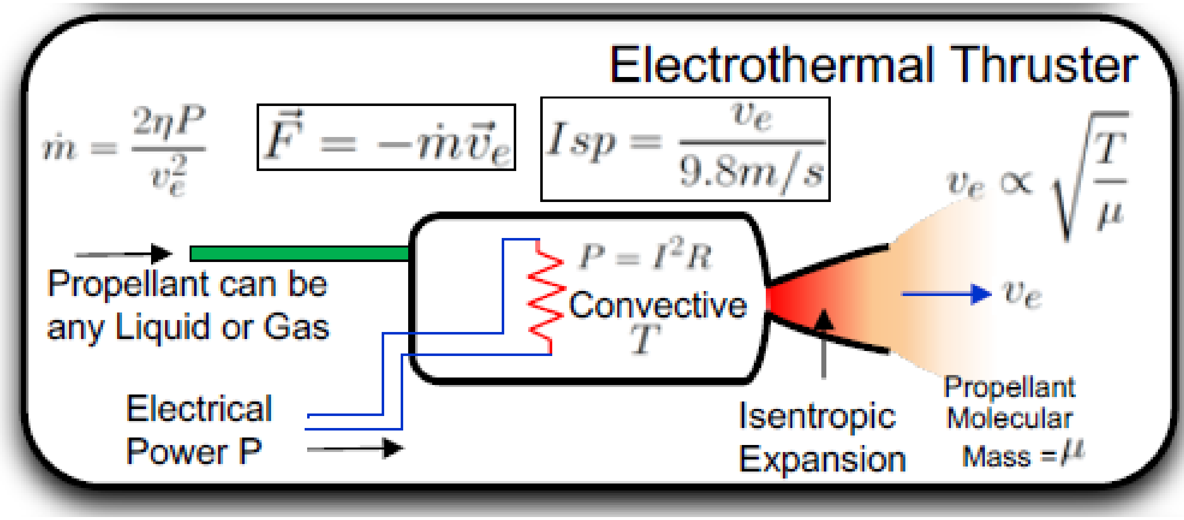


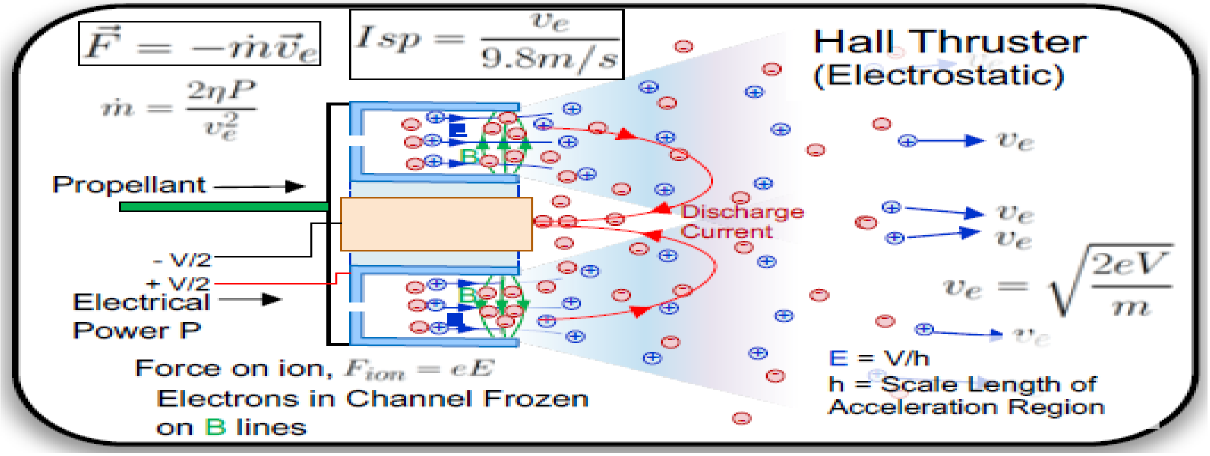
Specific Impulse: 300 s – 3000 s



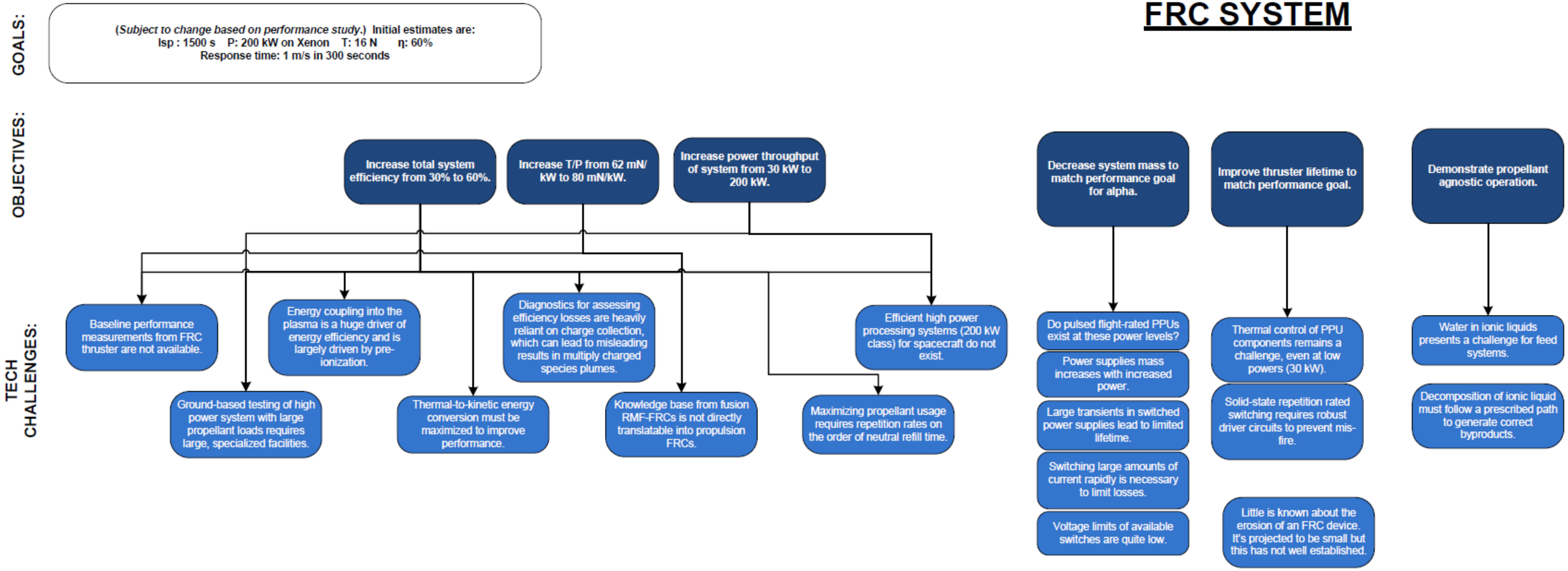
Realistic options for High Power EP







Some identified challenges



FRC SYSTEM

GOALS:

(*Subject to change based on performance study.*) Initial estimates are:
Isp : 1500 s P: 200 kW on Xenon T: 16 N η: 60%
Response time: 1 m/s in 300 seconds

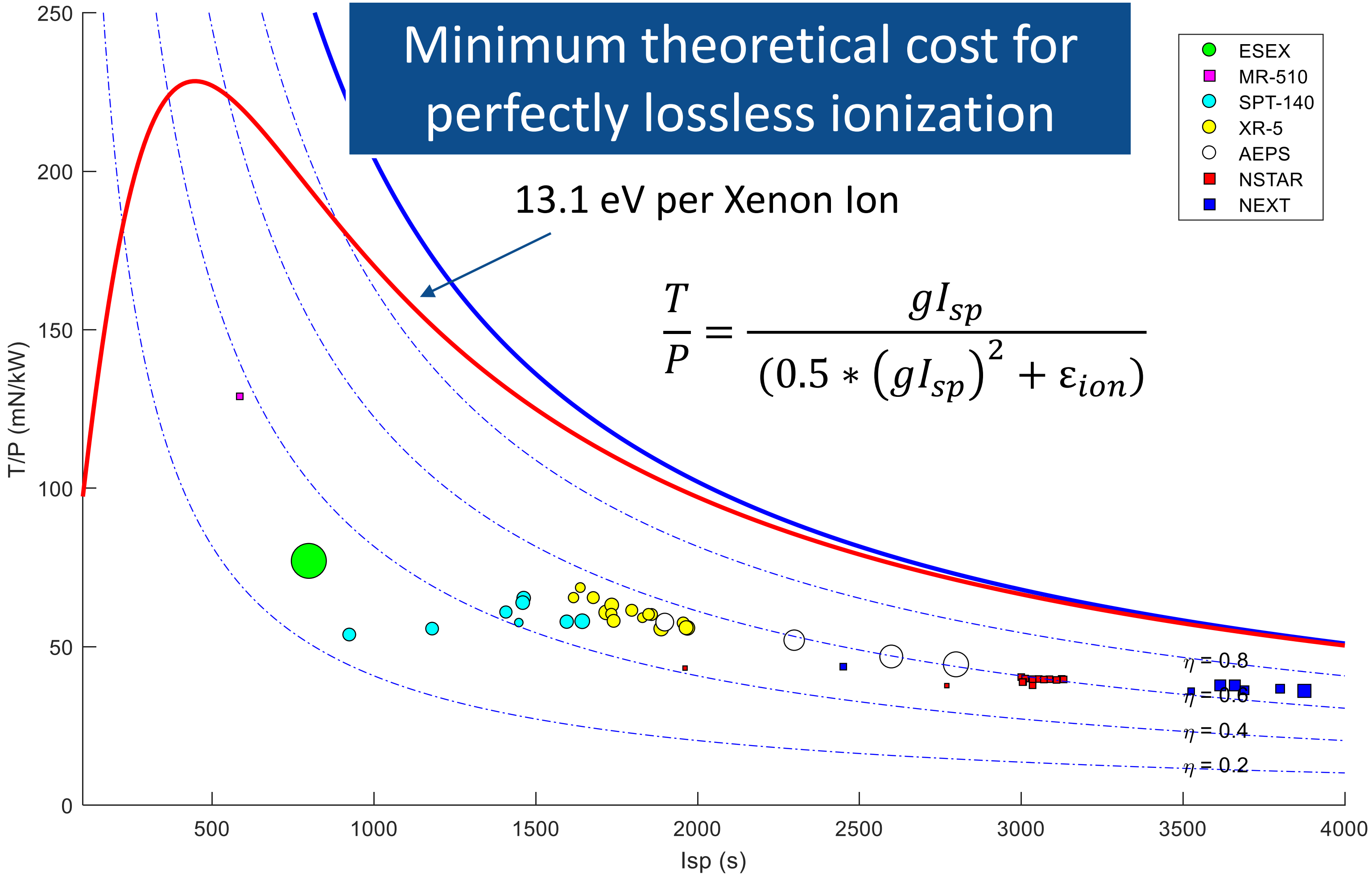
OBJECTIVES:

- Increase total system efficiency from 30% to 60%.
- Increase T/P from 62 mN/kW to 80 mN/kW.
- Increase power throughput of system from 30 kW to 200 kW.
- Decrease system mass to match performance goal for alpha.
- Improve thruster lifetime to match performance goal.
- Demonstrate propellant agnostic operation.

