Carbon Back Sputter Modeling for Hall Thruster Testing

James H. Gilland[*], George J. Williams[*],
Jonathan M. Burt[*], John T. Yim[†]
[*]Ohio Aerospace Institute
[†]NASA Glenn Research Center

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Outline

- Statement of Problem
- Carbon Back Sputter Review
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  - Sputter Yields
  - Sputter Models
- Current Work
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    - *Numerical*
      - HAP
    - *Experiment*
  - Results
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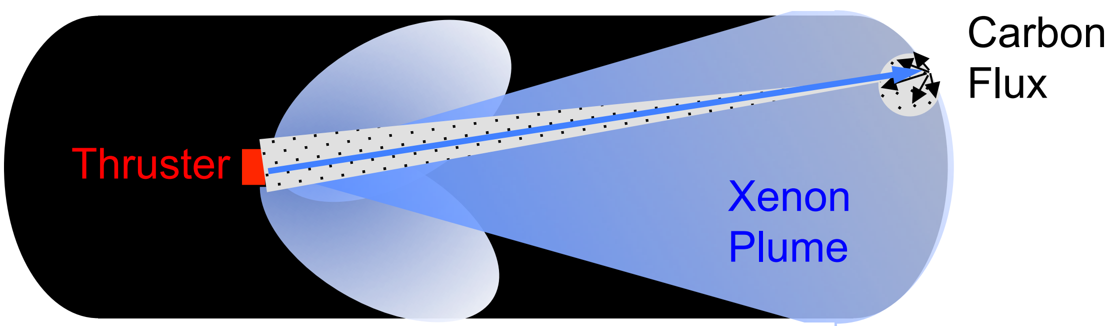
    - *Experiment*
  - Conclusions

Facility Back Sputter Affects on Thruster Life Validation

- Carbon sputtering from vacuum facility walls introduces contamination and deposition back to thruster surfaces
- As space based erosion mechanisms are progressively reduced, facility deposition effects become more important.
  - NEXT Ion thruster grid life (51.2 kh Extended Life Test)
  - Magnetically Shielded Hall Thruster insulator life (50 kh design life)
- Possible effects of back sputter on life testing
  - Competitive deposition/erosion processes on insulator surfaces could mask erosion process in space
  - Build up of conductive carbon layers could introduce arcing or shorting in ground test thrusters



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Tests with facility carbon observed

- Previous life and wear tests have experienced facility back sputter
- Ion
  - NSTAR Extended Life Test (~30,000 h/150 kg throughput)
    - *Net erosion observed on grid*
  - NEXT 2000 h wear test
  - NEXT Long Duration Test (51,200 h/918 kg)
    - *Carbon lined chamber*
    - *QCM measurement*
    - *Carbon deposition at localized positions on grid*
- Hall
  - SPT-100 (90's)
    - *Low accuracy – visual observance of films on back of witness plates*
  - H6 Magnetic Shield Testing (100's of h)
    - *QCM measurement at single location near thruster*
    - *BN surface profiles*
  - HERMeS Thruster (on going)

Summary of Carbon/Life Tests

Thruster	Tank	L (m), D(m)	λ	n	Specific Impulse sec	Beam Voltage V	Beam Current A	Measured Carbon Deposition μm/khr	Predicted μm/khr	Measured as % of Predicted	Normal Sputter Yield Atoms/ion
NSTAR ELT, wear test	JPL 148	10, 3	64	0.94	2000-3000	650-1100		14-20 μm/ 0.7	18 μm/ 0.6	78-110	
NEXT 2khr	GRC VF 6	21, 7.3	64	0.94	4000	1800	3.52	2	0.56	360	0.718
NEXT LDT c. 2005	GRC VF 16	7.6, 3	64	0.94	4000	1800	3.52	3.02	3.94	77	0.718
HiPEP (Herakles Precursor) 2khr	GRC VF 6	21, 7.3	64	0.94	7440	5500	3.6	2-2.5	1.59	126-160	1.638
NEXIS (Herakles Precursor) 2khr	JPL 248	8, 2.6	64	1.94	7080	4809	4.09	7.2-7.8	9.78^	74-80	1.517
NEXT Aerospace	EP2	9.4, 2.4			4000	1800	5	3-10			
T6	IV10	10, 6			4632	~2700	4.5				
MS Hall	JPL 148	10, 3			2000	300	20	4			
MS Hall 113 h wear test	JPL 148	10, 3			3000	800	11	2.5			
SPT-100	VF-5	9, 4			2500	300	4.5				

