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MEMORANDUM FOR PRS (In-House Publication)

FROM: PROI (STINFO) 04 May 2001

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-VG-2001-108**
Fife, J.M., "Electric Propulsion Research at AFRL"

AFOSR Molecular Dynamics Contractors' Meeting **(Statement A)**
(Irvine, CA, 21 May 01) (Deadline: 21 May 01)

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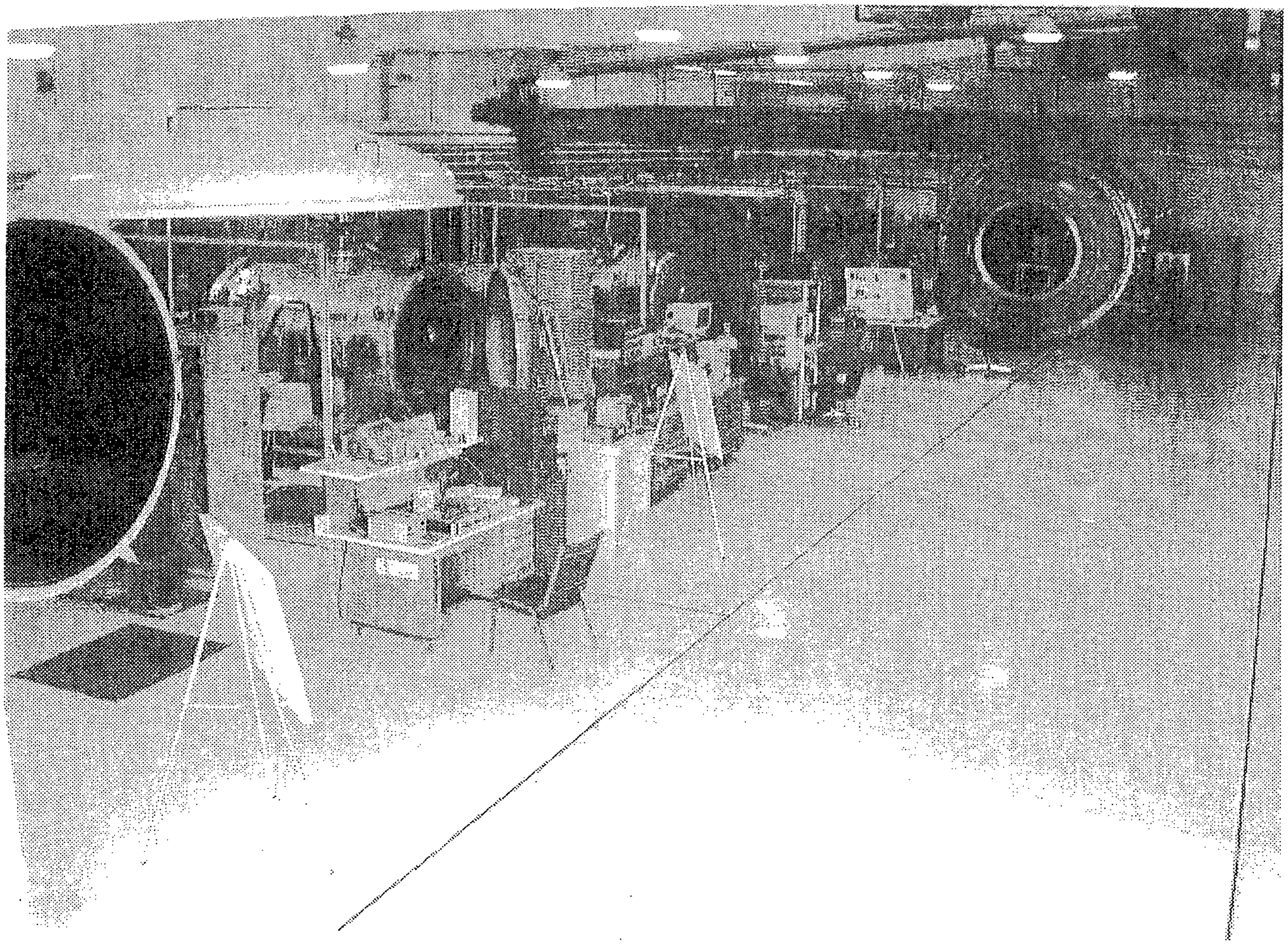
PHILIP A. KESSEL Date
Technical Advisor
Space and Missile Propulsion Division

Electric Propulsion Research at AFRL

21 May 01

John Michael Fife
Research Scientist
Electric Propulsion Group, PRRS
Air Force Research Laboratory

AFRL Electric Propulsion Laboratory



Edwards AFB, CA

6 Vacuum Chambers

Full Time Personnel:

- 8 PhDs
- 3 Engineers
- 3 Technicians
- 1 Financial Analyst
- 1 Admin. Assistant

Air Force Electric Propulsion Research Emphasis

Air Force Missions (from AFSPC):

- Space-Based Radar
- Space Control
- On-Orbit Inspection
- Microsatellites

Low Power
$P < 200$ W

- Small Propulsion (10-200W)
- Micropropulsion (1-10W)
- Dual-Mode Propulsion
  High Thrust or High Isp

- Stationkeeping
- Rephasing
- Orbit Topping

Medium Power
0.5 to 1 kW Arcjets
1 to 5 kW Hall Thrusters

4.5 kW Hall System

- Largely Commercial
  Arcjets: Primex
  Resistojets: TRW, Primex
  Hall: ARC, Busek, Primex, TRW
  Ion Thrusters: Hughes

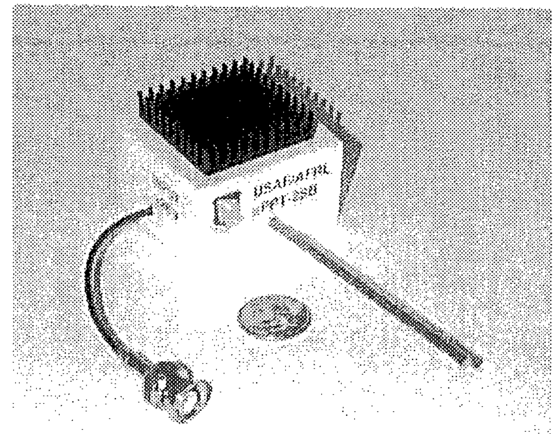
- Orbit Transfer
- On-Orbit Servicing
- Reposition

High Power
$P > 30$ kW

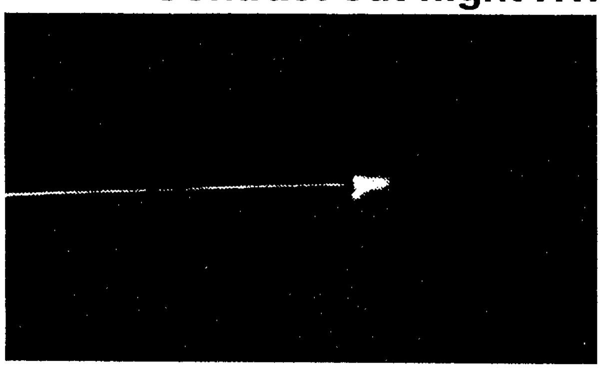
- Hall Thrusters
- Hall Clusters
- Solar Thermal

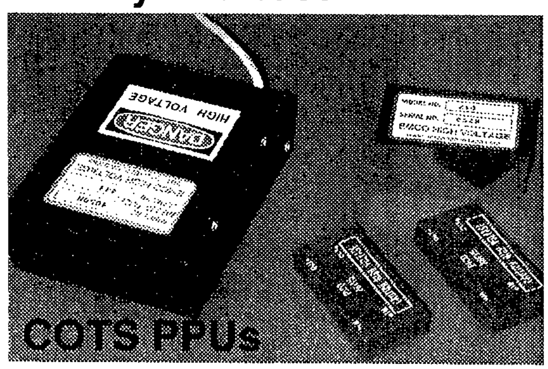
Micro-PPT Technical Approach

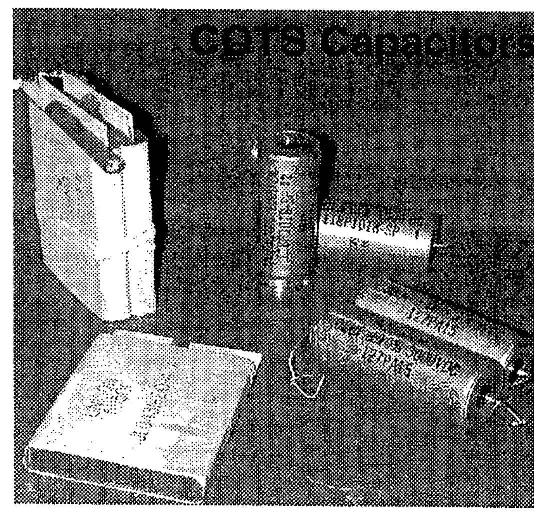
- Develop μ-PPT for IHPRPT Phase II goals
- Flight Demo on TS21
- Address key development issues
  - Thruster life as propellant recedes
  - Minimize operational voltage
  - Low mass power supplies and switching mechanisms
  - Quantify effluents
- M&S to address spacecraft integration issues
- Approach - medium risk, high payoff
  - Propellant module development in-house
  - Contract out flight HW assembly and test