TECH CHALLENGES:

- Baseline performance measurements from FRC thruster are not available.
- Ground-based testing of high power system with large propellant loads requires large, specialized facilities.
- Energy coupling into the plasma is a huge driver of energy efficiency and is largely driven by pre-ionization.
- Thermal-to-kinetic energy conversion must be maximized to improve performance.
- Diagnostics for assessing efficiency losses are heavily reliant on charge collection, which can lead to misleading results in multiply charged species plumes.
- Knowledge base from fusion RMF-FRCs is not directly translatable into propulsion FRCs.
- Maximizing propellant usage requires repetition rates on the order of neutral refill time.
- Efficient high power processing systems (200 kW class) for spacecraft do not exist.
- Do pulsed flight-rated PPUs exist at these power levels?
- Power supplies mass increases with increased power.
- Large transients in switched power supplies lead to limited lifetime.
- Switching large amounts of current rapidly is necessary to limit losses.
- Voltage limits of available switches are quite low.
- Thermal control of PPU components remains a challenge, even at low powers (30 kW).
- Solid-state repetition rated switching requires robust driver circuits to prevent mis-fire.
- Little is known about the erosion of an FRC device. It's projected to be small but this has not well established.
- Water in ionic liquids presents a challenge for feed systems.
- Decomposition of ionic liquid must follow a prescribed path to generate correct byproducts.

Theoretical Limits of all plasma propulsion (Xenon)

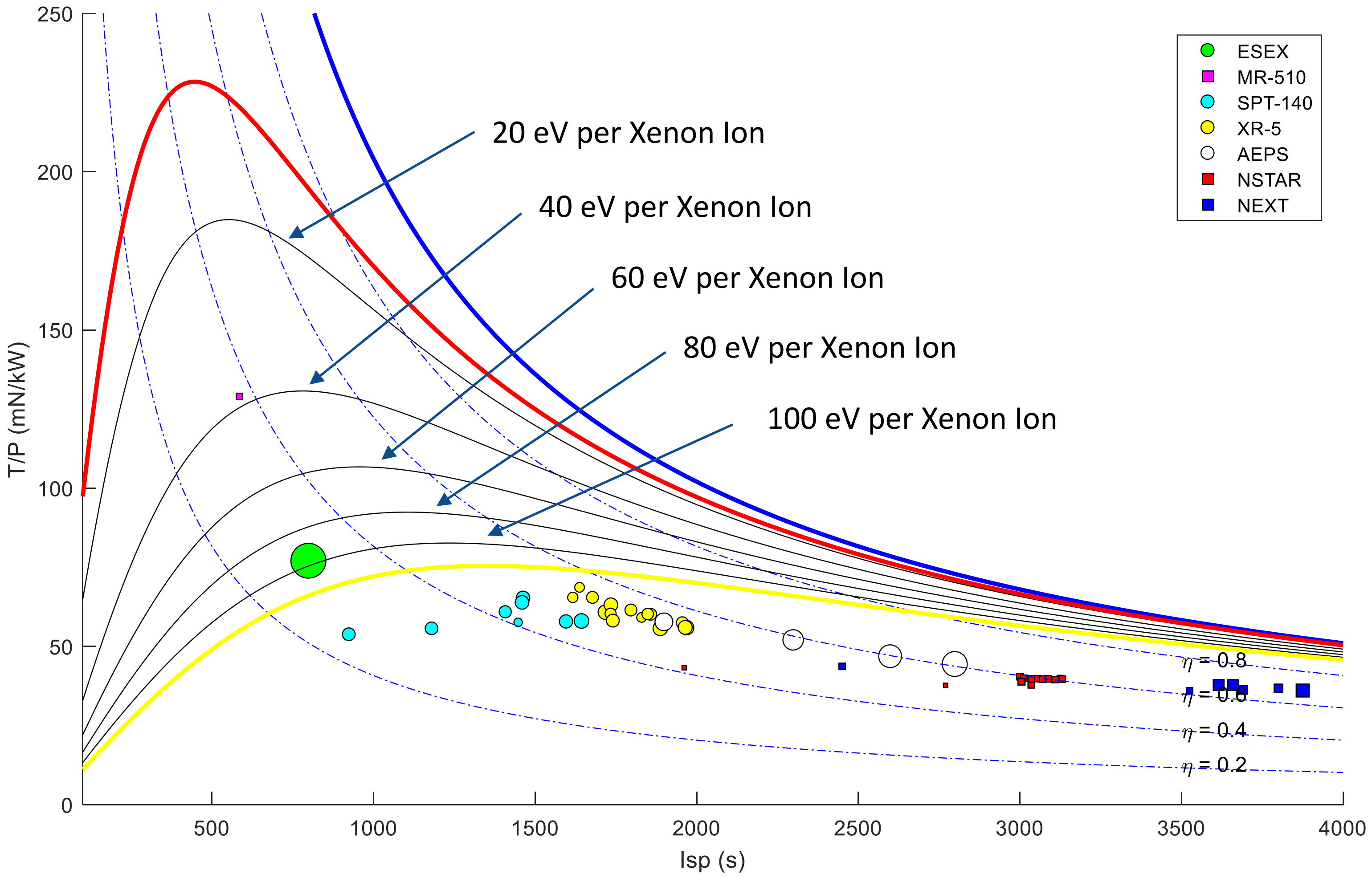


Minimum theoretical cost for perfectly lossless ionization

13.1 eV per Xenon Ion

$$\frac{T}{P} = \frac{gI_{sp}}{\left(0.5 * \left(gI_{sp}\right)^2 + \varepsilon_{ion}\right)}$$

Practical limits on next-generation EP



20 eV per Xenon Ion

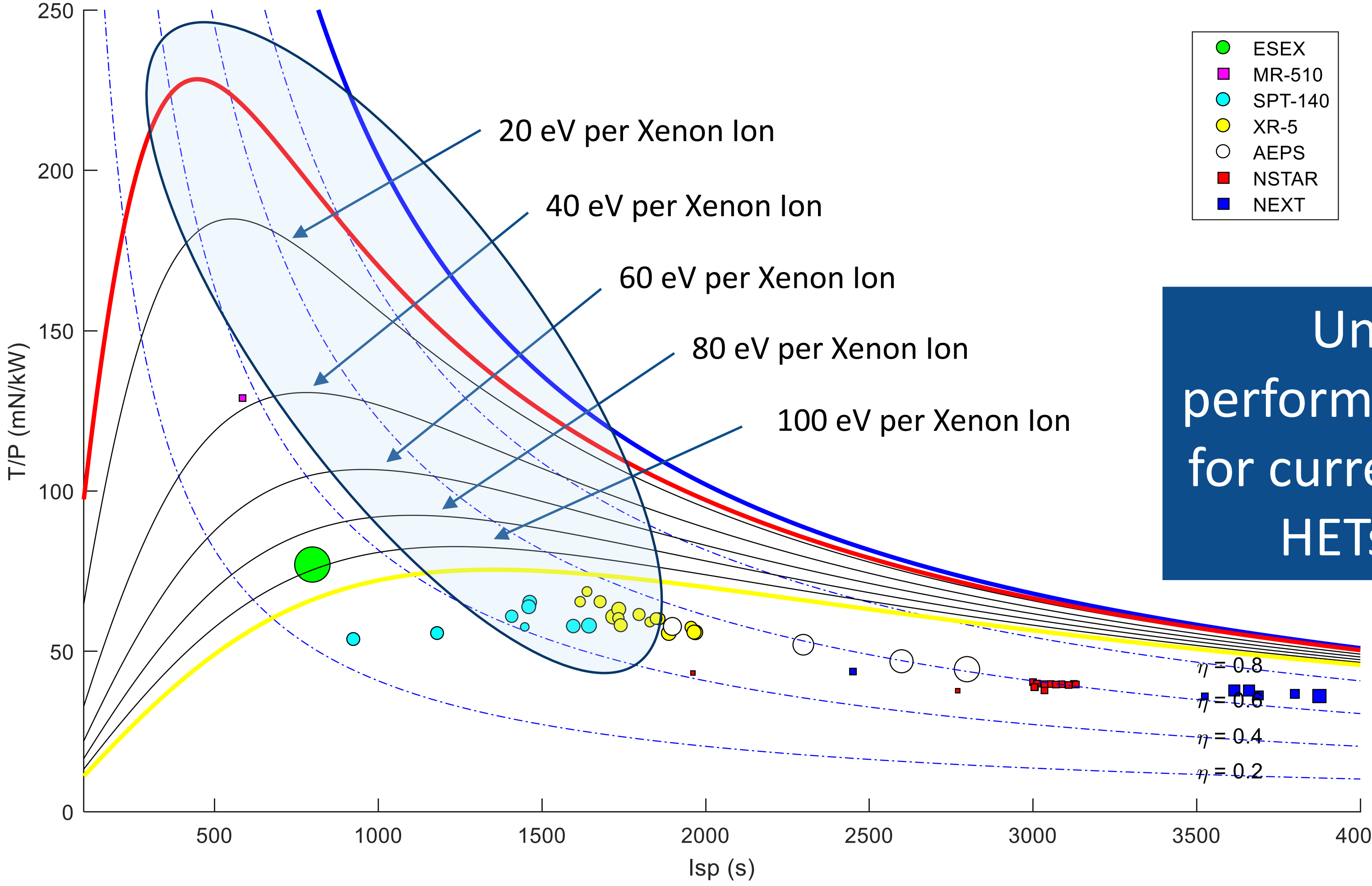
40 eV per Xenon Ion

60 eV per Xenon Ion

80 eV per Xenon Ion

100 eV per Xenon Ion

Practical Limits on Next-generation Xenon EP



20 eV per Xenon Ion

40 eV per Xenon Ion

60 eV per Xenon Ion

80 eV per Xenon Ion

100 eV per Xenon Ion

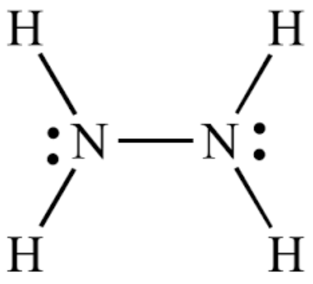
Unexplored performance envelope for current generation HETs is limited