Based on Van Noord and Soulas, "A Facility and Ion Thruster Back Sputter Survey for Higher Power Ion Thrusters," AIAA 2005-4067

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HERMeS Back Sputter Modeling Approach

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Analytic and Numerical Modeling

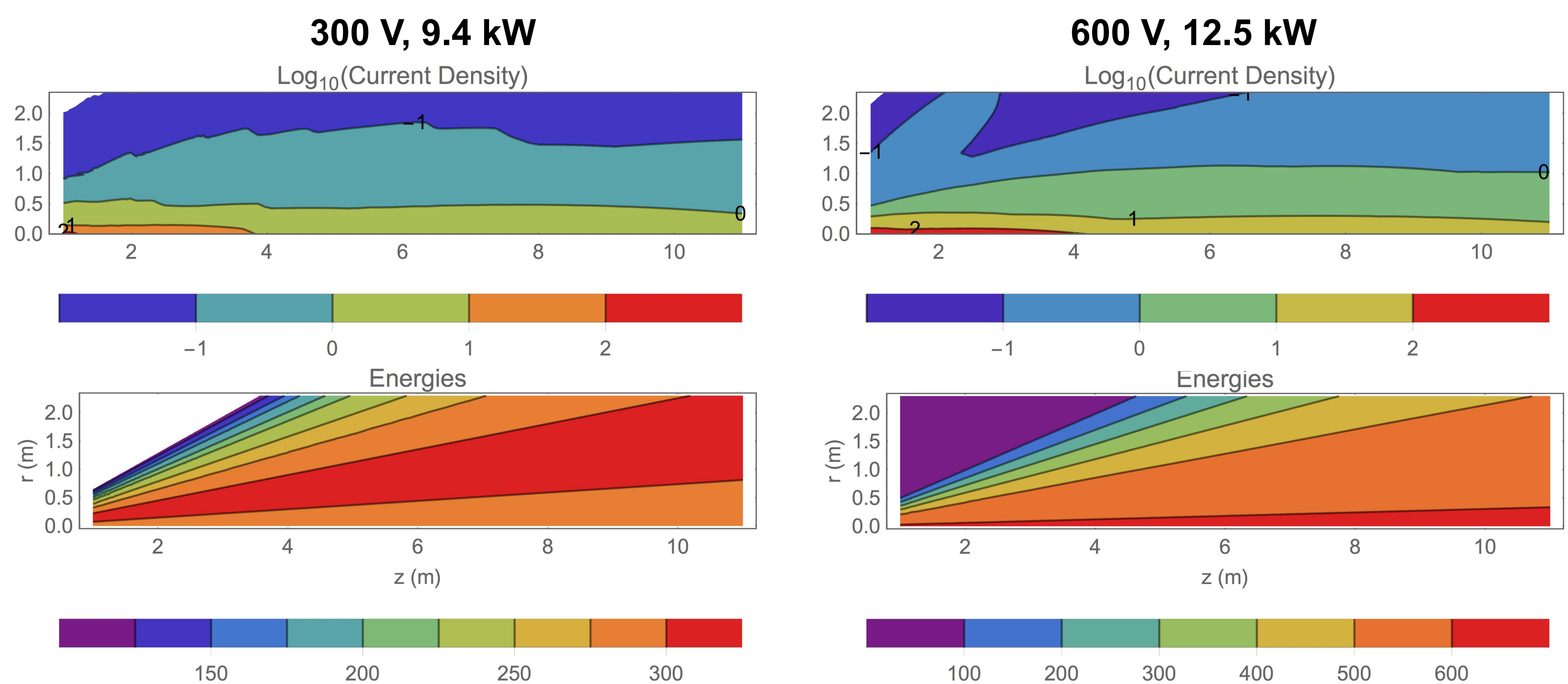
- **In Parallel:**
  - Adapt analytic approach (Van Noord, Soulas, Reynolds) to Hall thruster plume
    - *Add empirical j(θ), E(θ) description for more divergent Hall thruster plume*
    - *Apply to VF-5 (cylindrical) geometry*
  - Detailed numerical model of full VF-5 geometry, HERMeS Plume
    - *HAP DSMC code to track Xe plume, model carbon sputtering particle distribution, and track carbon flux to thruster plane.*
    - *HAP already used to model pumping speeds in VF-5 with actual cryopanel geometry*