AFRL Patented Designs



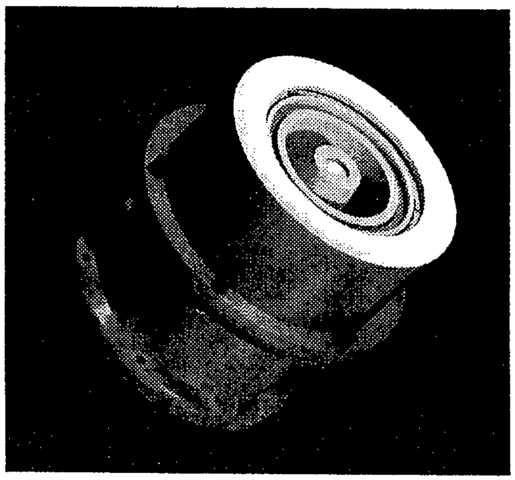




200W Hall Thrusters
AFOSR/AFRL SBIR Funding

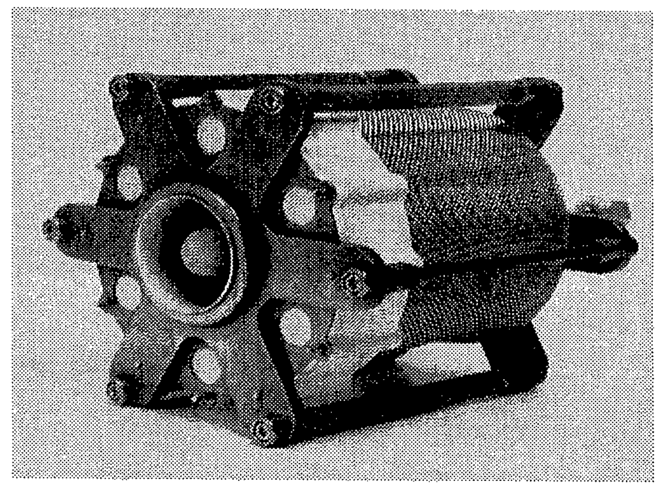
Space Power Inc

- Thruster: AFOSR SBIR
- PPU/PFS: BMDO SBIR
  (Managed by AFRL)



Busek Co.

- Thruster: AFRL SBIR
- PPU: AFOSR STTR



- Both systems tested at AFRL, spring 2000
- 200W Hall in consideration for several Air Force spacecraft
- Busek 200W delivered to MIT
  - Plume measurements in preparation for MIT Hitchhiker on Shuttle

100W Hall Thrusters

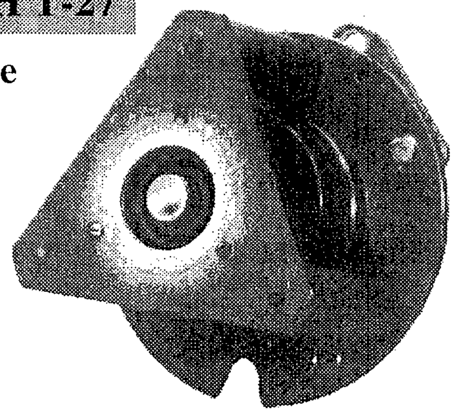
Fakel, Tsnimash – EOARD Funding

TSNIIMASH T-27

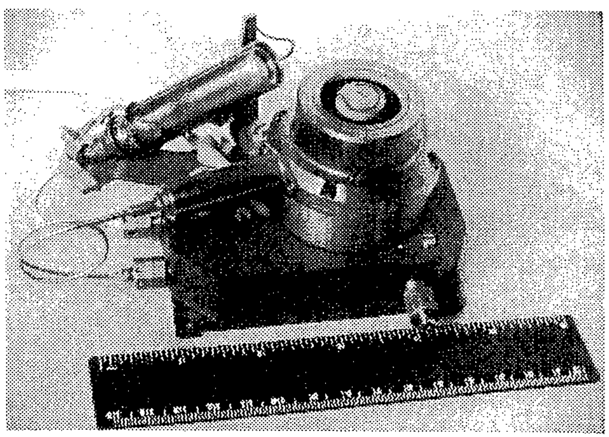
Characterized performance from 40 – 150W

Measure effects of varied:

- Power
- Propellant flow rate
- B field Strength



FAKEL 100W Hall & Miniature Neutralizer

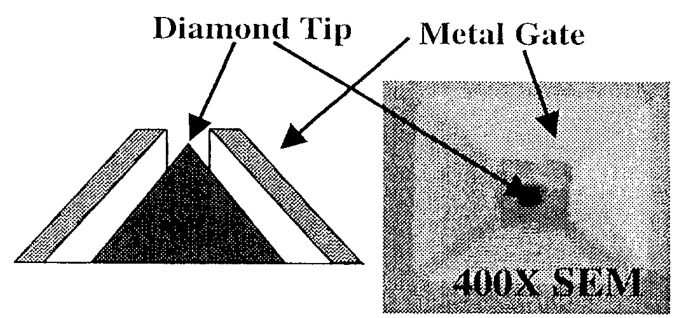


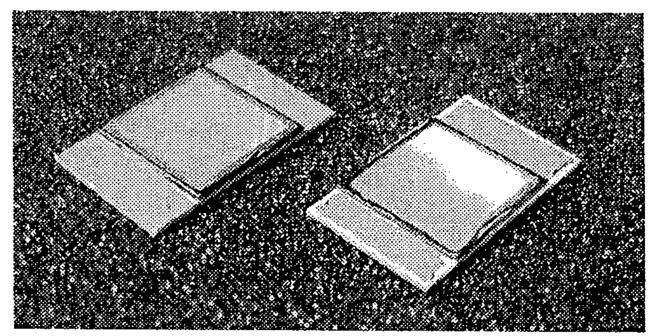
Power = 94.5 W
Thrust = 4.7 mN
Isp = 1000 s
η= 24% (incl. cathode)

Hardware delivered to AFRL

Diamond Field-Emission Cathodes
Busek – AFRL Phase II SBIR

- Low Power , No Propellant
- Characterization in progress





Each 1 cm^2 array has 100,000 Emitters

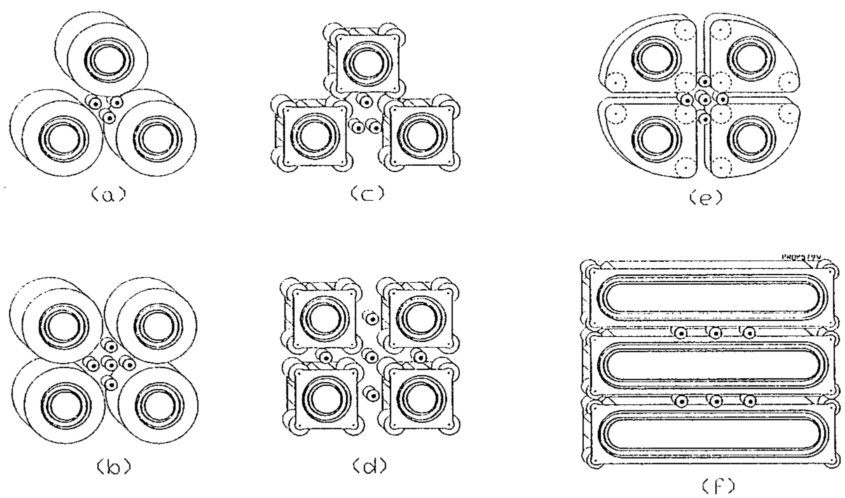
Hall Thruster Cluster R&D

Busek & AFRL - AFRL Core and SBIR funding

BUSEK

Goal: Investigate cluster issues using small grouping of low-power Halls (~600W)
- Enables cluster testing in smaller chambers

Cluster options for R&D effort:

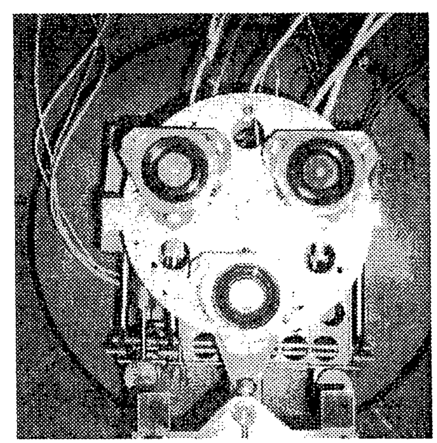


Research Issues:

– Predict cluster S/C interaction using plume measurement from single thruster
– Determine degree of electrical cross-talk through plume plasma
– Determine optimal geometry
– Investigate neutralization techniques

Primary Goal for FY01:

- Identify critical issues requiring Basic Research
- Fire cluster at AFRL and characterize performance and behavior