Solution is to Explore Alternative Propellants

Challenges of finding an optimal Propellant

High performance monopropellant characteristics

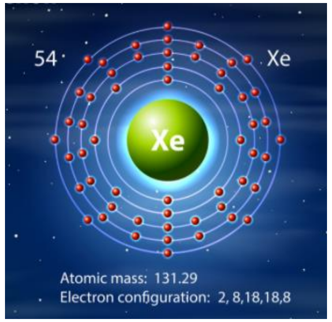
1. Large amounts of chemical energy → many internal bonds
2. Low mass combustion products → provides higher efficiency



Molecular Hydrazine

High Performance EP propellant characteristics

1. No internal bonds → fewer inelastic energy loss mechanisms
2. High mass propellant → increase thrust
3. Low ionization cost → reduced cost to generate plasma

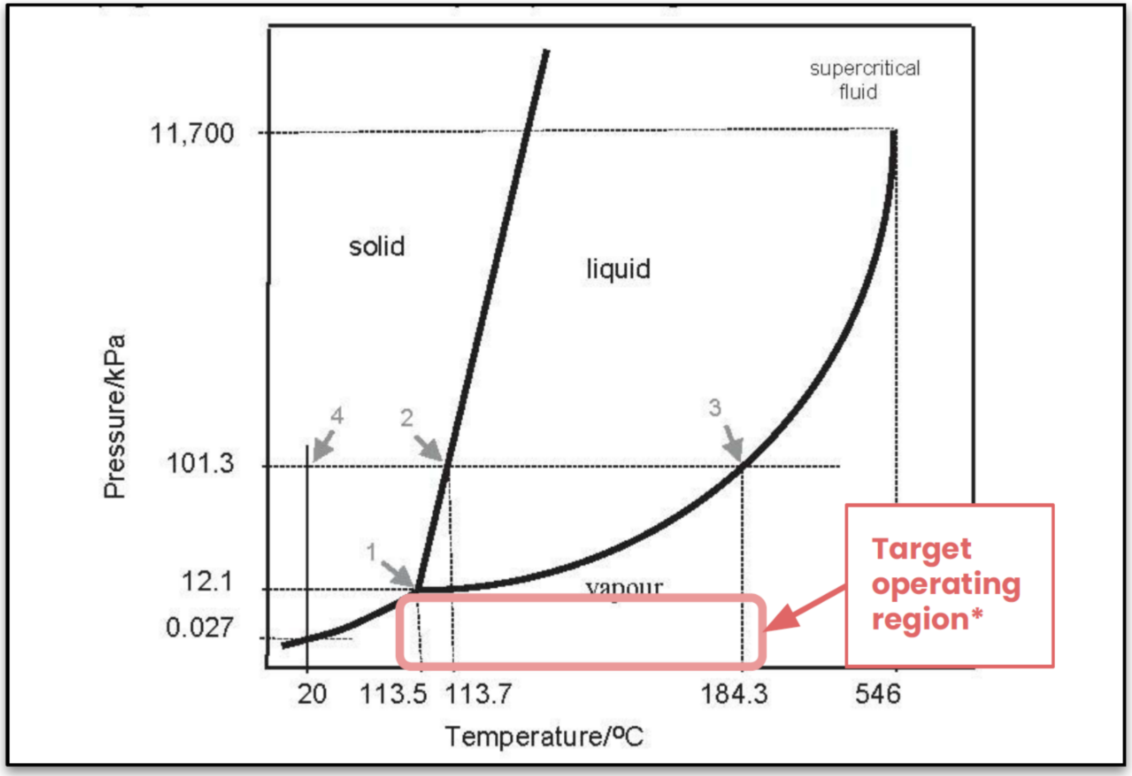


Atom Xenon
High atomic mass – 131 amu
Low ionization cost – 13.1 eV

Propellant will inherently be a compromise → payoff is at system level

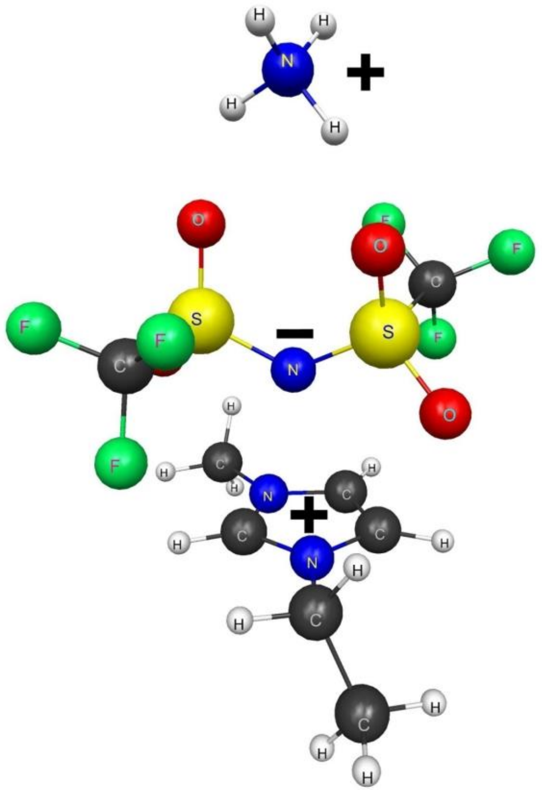
What about Iodine?

- Triple storage density of xenon
- Allows for use of conformal tanks
- Highly reactive
- Potential spacecraft interaction
- Ground test facility considerations



https://uwaterloo.ca/chem13-news-magazine/october-2015/feature/sublimation-iodine-rise-and-fall-misconception

Ionic Liquids (ILs)

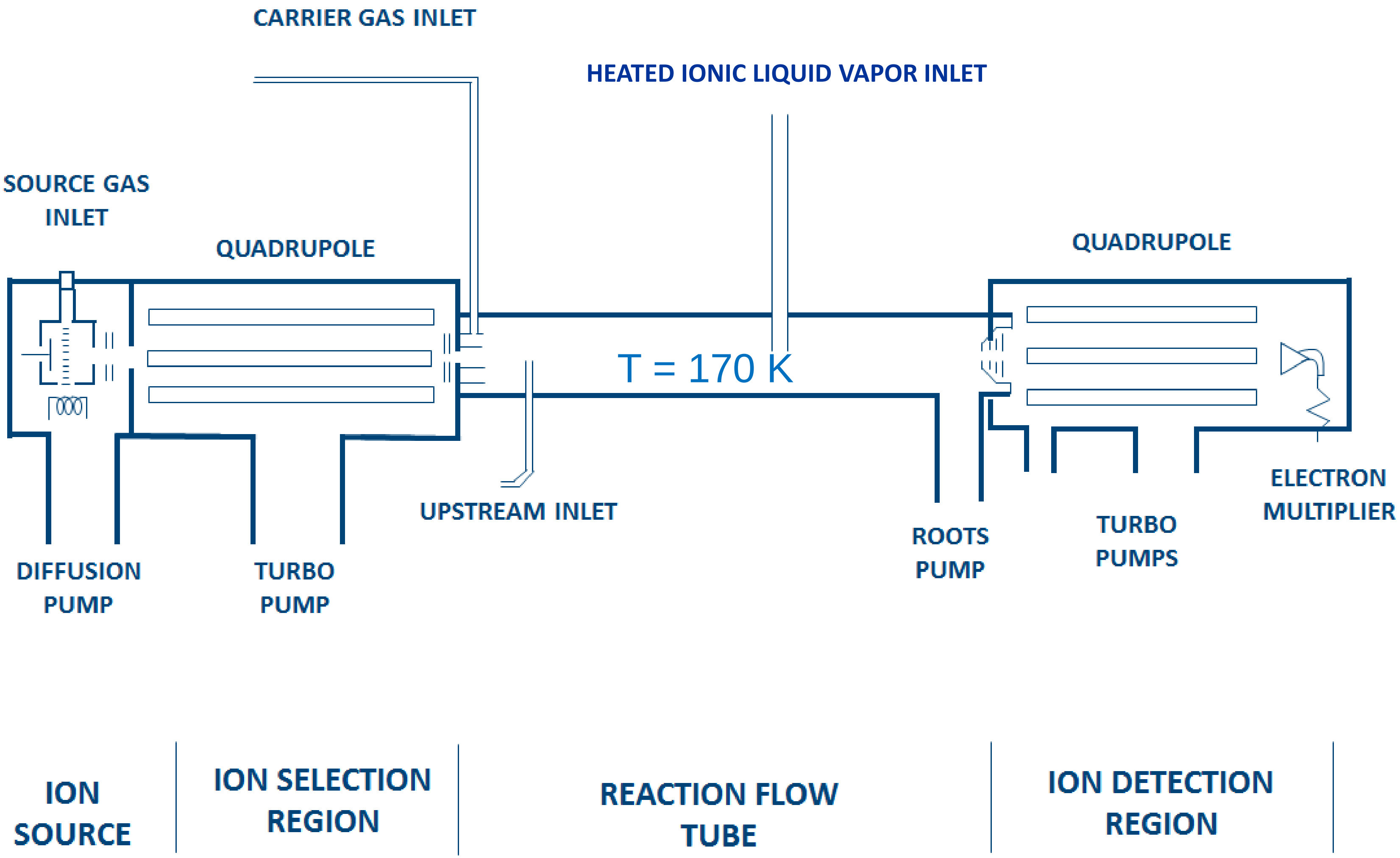


- Molten salts with m.p. ≤100 °C.
- Asymmetric ions with diffuse charge distributions.
- C^+A^- : 10^{18} possible combinations of cations and anions.