Analytic Model

- Ray tracing/Free Molecular Flow
- Axisymmetric
- Trace thruster plume flow to walls
  - Line of site plume propagation to walls
    - *j(θ) ➔ j(r,z)*
  - Angle of incidence from geometry
    - *(β) ➔ β(r,z)*
  - Calculate yield of sputtered particles production to emission angle α(r,z)
    - $Y(E_i,\beta,\alpha)=Y_0(E_i)f(\beta)\ Cos(\alpha)/\pi$
  - Track flux of particles back to thruster plane through view factors

Analytic Model

- **Input profiles**
  - Plume data obtained from HERMeS probe measurements
    - *Faraday, Langmuir, EXB probes*
  - Using a quasi-analytic approach – spline fit j(θ), E(θ) data instead of a single function curve fit

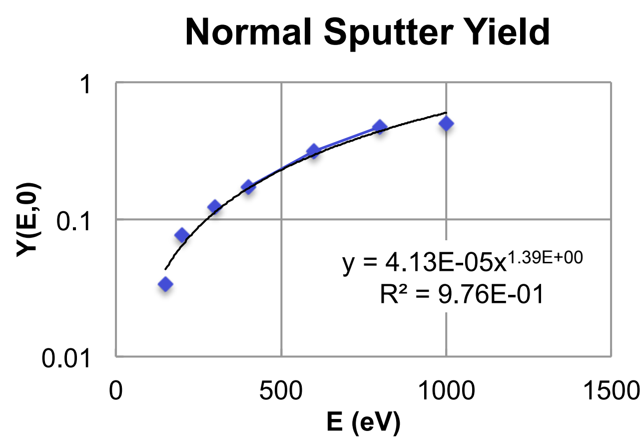


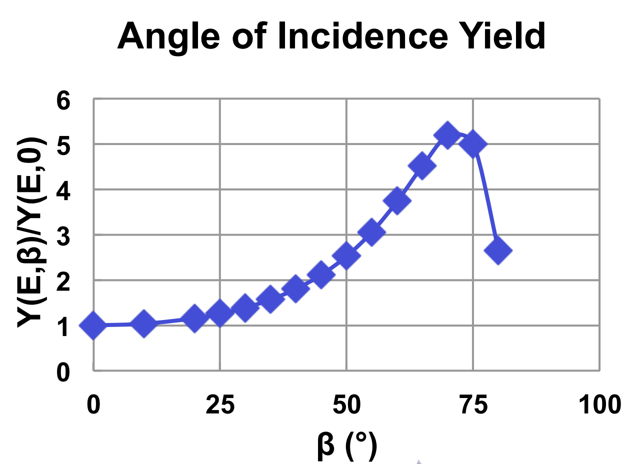
Sputter Yield Model

- **Total number of particles sputtered determined by incident energy (E) and angle (β)**
  - Empirical fit to data

$$Y(E,\beta) = 4.123 \times 10^{-5} E^{1.388} \frac{e^{-1.0556(-1+Sec(\beta))}}{Cos(\beta)^{3.427}}$$

  - Defines total number of particles produced, not the direction of the sputtered atoms
  - For HAP, assumed a constant sputtered particle energy of 3 eV





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Hypersonic Aerothermodynamics Particle (HAP) Code

- **Direct Simulation Monte Carlo Code developed for hypersonic applications**
  - Previously used to predict pumping performance in NASA GRC VF-5
  - Thruster plume is defined on a 1 m radius, ¼ spherical surface
    - *Data obtained from HERMeS probe measurements*
    - *Faraday, Langmuir, EXB probes*
  - Variable Hard Sphere energy-dependent cross sections
    - *Xe:* d_{ref} = 5.74 Å, ω=0.35
    - *C:* d_{ref} = 3.23 Å
    - T_{ref}: 273K