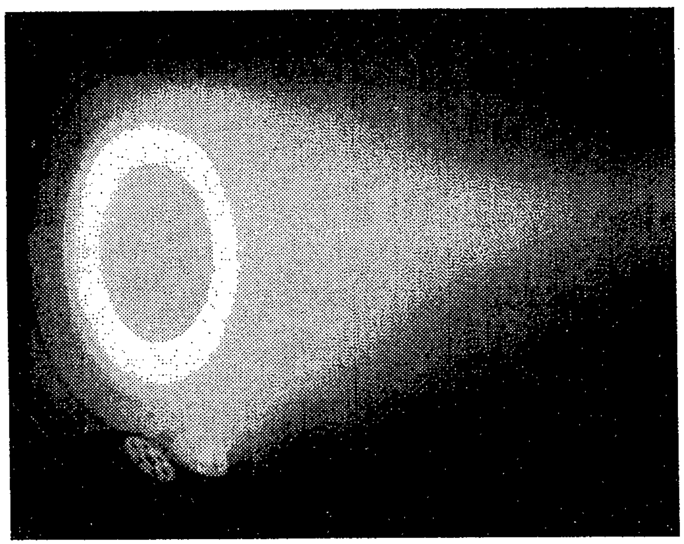
COMPLEMENTARY PROGRAM:

AFOSR/AFRL-Sponsored Hall Cluster Research at TsNIIMASH

High Performance Hall System (HPHS) Overview

OBJECTIVE:

To develop and demonstrate the electric propulsion technology needed to meet the IHPRPT Phase I Goal -- Increase total impulse over wet mass by 20%



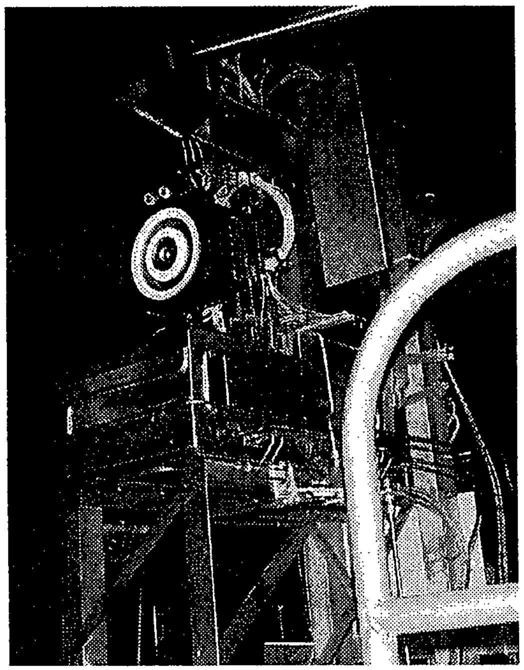
PERFORMANCE OBJECTIVES:

I_{sp}=1800 sec, η=55%, life=7200 hrs

- Supports Critical DoD Satellite Missions with Demanding Propulsion Requirements for Orbit Raising, Repositioning, and Stationkeeping
- Can Reduce Air Force Launch Costs by ~$30M Per GEO Mission
- Also Supports Propulsion Requirements of MILSATCOM Advanced EHF
- Cost Shared $6.5M Contract
  - 56% Govt., 44% Contractor
  - Prime Contractor: Atlantic Research Corp.
- Status:
  - Exceeding IHPRPT Phase I Goal 22% increase in I_{tot} / M_{wet}
  - Program Completes in December 2001

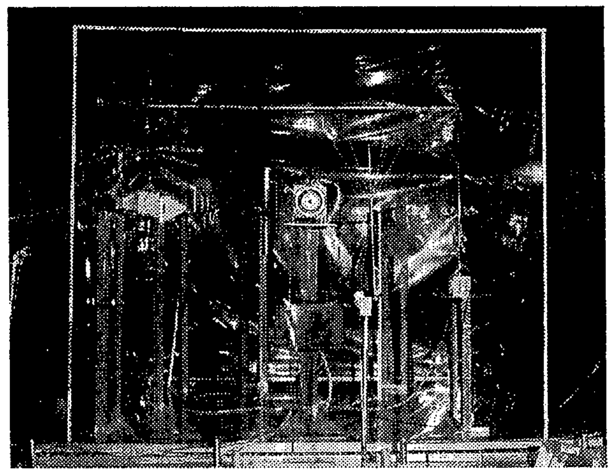
HPHS Accomplishments: U.S. Risk Reduction Testing

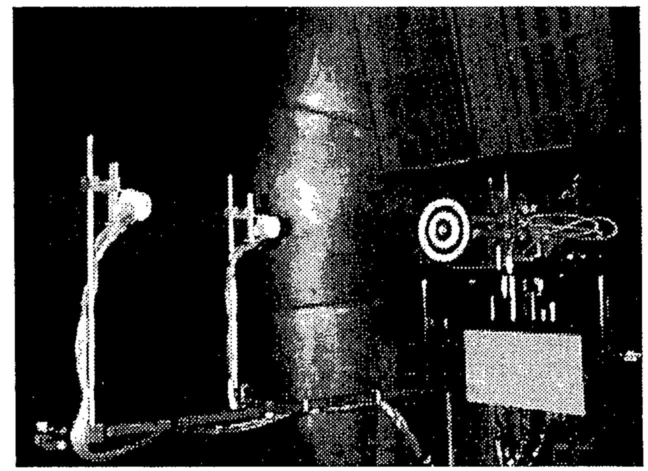
Performance Mapping (NASA Glenn)



- Verified attainment of system performance goals
- AIAA-2000-3250

Spacecraft Interaction Assessment (U. of Michigan and NASA Glenn)



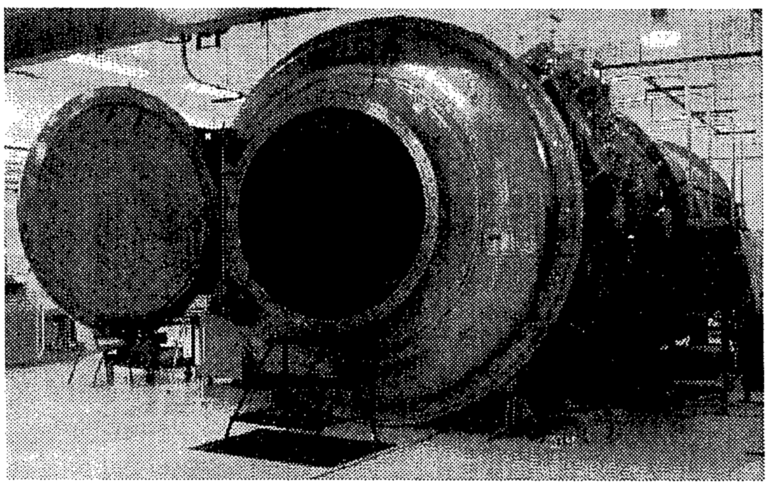


- Successfully characterized impact of SPT-140 DM on spacecraft
  - Plume divergence
  - Sputtering/Contamination
  - Electromagnetic Interference
- AIAA-2000-3521

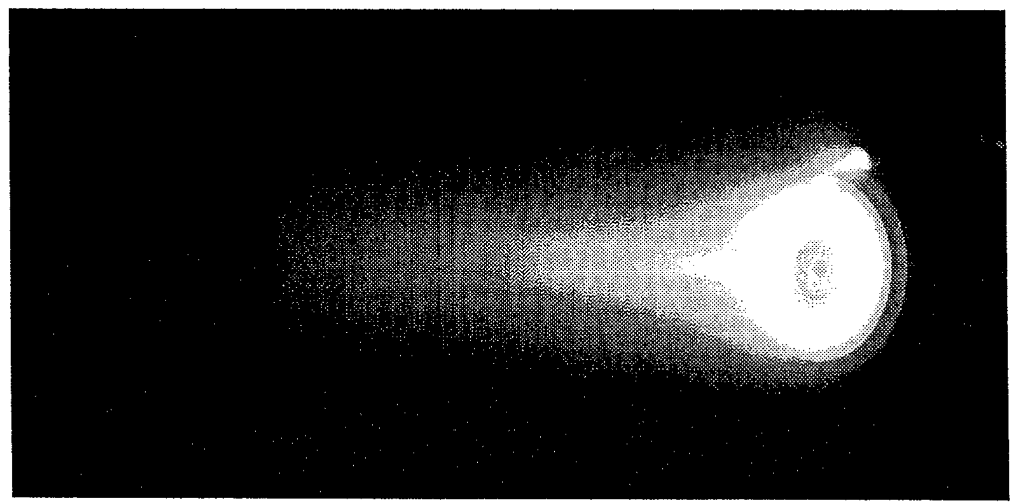
Technology Transition

HPHS 7200 Hour Life Test Begins March 2001

<u>AFRL Chamber #3</u>:
- 3.3 m diameter, 8 m long
- Cryogenic pumping
- Performance: 150,000 std. xenon l/s
- 10^{-7} Torr base pressure