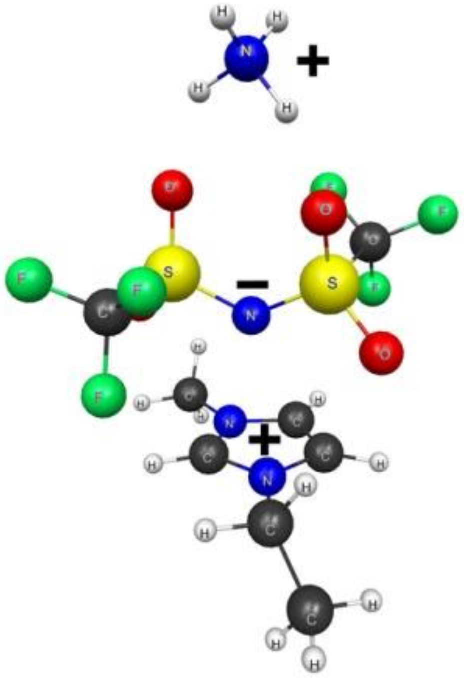
Vaporization pathways

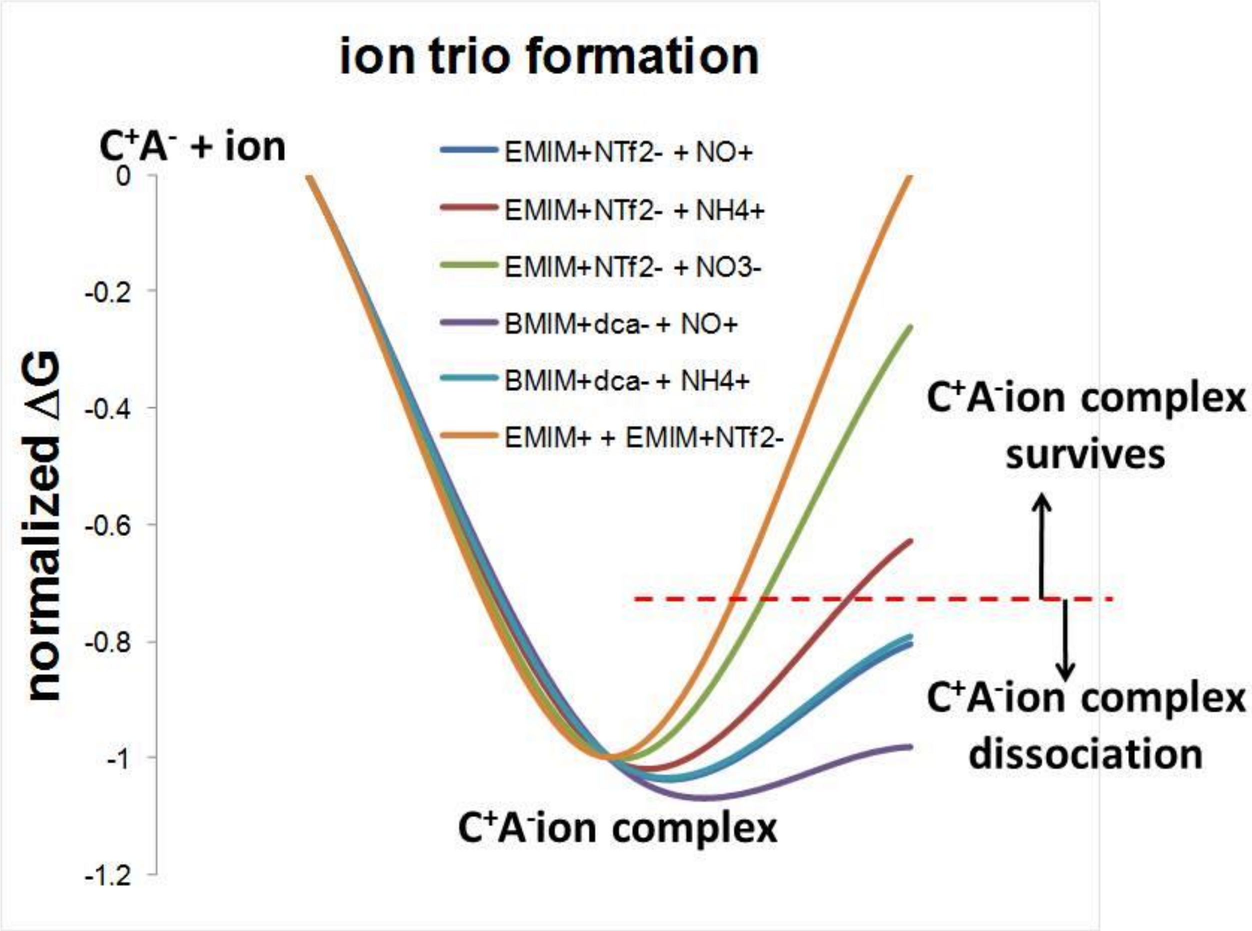
- $C^+A^-(l) \rightarrow C^+A^-(g)$
- $C^+A^- \rightarrow C^+A\cdot + e^-$
  - $C^+A\cdot$ only weakly bound.
- $C^+A^- \rightarrow C^+ + A\cdot + e^-$
  - Detection of C^+ basis for evaporation as ion pair.
- Ion attachment to ion pair?
- Determine dipole of ion pair?

Experimental: SIFT Spectroscopy



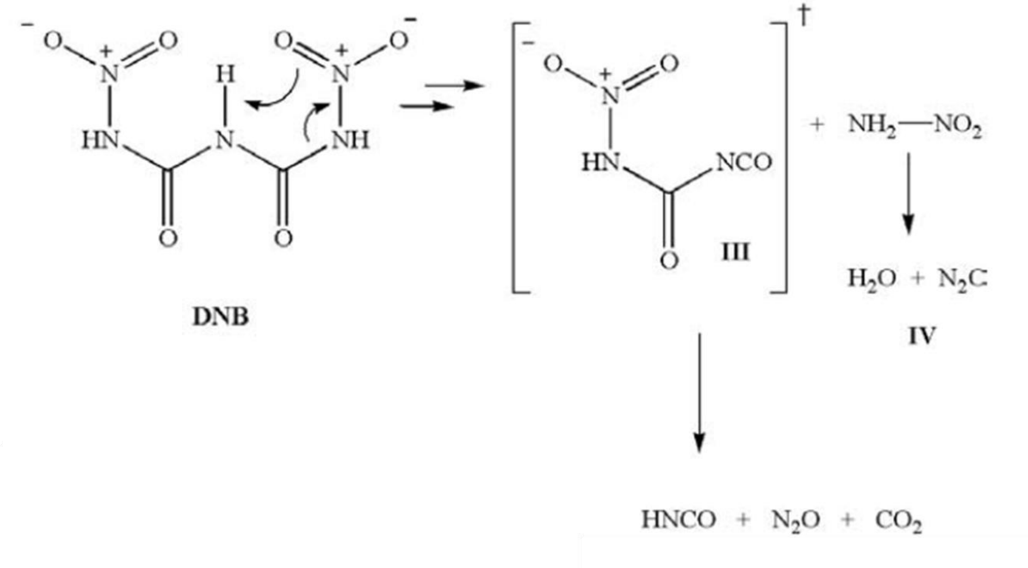
IL Vaporization





J. Phys. Chem. Lett., **2011**, *2* (8), pp 874–879

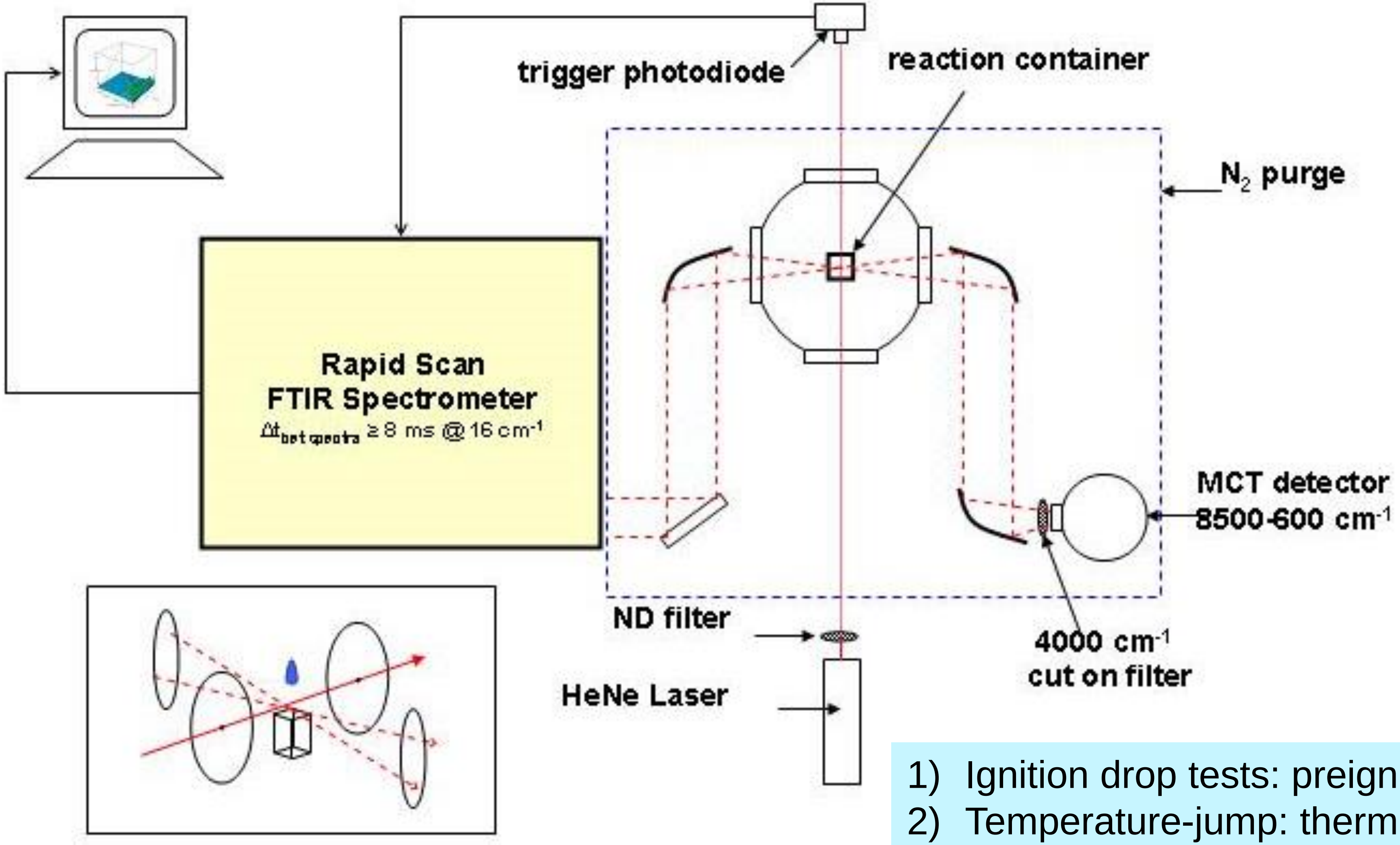
Hypergolics and Hydrocarbons



Geith, J., Holl, G., Klapötke, T. M., Weigland, J. J., *Combust. Flame*, **2004**, *139*, 358-366