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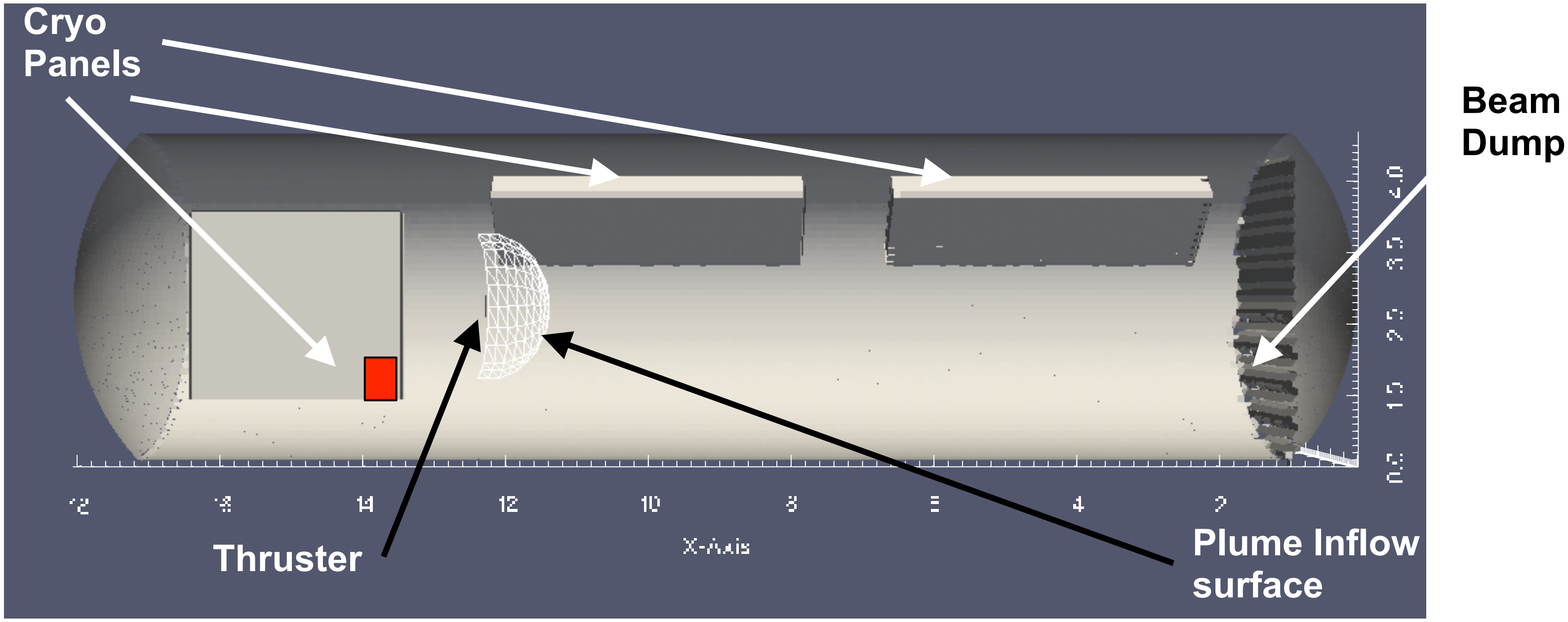
Vacuum Facility 5 geometry for HAP



- Half of chamber simulated due to symmetry
- Thruster is located 0.1 m below center line
- Cryo pump surfaces included
- End beam dump made of angled carbon plates
  - 10° upper plates to the vertical upper plates, 30° lower plates
- All surfaces assumed carbon coated
- Plume inflow defined over ¼ sphere at 1 m radius
- Calculations within flux surface (at thruster) not accurate