<u>AFRL Chamber #3 Check-Out</u>:
- 8 hour test with SPT-140 DM4
- 17.2 mg/s Xe flow
- 4.5 kW input power
- Maintained 1.5×10^{-5} Torr
  - 150,000 l/s Xe with thermal load
  - 5×10^{-5} Torr required for SPT-140 test

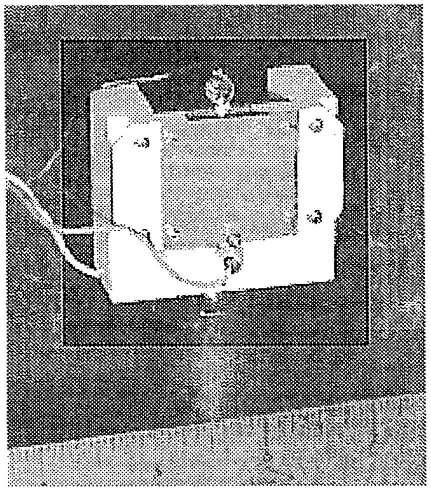


<u>Next Step</u>: Validation with 4.5kW DM Thruster

Colloid Thrusters

Stanford and Phrasor Scientific -- AFOSR STTR

10 cm x 10 cm emitter array

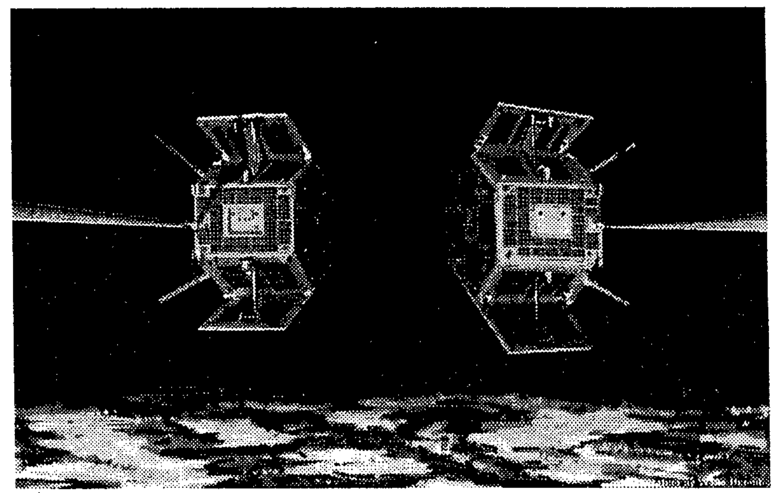


Colloid Thrusters Offer:

- High Efficiency (50-80%),
- Variable Exhaust Velocity,
- No Plasmas (Liquid Phase Charging)
- Longer Life

- Targeted 0.1 mN thrust, 1000 s Isp
- Two 100 (2-mil) emitter arrays
- Bi-polar mode eliminates neutralizer
- 0.5 kg package, 10 x 10 x 20 cm

- Emerald hardware delivery Fall 2000
- Launch in Feb 2002

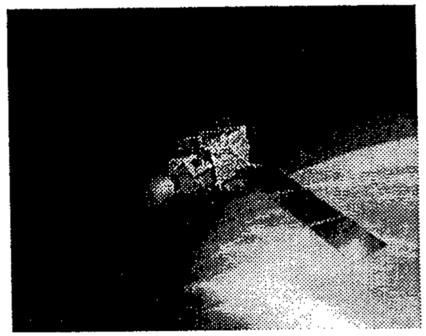


Stanford EMERALD PAIR

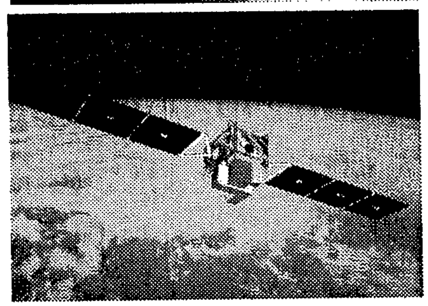
AFOSR/DARPA Support

AFRL EP Space Demonstrators

ESEX
- Primex 27kW Arcjet



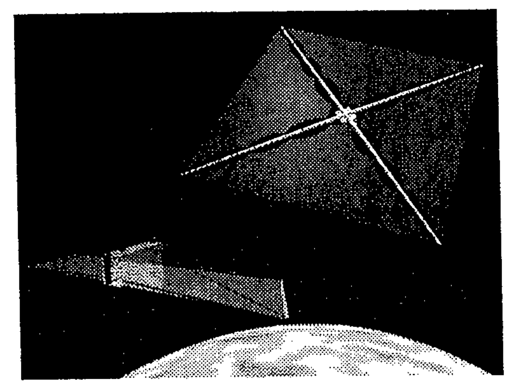
MightySat II.1
- Primex PPT
- Surrey Resistojet



TechSat 21
- Busek 200W Hall
- AFRL MicroPPT

- Push AF technology development and transition to commercial market
- Contract propulsion system
  - Transition from AFOSR 6.1 research
  - Commercialize thruster
  - Use AFRL personnel and facilities to reduce cost (i.e. life, performance testing)
- Develop flight diagnostics in-house
  - Perform Flight Ops and Data Analysis
  - Risk Reduction for Tech Transition

Power Sail
- 30 –150 kW



Thruster-S/C Interaction M&S

Required AF Capability

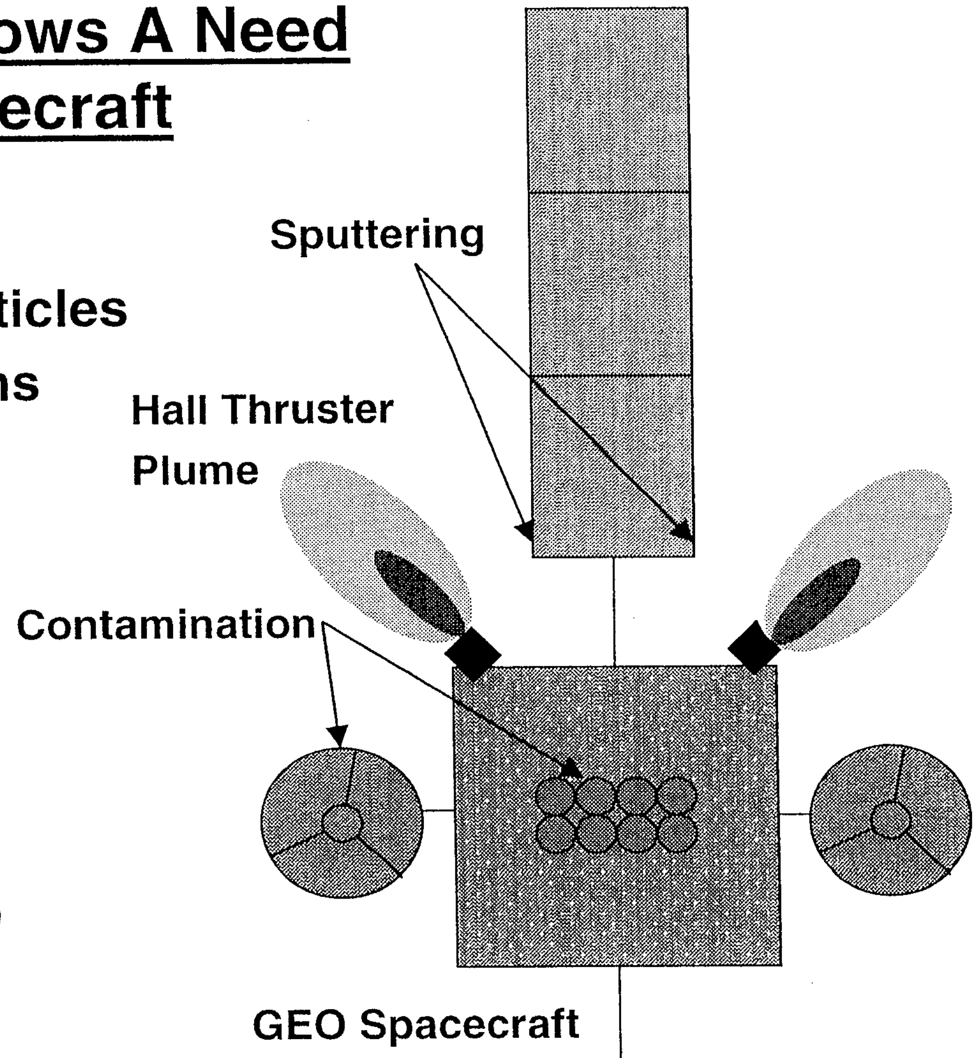
AFRL M&S Gap Analysis Shows A Need for Integrated Thruster-Spacecraft Simulation Capability

EP Engines Emit High-Energy Particles

Hall/Ion Engine: ~300eV Xenon Ions

Need to Predict:

- Contamination and Sputtering of Spacecraft Surfaces
  - Solar Arrays
  - Radiators
  - Sensors
  - Optics
- Cross-Contamination (S/C Clusters)
- Electromagnetic Interference
- Spacecraft Charging
- Observability