J. Phys. Chem. A, **2008**, *112* (34), pp 7816–7824
DOI: 10.1021/jp8038175

Experimental

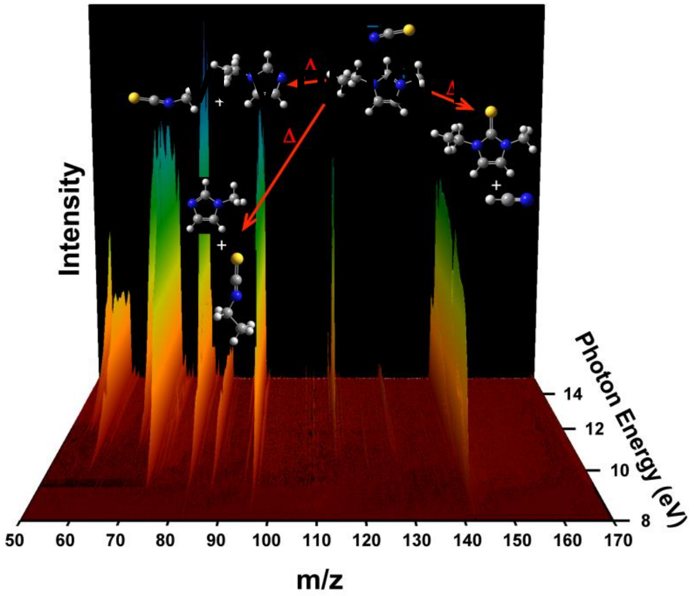


1) Ignition drop tests: preignition chemistry
2) Temperature-jump: thermal decomposition

Ionic Liquids Ignition

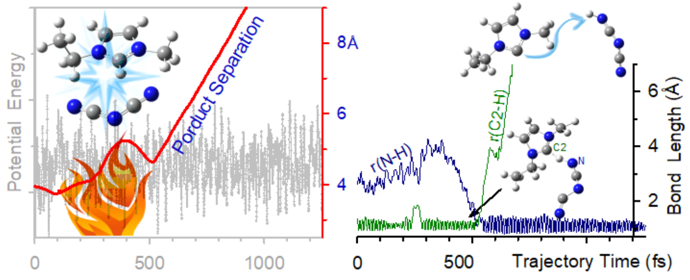
- How do hypergolic ionic liquids thermally decompose?
- Ionic liquid heated in vacuum and vapors detected by tunable VUV photoionization TOFMS.
- Thermal decomposition mechanisms confirmed by molecular dynamics and by *ab initio* calculation of ionization potentials of products detected by VUV-PI-TOFMS.
- Incorporate thermal decomposition products into improved chemical kinetics model to calculate ignition delay times.

(AFRL/RQ, Leone Group/UC Berkeley/LBNL and Liu Group/CUNY)



J. Phys. Chem. A, **2014**, *118* (47), pp 11119–11132

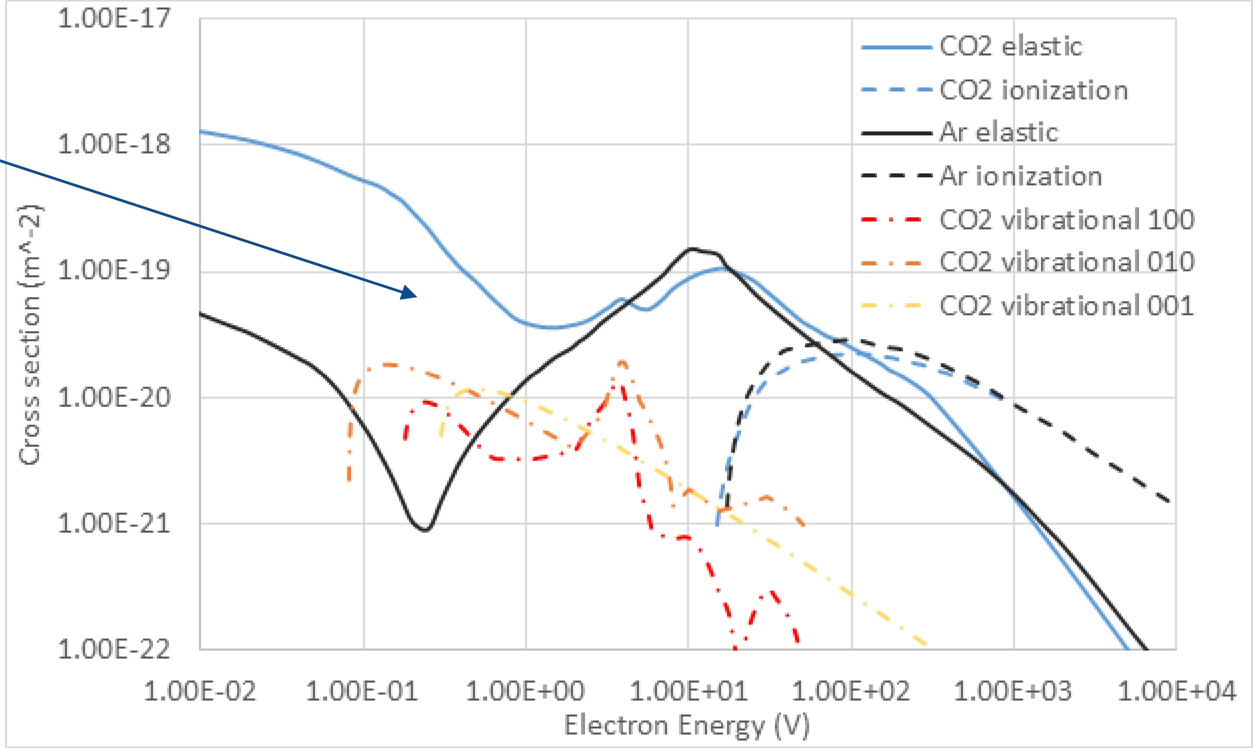
molecular dynamics

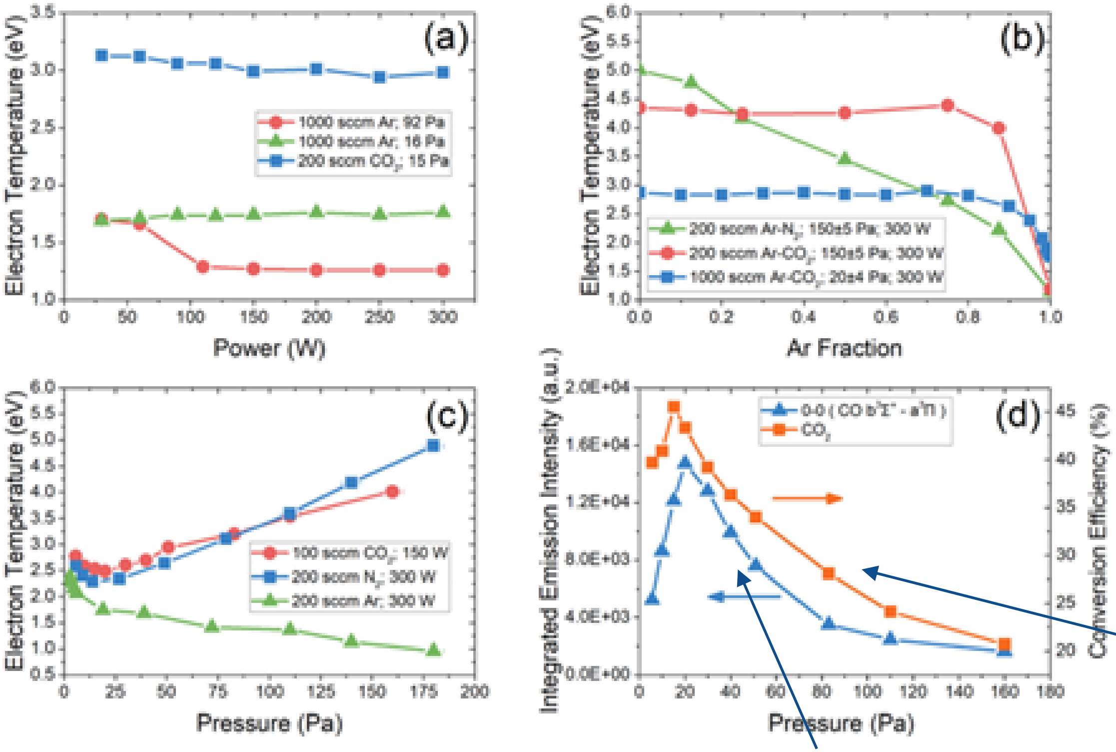


J. Phys. Chem. A, **2014**, *118* (47), pp 11133–11144

Reactive Species Phenomena and Modeling

Molecular propellants have more reaction pathways that absorb electron energy.



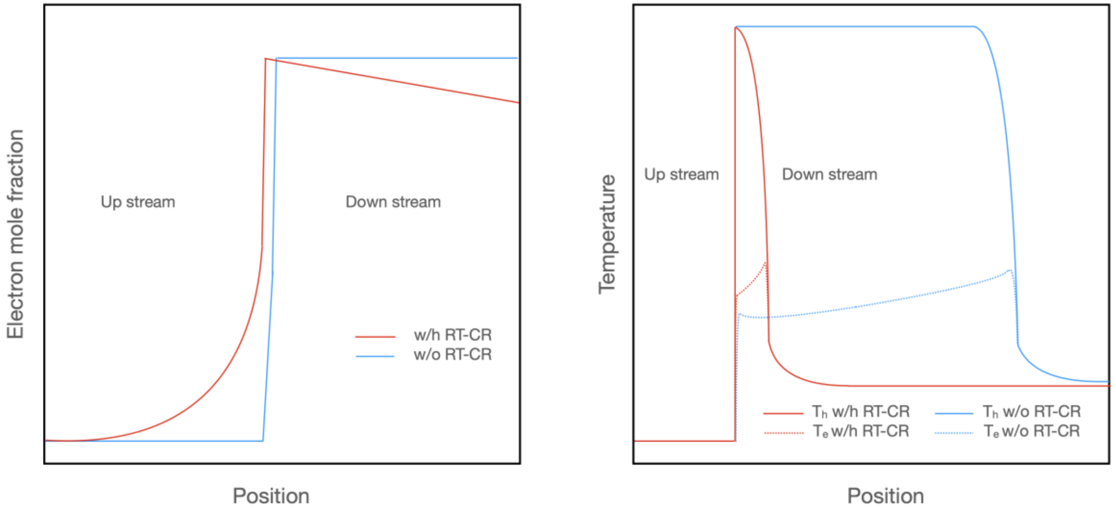


Molecular gases have a flow rate at which they generate peak density

∝ Density

Multiphysics and Multiscale Challenges

- Disparate length-scales (conditions from J. Slough et al., IEPC 2009-265, 2009)
  - $10\mu m < \lambda_{De} < 100\mu m$ <— Quasineutral
  - $L_{device} \sim 100cm$
  - $100cm < \lambda_{ii} < 1000cm$ <— kinetic ions
  - $80cm < \lambda_{ee} < 500cm$ <— kinetic electrons
- FRCs are dynamical systems (relative to quasi steady-state HET). Transient physics of plasmoid formation dictates the performance of the device
  - $\tau_{p,e} \sim 1fs$
  - $\tau_{gyro,e} \sim 100fs$
  - $\tau_{ee} \sim 0.1\mu s$
  - $\tau_{sim} \sim 20\mu s$ <— Plasmoid formation time-scale
- Multiphysics: System evolution and energy transport driven by complex interaction between plasma and radiation



Traveling ionization shock wave illustrates the importance of coupling between plasmas and radiation at high temperature and high density conditions. Photo-ionization increases electron number density upstream of shock, increasing electron concentration. Further, radiative transition leads to narrower internal relaxation region due to larger concentration of free electrons at the shock location.