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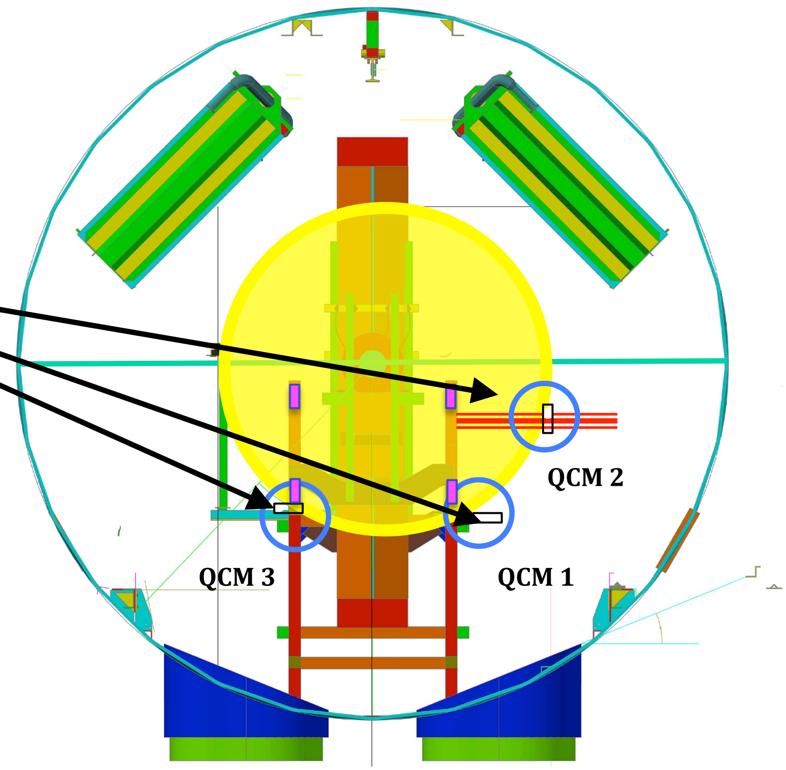
Experimental Measurements

- Ongoing wear testing of HERMeS TDU-1 thruster
  - Wear operating condition: 600 V, 12.5 kW
  - Testing has exceeded 1000 hours
- As part of testing, 3 Quartz Crystal Microbalances located near thruster plane
- Back sputter deposition measured continuously during testing



RESULTS

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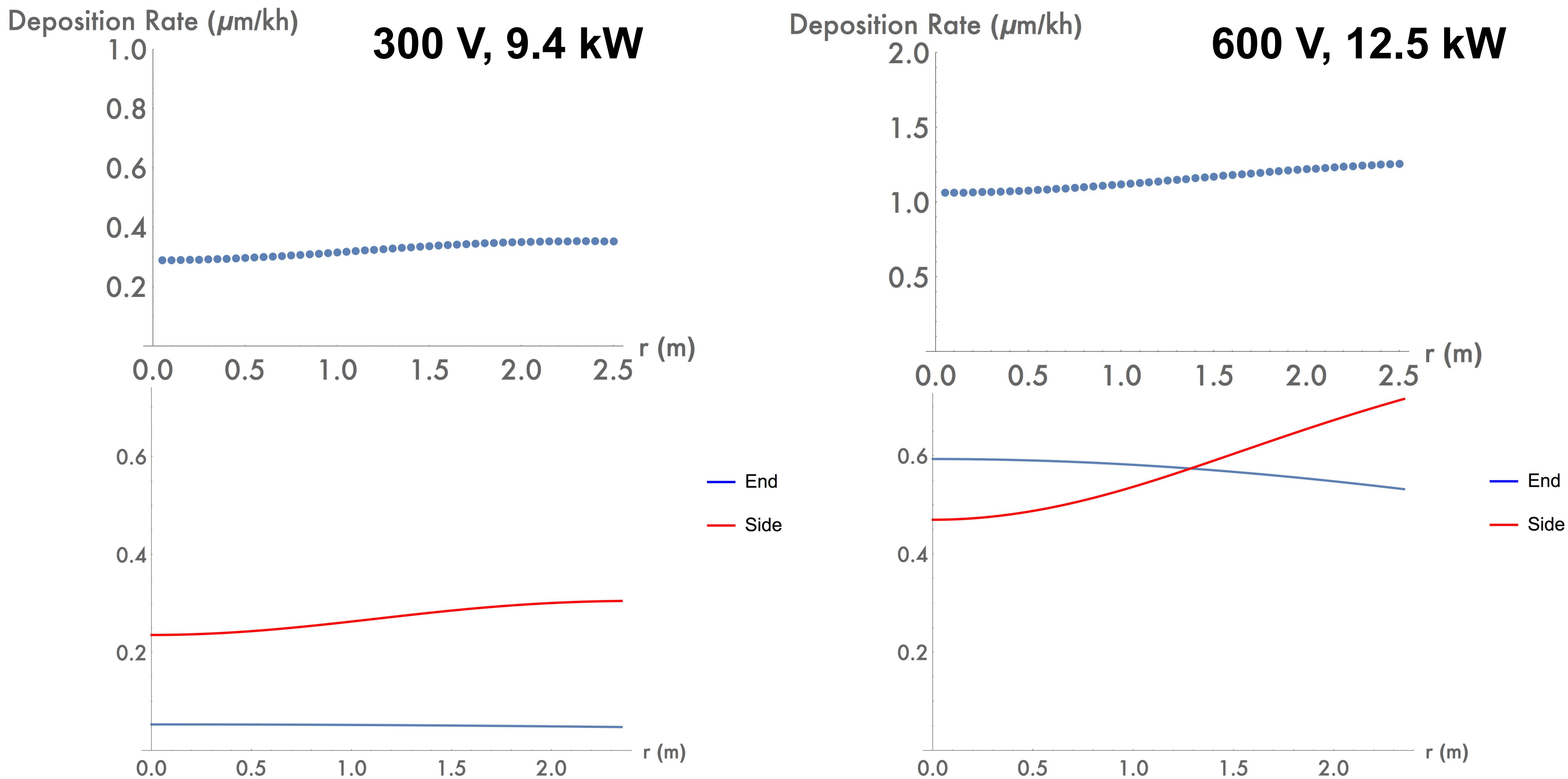
Analytic Model – Total Deposition Rate