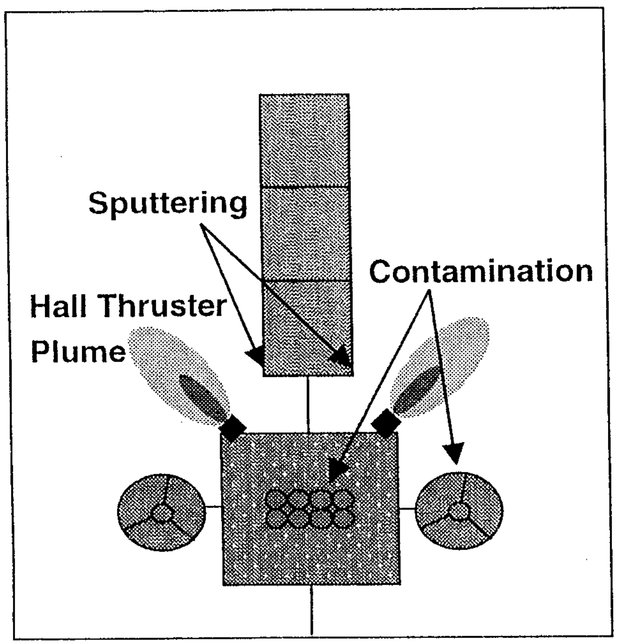


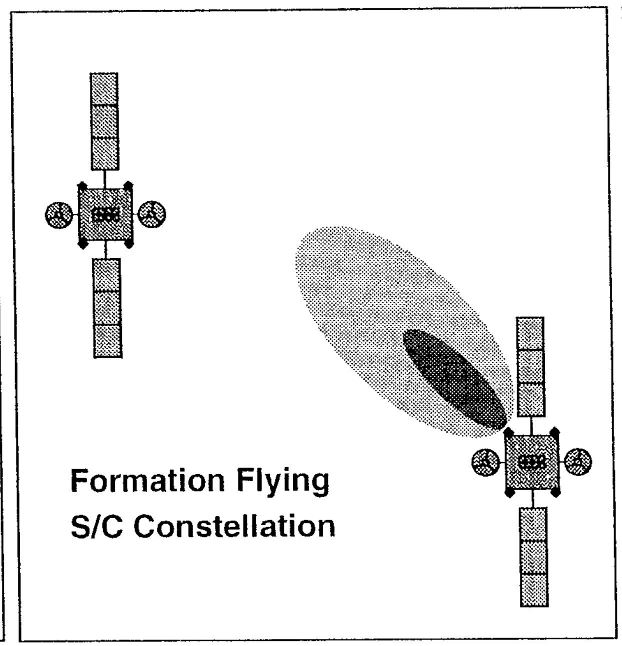
Thruster-S/C Interaction M&S

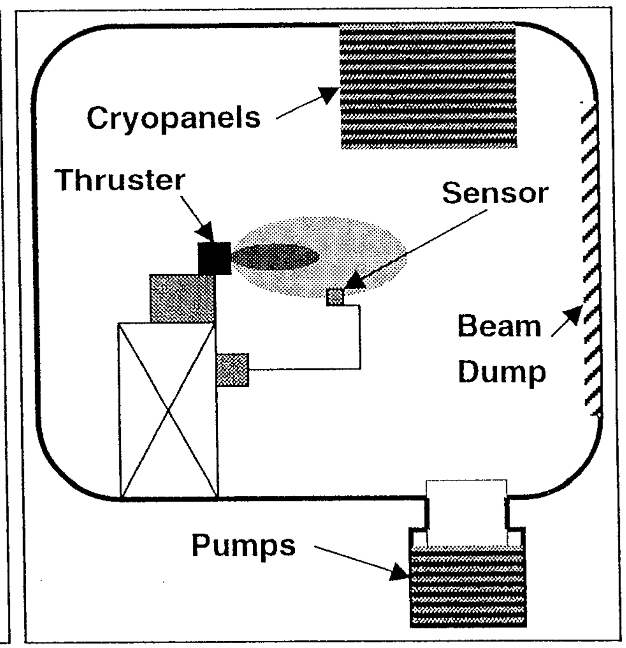
Required AF Capability

A single <u>FLEXIBLE</u> 3-D code which can be used to model thruster plumes in ALL of the following situations:

1. A spacecraft in LEO or GEO
   - Most common application
   - Greatest immediate need
2. Multiple nearby spacecraft in LEO or GEO
   - Supports new AF thrusts
   - Never-before modeled
3. Inside a vacuum test facility
   - Necessary for strong code validation
   - Independent utility: Design of vacuum test facilities





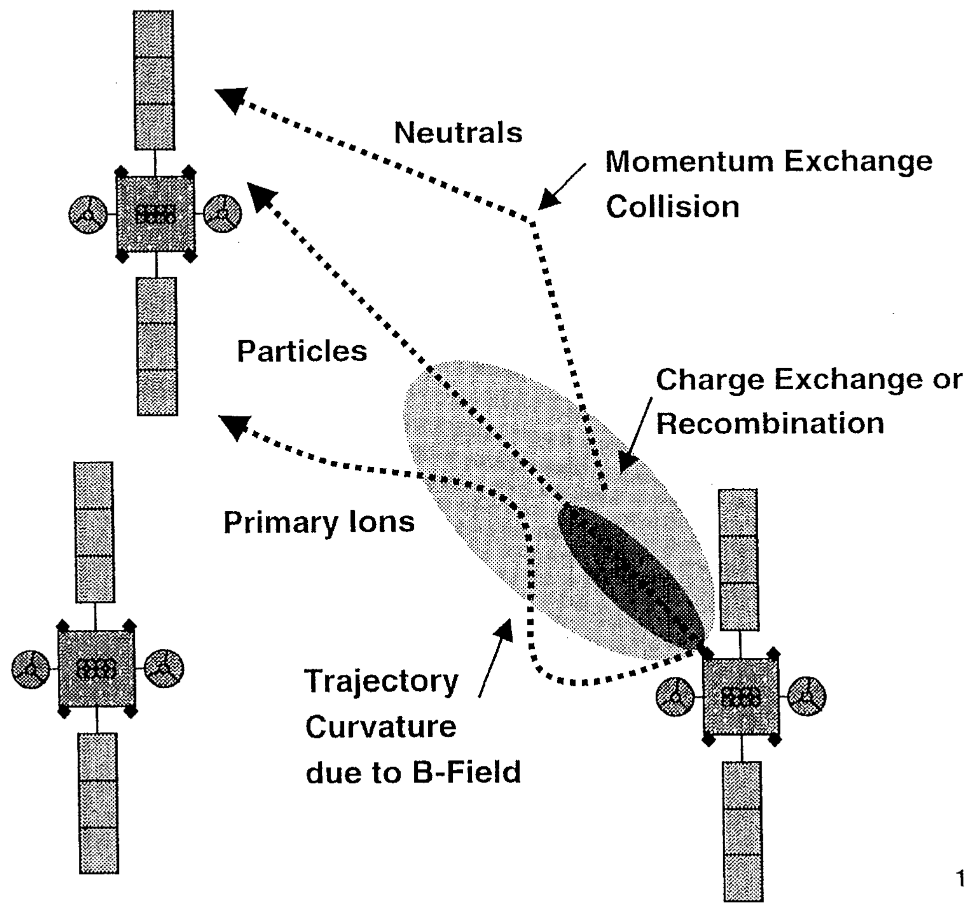


Thruster-S/C Interaction M&S
Application to Formation Flying Satellites

- TechSat 21 baselines 100m between spacecraft during engine firings.
- Future missions may require firing at much closer ranges.
- Need to predict sputtering and cross-contamination.