Kinetic Treatment for Plasmas and Radiation: Curse of Dimensionality

Plasma: $\partial_t f_\alpha + \nabla_x \cdot (\vec{v} f_\alpha) + \nabla_v \cdot (\vec{a} f_\alpha) = \sum_\beta C\left(f_\beta, f_\alpha\right) + C(I, f_\alpha)$

Radiation: $c^{-1}\partial_t I + \vec{\Omega} \cdot \nabla_x I + \sigma[f]I = \sum_i S_i[f]$

$f = f(\mathbf{x}, \mathbf{v}, t)$ and $I_\nu = I_\nu(\mathbf{x}, \theta, \phi, \nu)$ are distribution functions for plasmas and photons

Approximate solution on a 6-D tensor product grid, $f(\mathbf{x}, \mathbf{v}, t^n) \approx \mathcal{F}^n \in \mathbb{R}^{N_x \times N_y \times N_z \times N_{v_x} \times N_{v_y} \times N_{v_z}}$

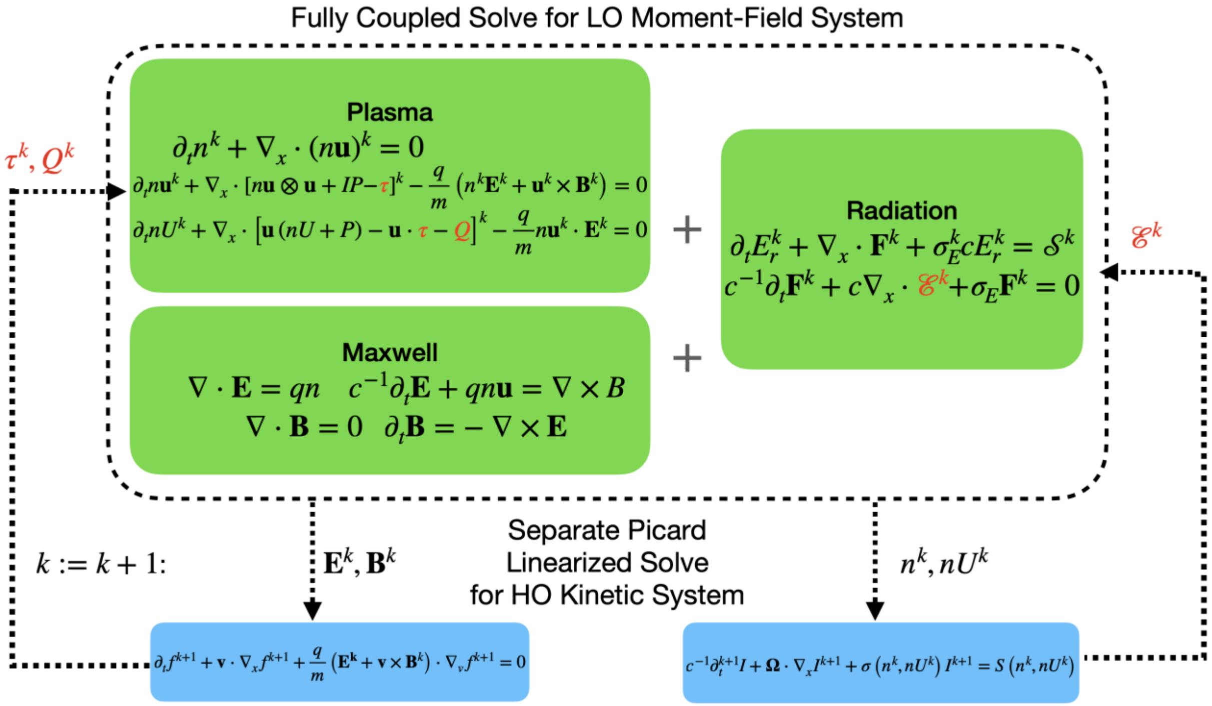
Classical grid-based approach scales ***exponentially*** w.r.t dimension (CPU cost $\propto N^6$).

Running a single resolved simulation requires world class compute resources

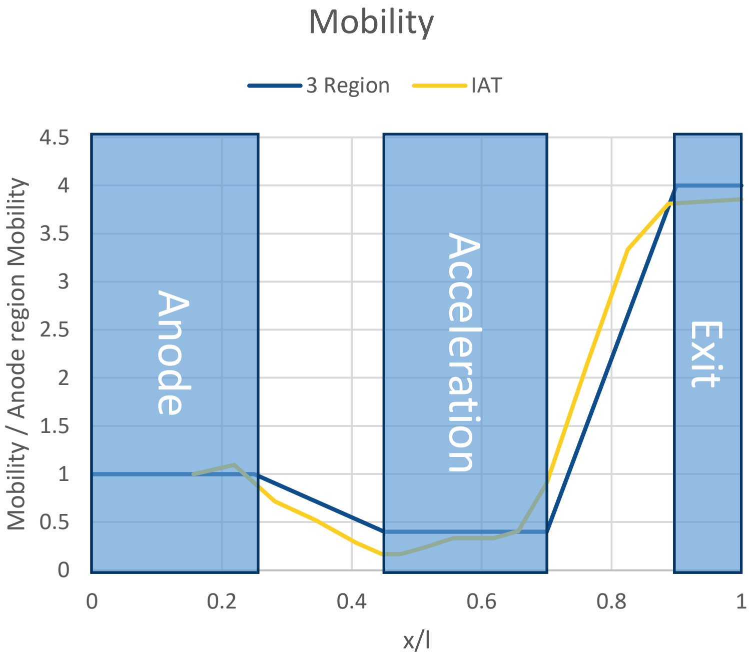
Routine calculations for parametric scan of design space are beyond tomorrow's compute capability. **We have to change our algorithms**

Algorithms to address dimensionality and time-scale challenges to enable routine simulations of coupled kinetic plasma and radiation physics

- Evolve compressed low-rank factorized ***tensor basis*** instead of the direct dense tensor representation (i.e., for 2D data, $F \approx \sum_{r=1}^{R} C_r X_r Y_r$ instead of $F \in \mathbb{R}^2$ where $C_r \in \mathbb{R}$, $(X_r, Y_r) \in \mathbb{R}^N$ and $R \ll N$)
- Storage and computational operation reduction of scaling from $\mathcal{O}(N^6) \rightarrow \mathcal{O}(6R^3 + 6RN)$ if low-rank manifold exists
- Time-scales to be dealt with using a multi-level HOLO method that uses self-consistent moment equations as a nonlinear preconditioner for the coupled kinetic equations

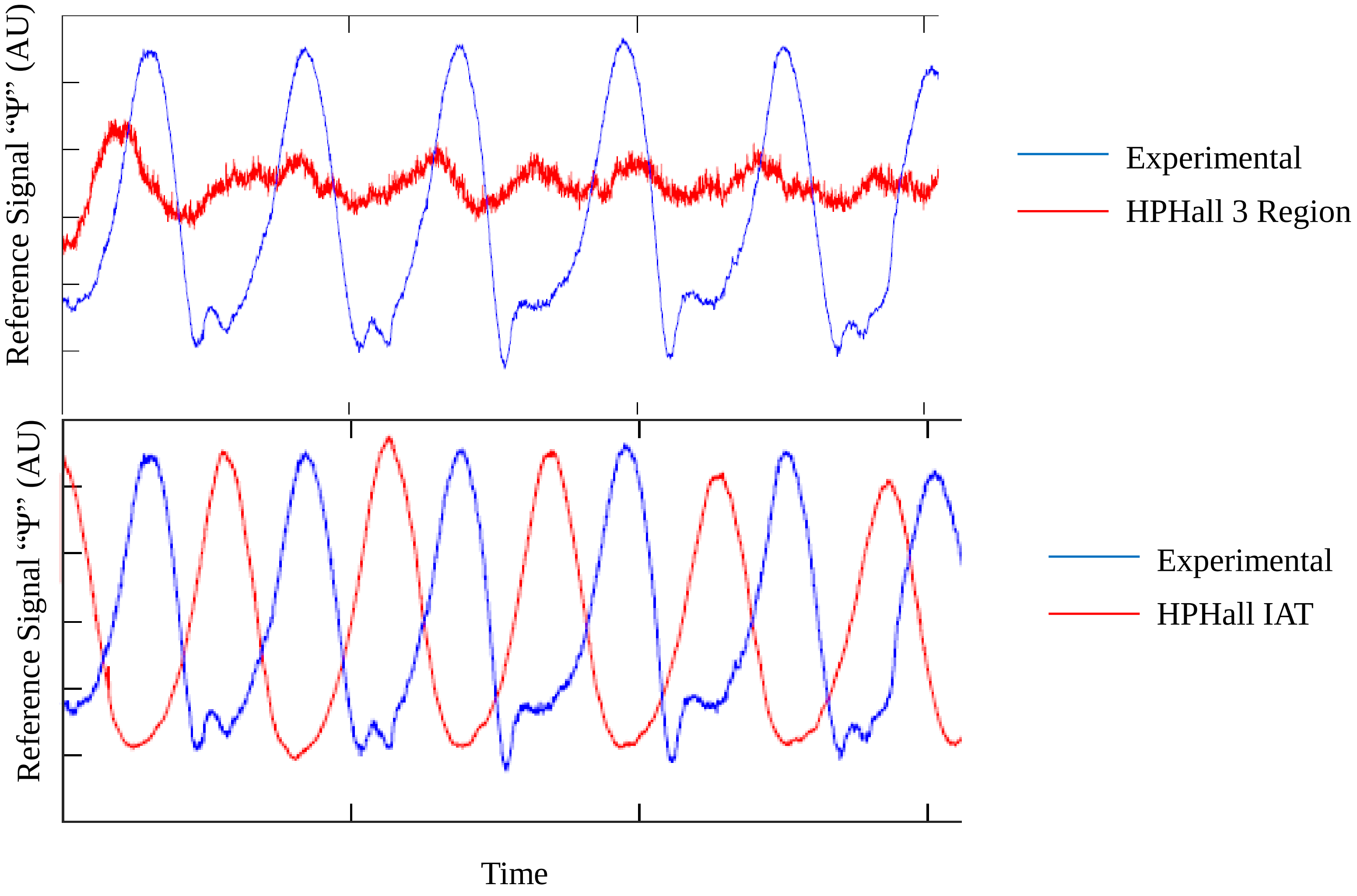


Modeling HET Using Unsteady Electron Mobility Model



$$\frac{\partial n_e v_{an}}{\partial t} + \frac{\partial V n_e v_{an}}{\partial z} = 2\gamma_k n_{e0} v_{an}$$