- **Total deposition at thruster**
  - **0.3 μm/kh (300 V**
  - **1.1 μm/kh (600V) at thruster**
- **Uniform (<10%) across thruster plane**
- **Relative contributions of walls and end cap dependent on power, energy, plume shape**

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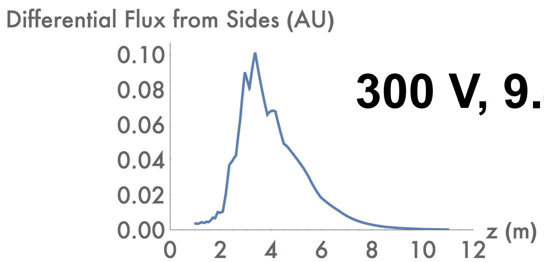
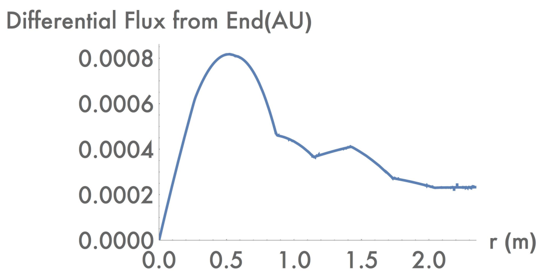
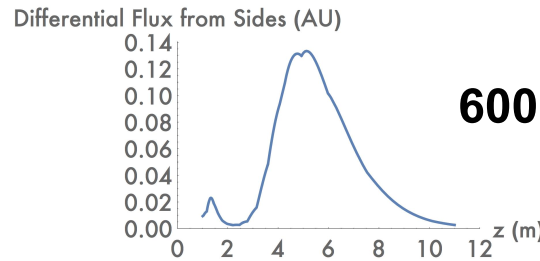
Analytic – Sputter erosion location

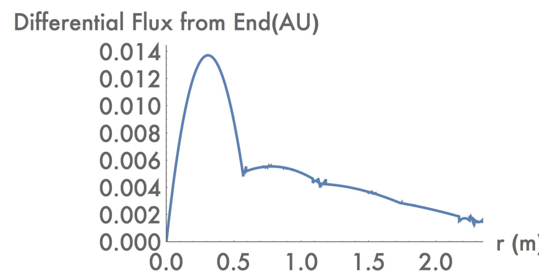
300 V, 9.4 kW





600 V, 12.5 kW





- 300 V case shows sputter from walls near thruster
  - Wall sputter from 2 – 6 m
  - End Cap sputter at 0.5-1.0 m radius
- 600 V case wall sputter occurs further from thruster
  - Wall sputter from 2 – 6 m
  - End Cap sputter at 0.2-0.5 m radius