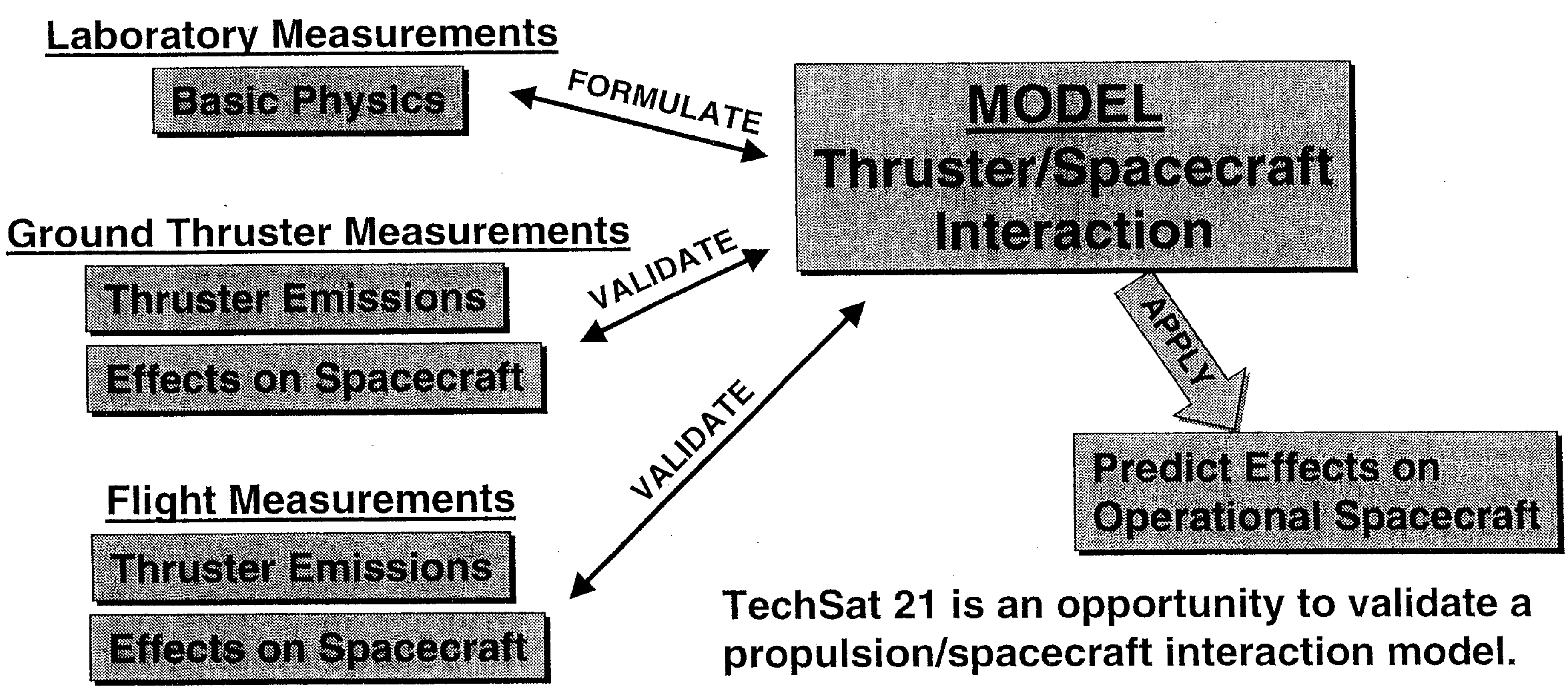
Primary Tech Challenges:

- Differing time scales and mean free paths for neutrals, ions, and electrons
- Collisionality (charge exchange, momentum exchange, recombination) on long length scales in the space environment.
- Modeling interaction (sputtering, deposition, chemistry) of primary ions, charge exchange neutrals, and neutral effluent with S/C surfaces.



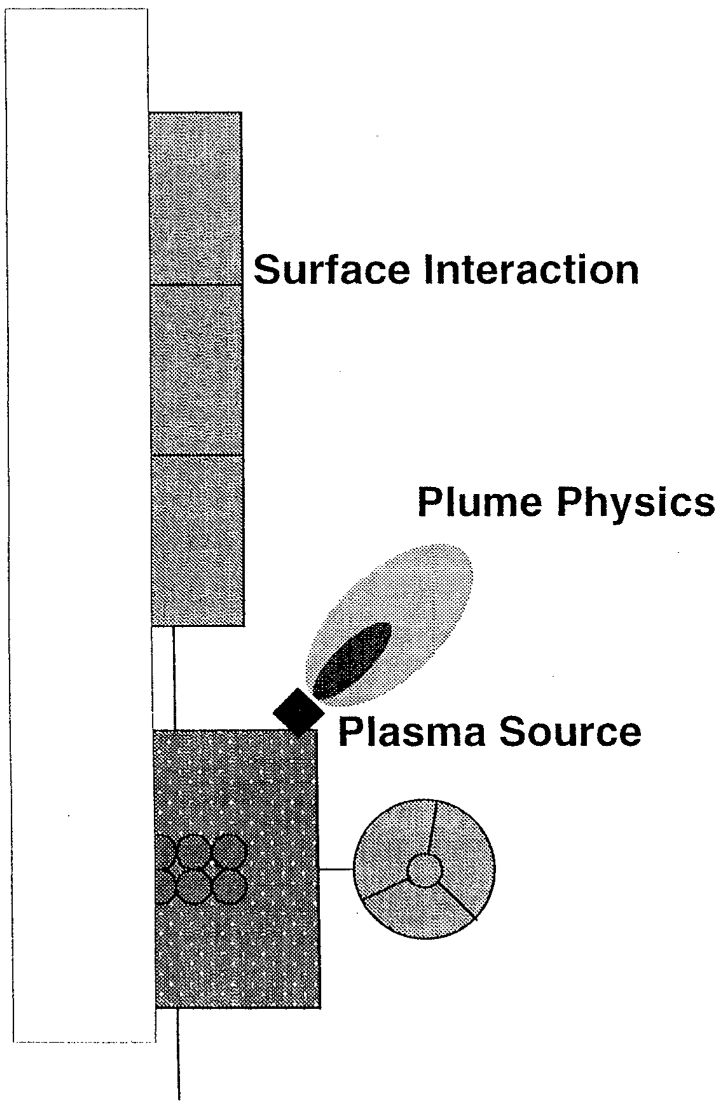
Modeling and Simulation of Propulsion/Spacecraft Interaction

GOAL: Construct and validate a predictive model of thruster/spacecraft interaction applicable to a wide range of space missions.



TechSat 21 is an opportunity to validate a propulsion/spacecraft interaction model.

Modeling and Simulation of Propulsion/Spacecraft Interaction



MODEL
Thruster/Spacecraft Interaction

1. Thruster Source
   - Ion, Neutral, and Particle Flux
   - Beam Divergence
   - Velocity Distributions
2. Plume Physics
   - Ion, Neutral, and Particle Trajectories
   - Plasma Parameters
   - Collisionality
   - Ambient Environment
3. Surface Interaction
   - Sputter Yield
   - Sticking Coefficient
   - Surface Chemistry
   - Surface Charging

Ground Measurements Needed – Thruster Emissions

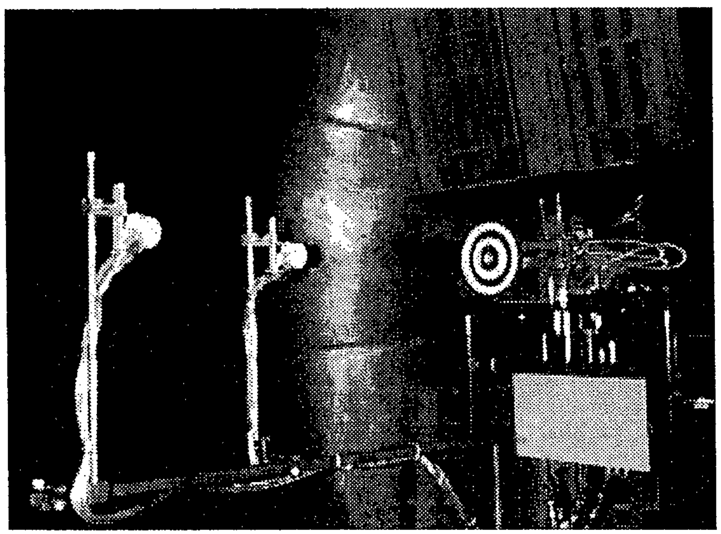
Thruster emission measurements are needed for:

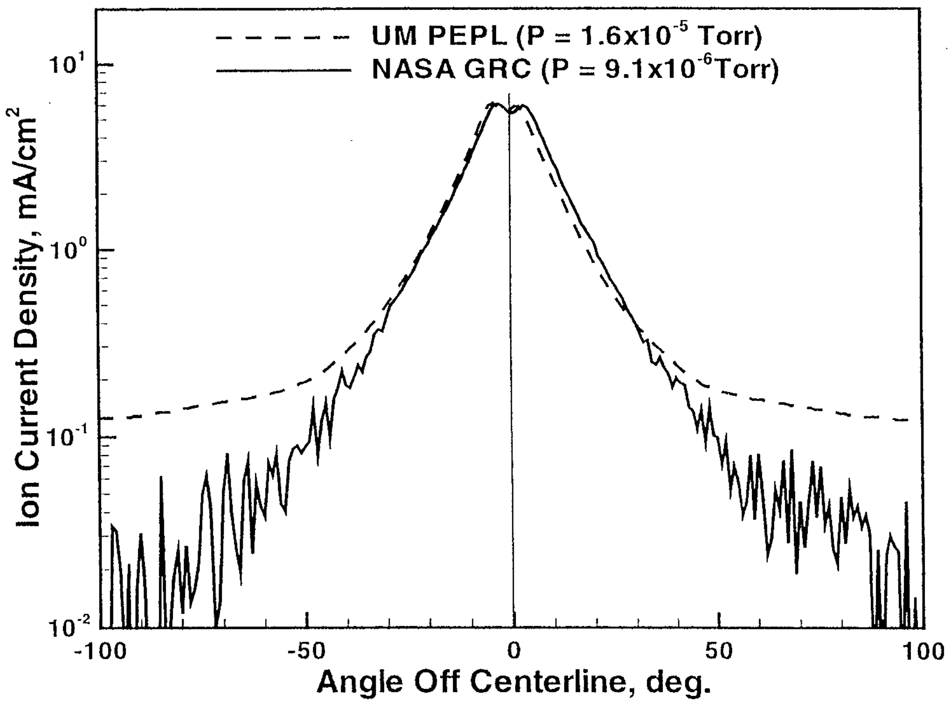
- verification of numerical/analytical source model

  or

- as a stand-alone empirical source model

- PPT Plume Composition
- Effect of Chamber Background Gas
- Multiply-Charged Ions
- Time Dependence