\gamma is a prescribed function of discharge current phase



Katz, et al., “Hall2De simulations with an anomalous transport model based on the electron cyclotron drift instability”, IEPC 2015

USSF Perspective

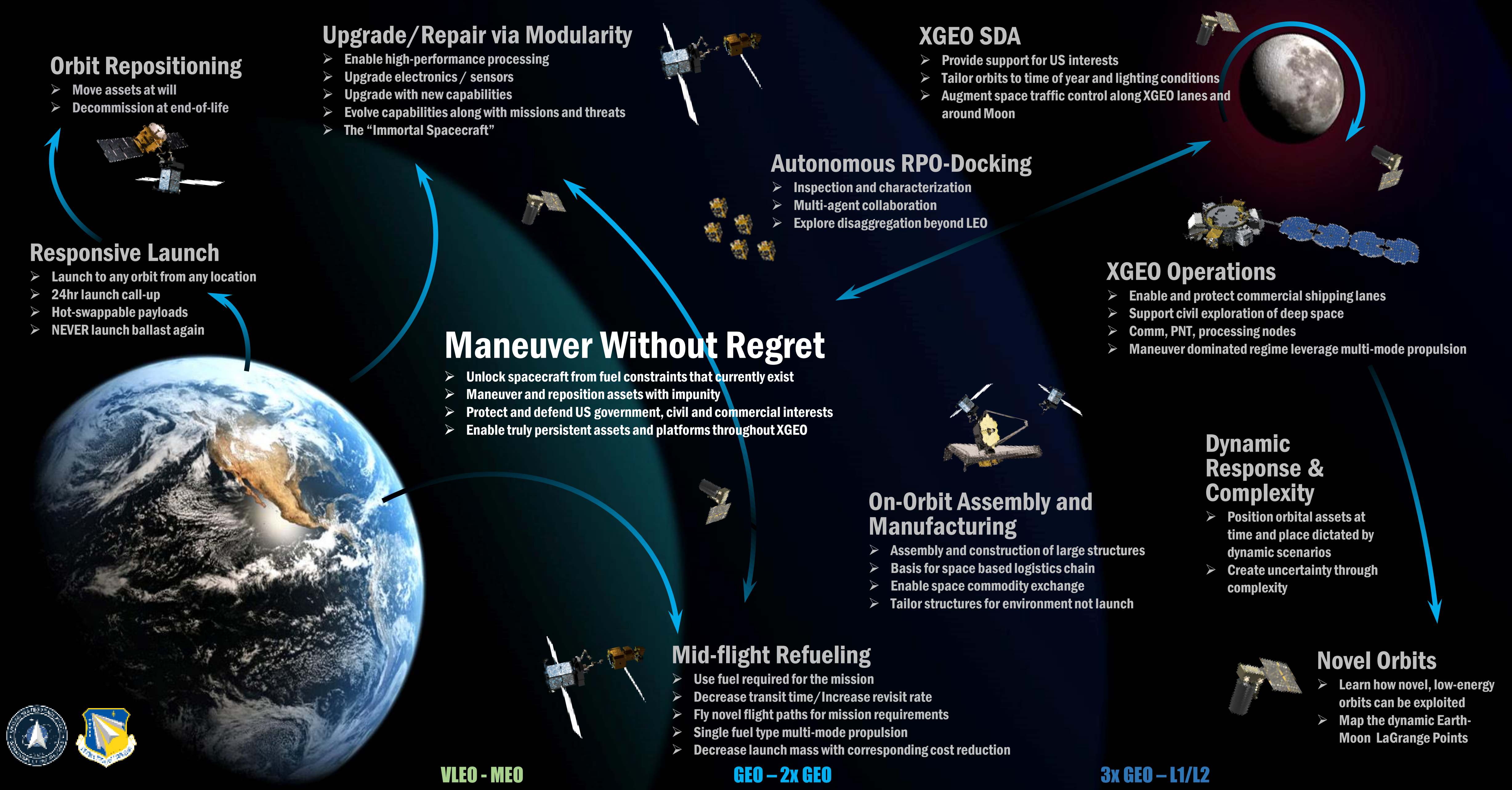
Realistic evaluation of Spacecraft Propulsion

- Spacecraft Propulsion is a subsystem
  - For most of the relatively brief history of spaceflight, the focus of satellites has always been on the payload
  - Even for the most energetic on-board propulsion system ever flown, the payload defined the mission
- Spacecraft designers and operators are masters in balancing subsystem selection and optimization to generate desired effects
  - Traditional spacecraft design and CONOPS do not value aggressive performance enhancement of spacecraft propulsion systems

DAWN
(Xenon Ion Engine)
~11 km/s Delta-V

AEHF
(Hydrazine)
(Biprop Apogee)
(Xenon HET)

Space Logistics and Mobility 2030



Orbit Repositioning

- Move assets at will
- Decommission at end-of-life

Upgrade/Repair via Modularity

- Enable high-performance processing
- Upgrade electronics / sensors
- Upgrade with new capabilities
- Evolve capabilities along with missions and threats
- The "Immortal Spacecraft"

XGEO SDA

- Provide support for US interests
- Tailor orbits to time of year and lighting conditions
- Augment space traffic control along XGEO lanes and around Moon

Autonomous RPO-Docking

- Inspection and characterization
- Multi-agent collaboration
- Explore disaggregation beyond LEO

Responsive Launch

- Launch to any orbit from any location
- 24hr launch call-up
- Hot-swappable payloads
- NEVER launch ballast again

XGEO Operations

- Enable and protect commercial shipping lanes
- Support civil exploration of deep space
- Comm, PNT, processing nodes
- Maneuver dominated regime leverage multi-mode propulsion

Maneuver Without Regret

- Unlock spacecraft from fuel constraints that currently exist
- Maneuver and reposition assets with impunity
- Protect and defend US government, civil and commercial interests
- Enable truly persistent assets and platforms throughout XGEO

Dynamic Response & Complexity

- Position orbital assets at time and place dictated by dynamic scenarios
- Create uncertainty through complexity

On-Orbit Assembly and Manufacturing

- Assembly and construction of large structures
- Basis for space based logistics chain
- Enable space commodity exchange
- Tailor structures for environment not launch

Mid-flight Refueling

- Use fuel required for the mission
- Decrease transit time/Increase revisit rate
- Fly novel flight paths for mission requirements
- Single fuel type multi-mode propulsion
- Decrease launch mass with corresponding cost reduction

Novel Orbits

- Learn how novel, low-energy orbits can be exploited
- Map the dynamic Earth-Moon LaGrange Points

P, α, η / Isp, $, t

USSF does not have a preferred spacecraft power level. Needs span the gamut:

- <1kW pLEO / CubeSats
- 1-10 kW ESPA thru GeoSats
- >100 kW Space Tugs / Manned Missions

→ C.G. is probably somewhere in the middle, but scalable technologies offer a lot of systems engineering flexibility.

P, α, η / Isp, $, t

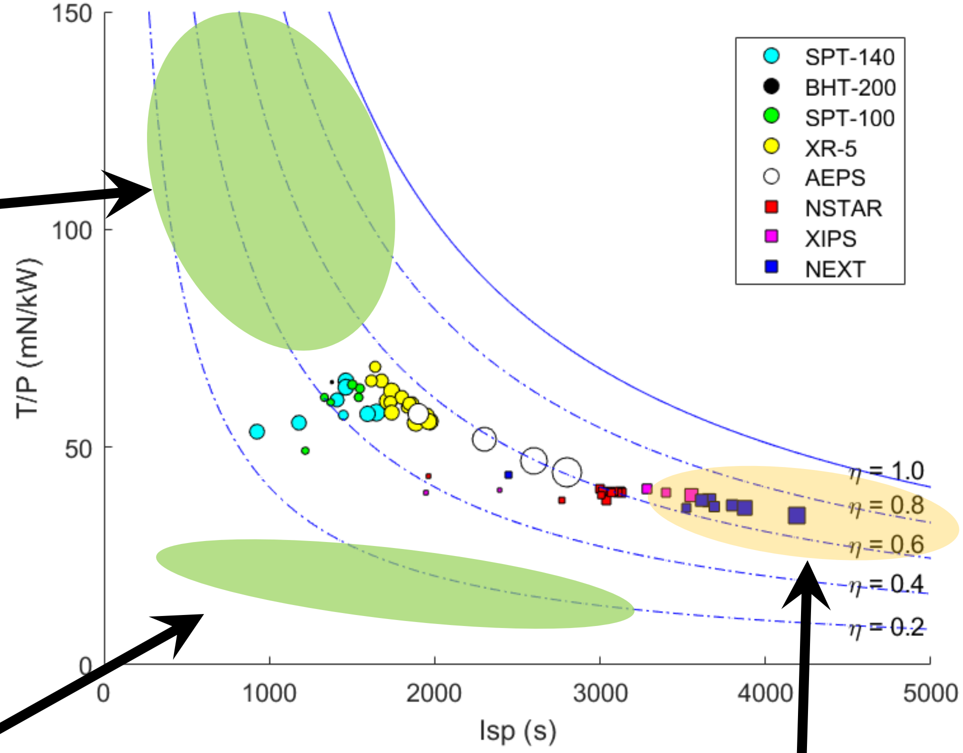
Solar panels are ~100W/kg (so 0.1 kg/kW for generation)

Current HET solutions at 10 kg/kW (including PPU)

→ There is are very large avenues for improvement in thruster system technology here

P, α, η / Isp, $, t

High T/P at low Isp is still of supports responsive space operations



Very little point in optimizing performance when the baseline is already fairly high.