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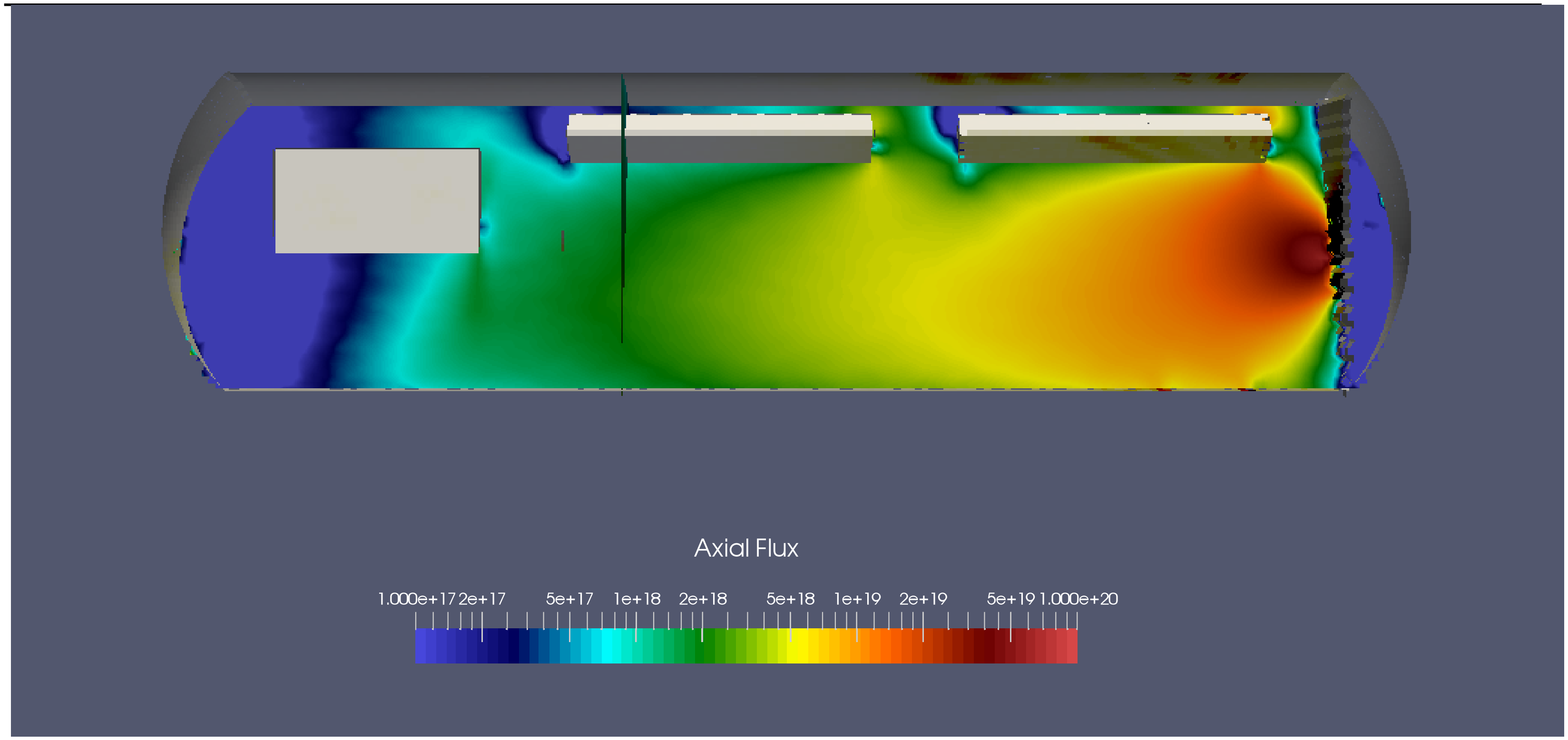
HAP Calculation
Axial Carbon Flux Back to Thruster