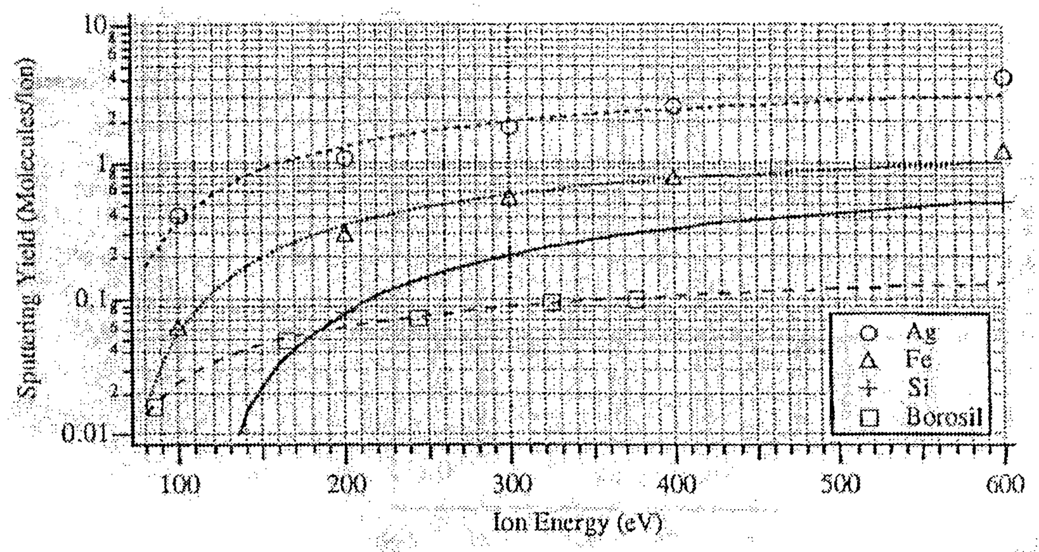


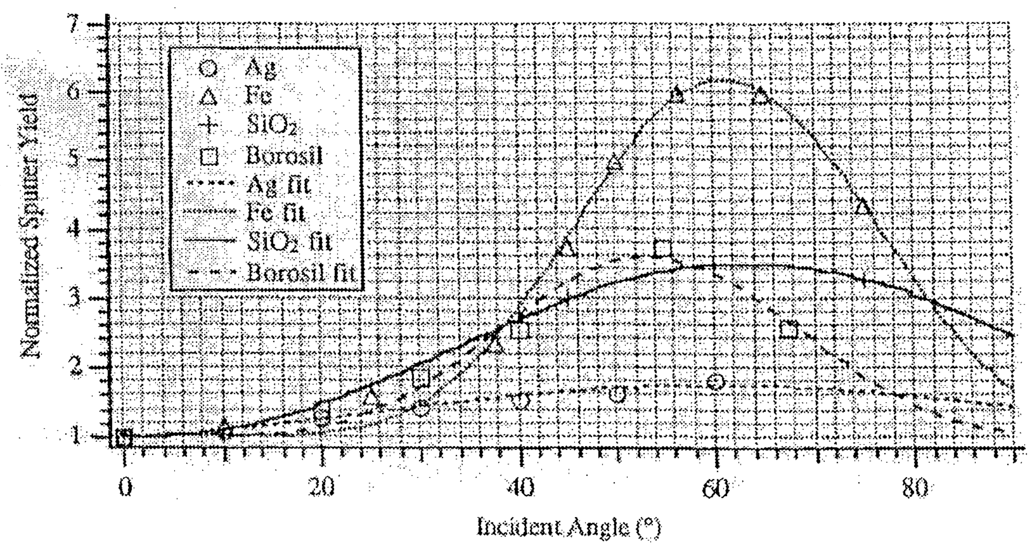


SPT-140 DM3 Plume Characterization at UM PEPL (AIAA-2000-3521)

Ground Measurements Needed — Basic Physics

- Ablation Physics
  - Sputter yield of spacecraft materials by xenon
  - 30 to 1000 eV
  - Low energy sputter yield is difficult to measure
- Thruster Discharge Physics
  - Late time ablation of PPT propellant
  - Hall thruster discharge
- Collision Cross Sections
  - Charge exchange*
  - Multiply charged ions
  - Sputtered materials

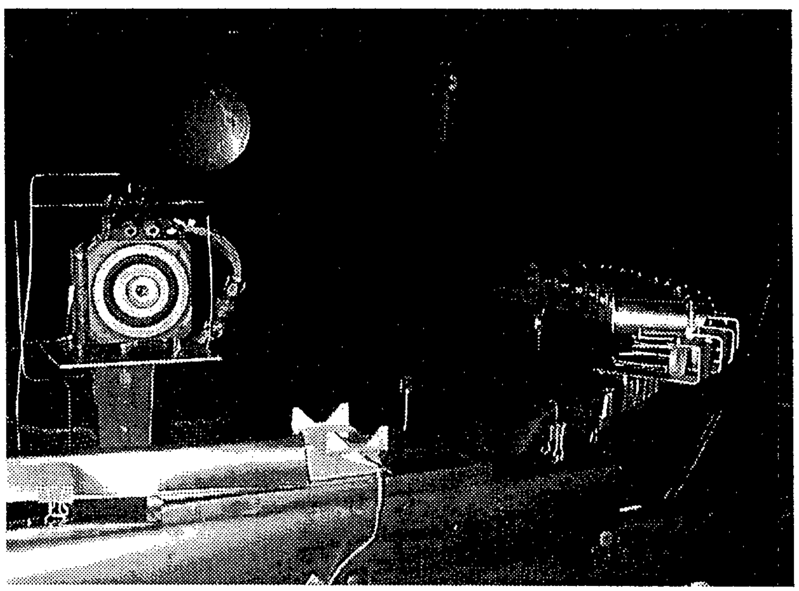


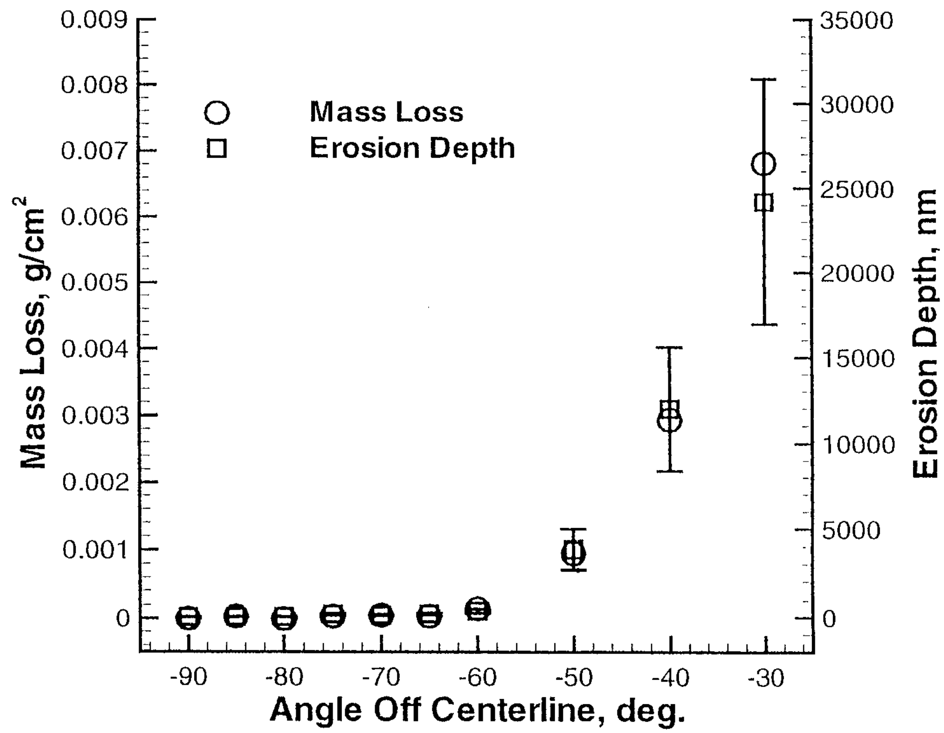


*AFRL Contribution: Pullins et al., AIAA-2000-0603
Plots: Rosenberg, Wehner, Kelly, Lam, Abgaryan