- Molecular propellants still have a lot of room for improvement

>3000s is of vanishing utility for all but the highest power systems

P, α, η / Isp, $, t

This is perhaps the hardest part of the puzzle → how can basic science address the cost and time to transition a technology to operation

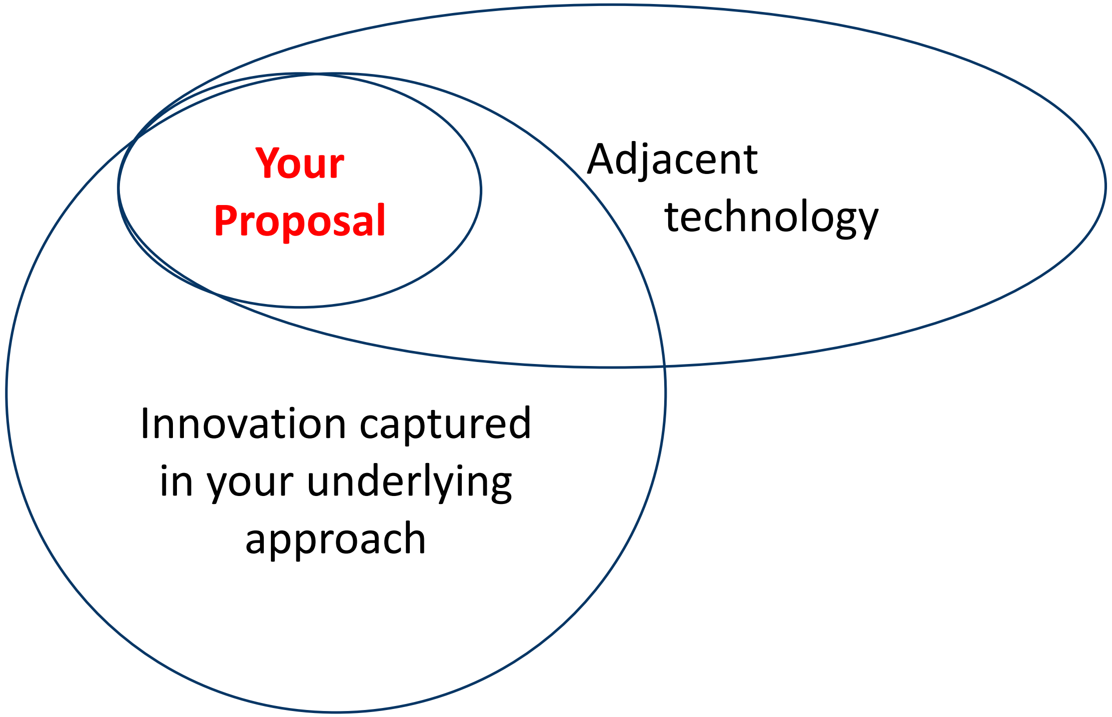
- Consider the mission assurance barrier to demonstrating high TRL

Key concerns (particularly associated with lifetime):

- How much extra confidence do we get from the N+1th hour of testing?
- How do we actually validate that our confidence predictions were good?

Adapting to the new paradigm

Great proposals may not be the *most* directly relevant to immediate problems

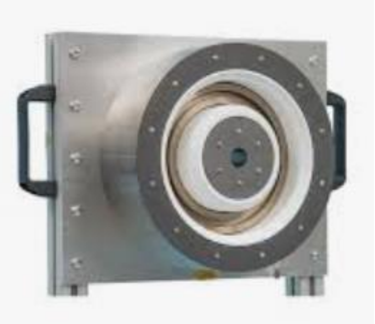


Relevance of Digital Twins to Rocket Propulsion

Present State

Mission Assurance is huge barrier to transition

- Expensive to deliver confidence in huge delivered total-impulse
- Less than stellar confidence



Upfront costs

Direct	~200k	>$15 M
Indirect	<1 M	>$50 M (Est) / 7 yrs

Baked into the entire space enterprise is a conservatism based on lack of feedback

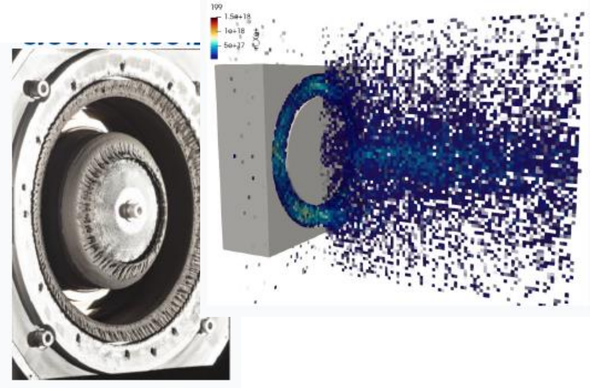
New opportunities

- Embedded sensors, high speed DAQ (data revolution)
- Better and faster models (physics-based and data-driven)
- Leaps in edge computing

Future State

Shift focus from up-front MA to learning over lifecycle

- Real thruster and DT are born at the same time (initial life estimate)
- During operation, continue to update lifetime estimate (with tighter error bounds)



Feedback from in on-orbit operation lets operator trade risk to learn from pushing performance envelope

Underlying challenges to DTs

- ***Nothing new here*** → Feedback loops are at the heart of knowledge generation
- DTs represents evolutionary integration of existing M&S and experimental competencies

Digital Age

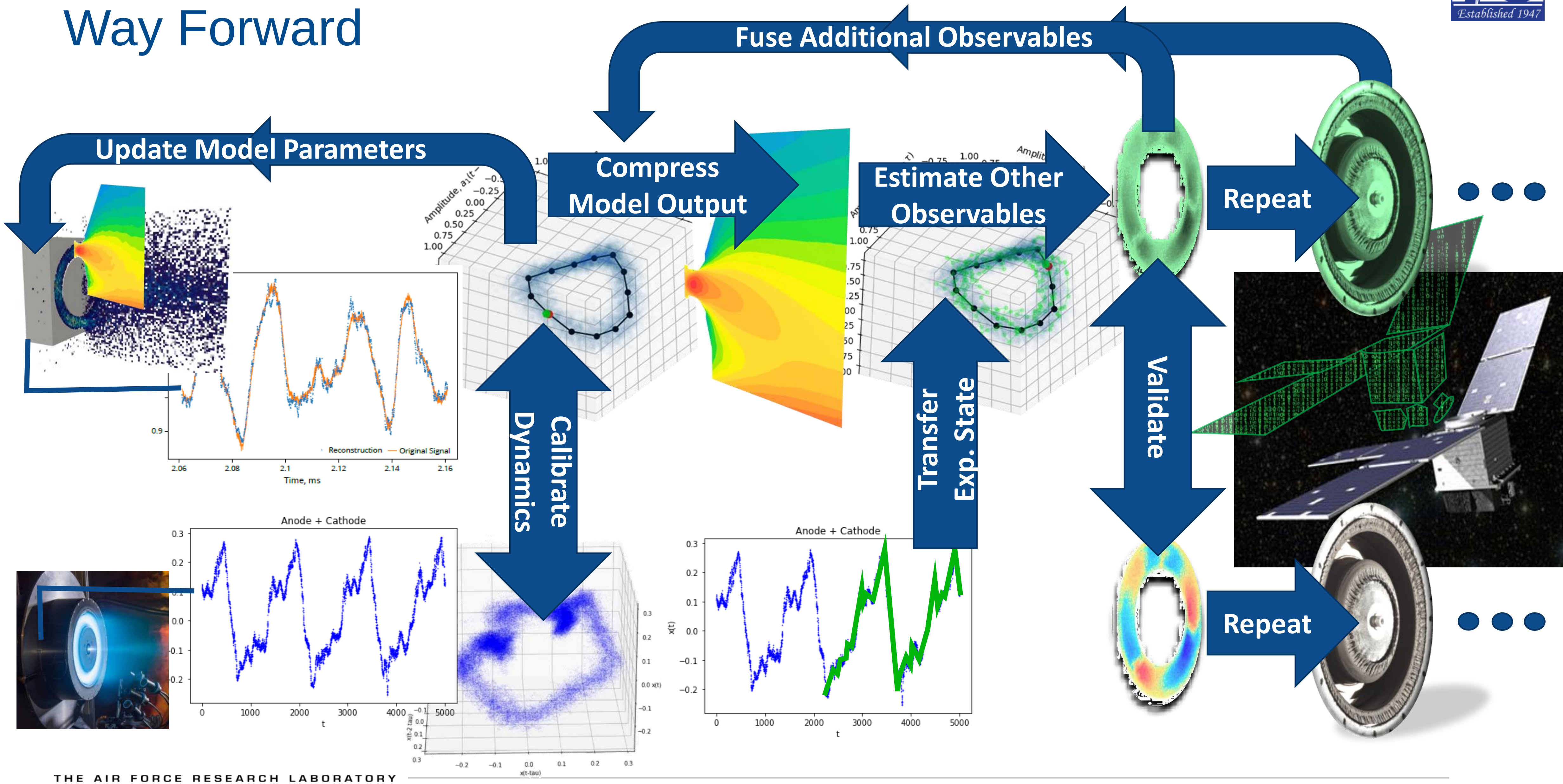
- Data is ubiquitous
  - DTs are about shrinking the gap between data-driven and physics-based models
    - Data-driven models → rapidly deployable; use fleet to build statistical confidence; critical for attacking lower end of market; but, interpolative
    - Physics-based models → anchor confidence to extrapolate (predict outside convex hull); necessary to reach new performance levels
- Models are ***scaleable*** and can be ***transferrable*** (especially physics-based)

Taming the Data dragon

- Not all data is created the same
- Shocking amount of data generated is redundant

Closing feedback loop is not trivial →
Learning to exploit nonlinearity →
Emergent dynamics are the key

Way Forward



Fuse Additional Observables

Update Model Parameters

Compress Model Output

Estimate Other Observables

Repeat

Calibrate Dynamics

Transfer Exp. State

Validate

Repeat

Questions?