- **Incorporates diffuse sputter directional distribution**
- **Over estimates flux magnitude**
- **Calculate axial flux at a plane 0.1 m in front of input boundary**

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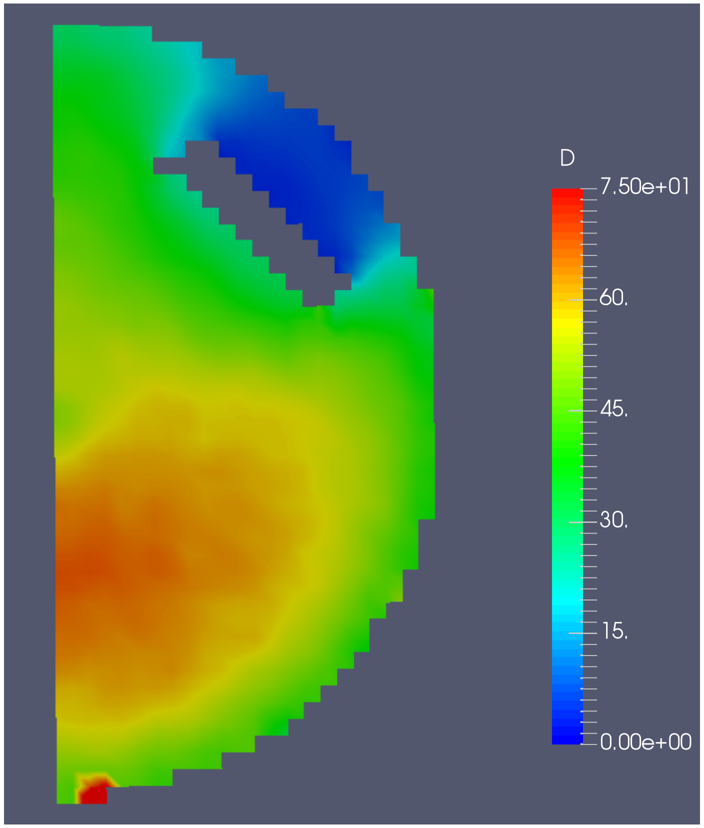
Calculated Sputter Deposition Profile 1.1 m from Thruster Plane

- **Deposition thickness rate across plane in front of the center**
  - Calculated from axial flux across the plane
  - Top/bottom asymmetry from beam dump, thruster location
  - Uniformity across symmetry axes is comparable to measurement, analysis.
- **Much higher rates than measured**
  - Cause under investigation
  - Plume data is the same as that used in analytic model
  - Yield calculation, particle propagation still being investigated



Experimental Measurements

- Primary wear test point: 600 V, 12.5 kWe
- During wear test, the thruster was tested with two pole cover materials:
  - Graphite
  - Alumina

Pole Cover	QCM 1 (μm/kh)	QCM 2 (μm/kh)	QCM 3 (μm/kh)	Analytic Prediction
Graphite	1.74	1.90	1.81	1.1 μm/kh
Al_2O_3	1.55	1.67	1.63	

- Measurements are 1.6 – 1.8 μm/kh, higher than analytic prediction

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Conclusions

- To support life validation of high power Hall thrusters such as the HERMeS thruster, analytic and DSMC models of carbon back sputter in the NASA GRC VF-5 facility have been developed.
  - Both models incorporate empirical Hall thruster plume profiles
  - Empirical sputter yields, distributions are used
- Model predictions are benchmarked with experimentally measured deposition rates in the HERMeS wear test
- At the HERMeS thruster wear test operating condition, 600 V and 12.5 kW:
  - Analytic model predicts 1.1 μm/kh
  - Measurements give 1.5 – 1.8 μm/kh
- Modeling is being benchmarked with back sputter measurements in the ongoing HERMeS thruster wear test
  - Analytic model under-predicts deposition by 50%
  - DSMC code gives unrealistically high deposition rates

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Future Work

- Resolve DSMC over-prediction
  - Generate test cases to evaluate accuracy
  - Refine inflow boundary (extends computational time)
- Examine model sensitivity to plume profiles
- Improve differential sputter yield relation to include both polar and azimuthal dependence of sputtered material
- Continue gathering experimental back sputter data for remainder of HERMeS wear test