Ground Measurements Needed – Effects on Spacecraft

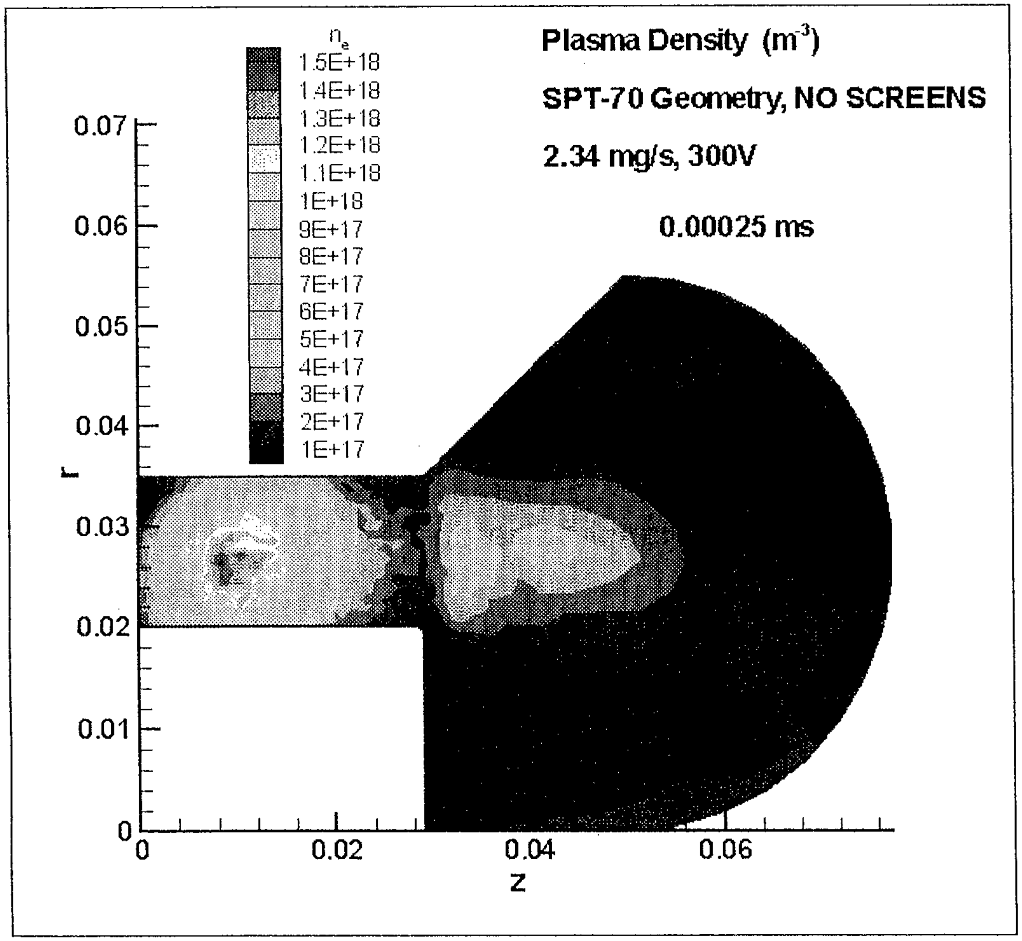
- Surface Erosion or Deposition
- Electromagnetic Interference
- Change in Optical Transmissivity





SPT-140 DM3 Sputter/Deposition Testing at NASA GRC (AIAA-2000-3521)

Modeling and Simulation
Hall Thruster Source Modeling



2-D Hybrid-PIC simulation of an SPT-70 without magnetic screens near the anode.

Current development program:

Collaborative effort between AFRL, MIT, and CNRS (France) sponsored by AFOSR/EOARD (~$60k)

Goals:
- Improved understanding of Hall thruster discharge physics
- Design tool for evaluating new Hall thruster concepts
- Realistic source model for a complete thruster/spacecraft interaction simulation

Methodology:
- Quasineutrality
- Particle-In-Cell propellant
- Fluid electrons

Two separate, parallel efforts (U.S., French) to compare and validate assumptions and methodologies.

Basic Research Needed for Modeling Effort

MODEL

Thruster/Spacecraft Interaction

1. Thruster Source
   - Ion, Neutral, and Particle Flux → Directly measure fluxes with mass spectrometer
   - Beam Divergence
   - Velocity Distributions
2. Plume Physics
   - Ion, Neutral, and Particle Trajectories → Directly measure fluxes with mass spectrometer
   - Plasma Parameters
   - Collisionality → Measure collision cross sections of propellant, thruster, and spacecraft material constituents
   - Ambient Environment
3. Surface Interaction
   - Sputter Yield → Measure angular-dependent sputter yield at various incident energies for various materials
   - Sticking Coefficient → Laboratory measurements
   - Surface Chemistry → Laboratory measurements

Basic Research Needed

(AFOSR may be able to support)

Directly measure fluxes with mass spectrometer

Measure collision cross sections of propellant, thruster, and spacecraft material constituents

Measure angular-dependent sputter yield at various incident energies for various materials

Laboratory measurements

Thruster-S/C Interaction M&S
Preliminary Program Plan

Design and build a code that meets AF requirements.

Flexibility is key. Focus on adaptive, unstructured grid techniques.

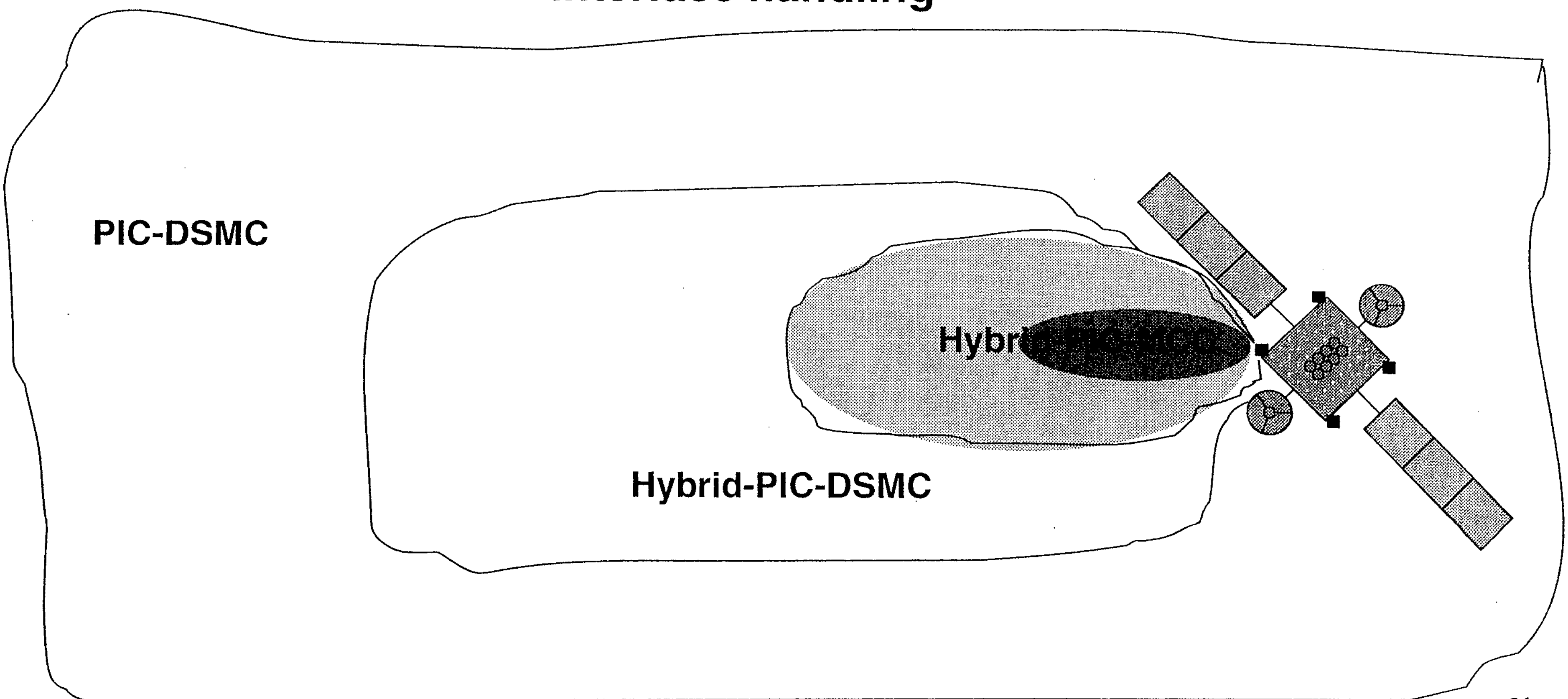
Development Approach:

- Modular, top-down design
- Step-wise refinement
- Configuration control (ICDs, etc.)
- Thorough research
- Quantifiable algorithmic error
- Validation

Thruster-S/C Interaction M&S
Preliminary Program Plan

Process controller:

- Sequencing
- Domain decomposition
- Interface handling



Thruster-S/C Interaction M&S
Preliminary Program Plan

Resources:

- 1.5 in-house programmers/scientists
- >$70k/year unburdened project dollars
- AF supercomputers
- Test facilities and flight data for validation
- Results from $30k feasibility study at MIT
- Results from $120k/year basic research grant to MIT

Currently: Planning a collaborative program based on a strong AFRL-MIT team.