National Aeronautics and Space Administration

AIAA-2016-4013

Characterization of DBD Plasma Actuators Performance without External Flow – Part I: Thrust-Voltage Quadratic Relationship in Logarithmic Space for Sinusoidal Excitation

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AIAA Aviation 2016

47th AIAA Plasmadynamics and Lasers Conference

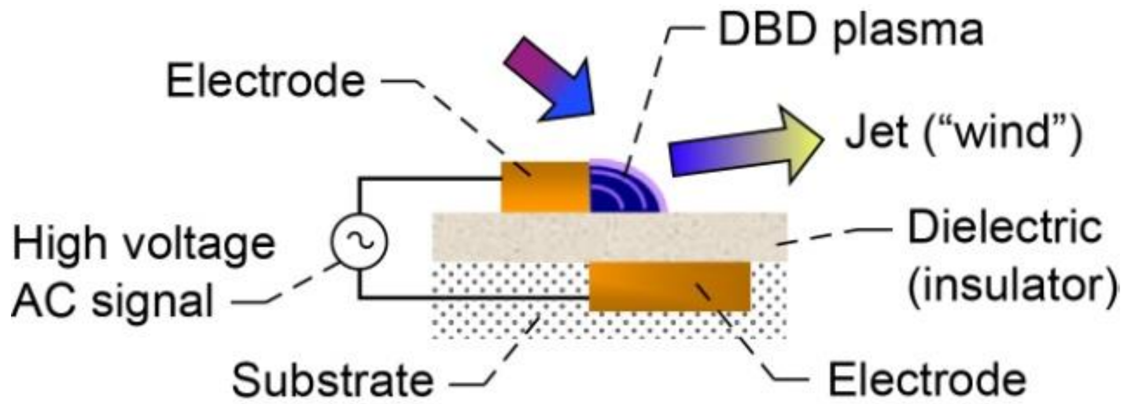
13-17 June , 2016, Washington, DC

OUTLINE

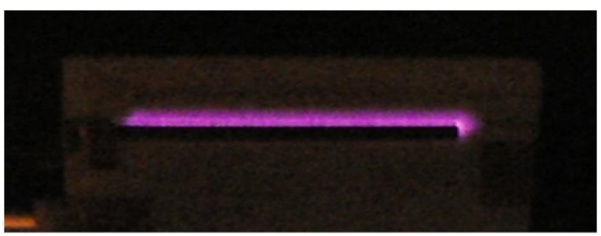
- Introduction
  - DBD actuator
  - DBD actuator thrust
- Test setup
  - Actuator test article
  - Suspended setup
  - Instrumentation
  - Humidity conditions
- Thrust measurement methodology
  - Burn-in
  - Voltage-frequency sweeps
  - Data correction with anti-thrust
- Results
  - Thrust vs voltage on log-log scale
  - Quadratic curve fit
- Concluding remarks

DBD Plasma Actuator

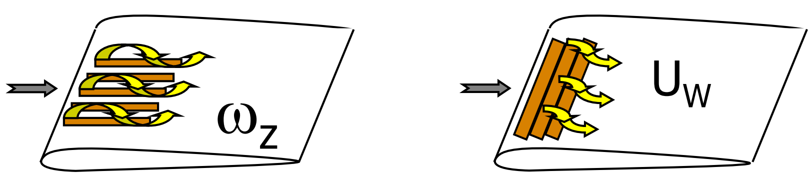
- AC-DBD
- NS-DBD ←
- Combined



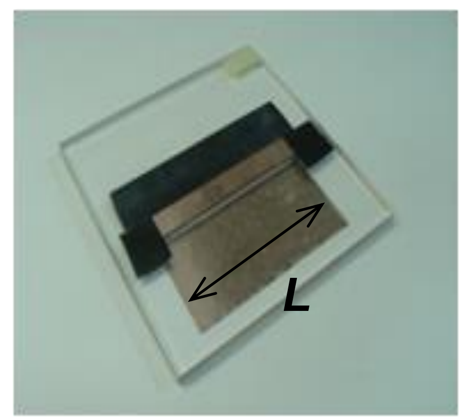
DBD ACTUATOR SCHEMATIC



TYPICAL DISCHARGE

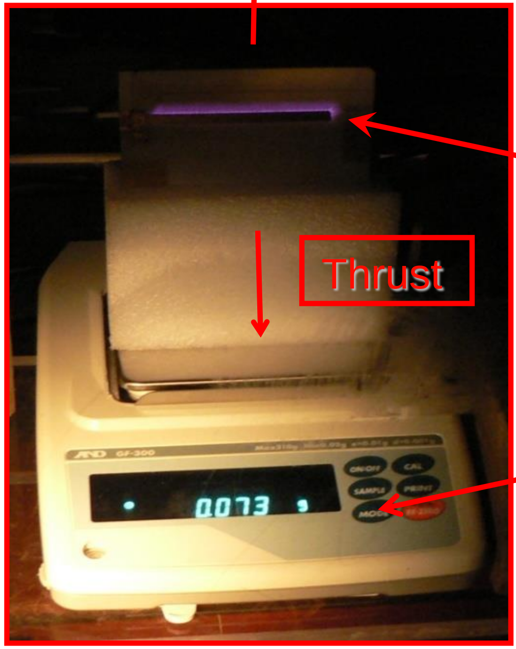


APPLICATIONS



Characterization of Aerodynamic Performance - Thrust Measurements

Jet

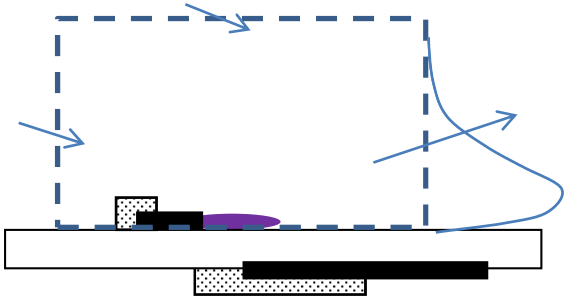


DBD Discharge

Analytic Balance

Thrust read by balance is equal to the momentum generated by the actuator

Control Volume



Surface-parallel direction x:

$$\frac{F_{\text{plasma}}}{L_z} + \frac{F_{\text{shear}}}{L_z} = \underbrace{\rho \int_{\text{right}} v_x^2 \, \mathrm{d}y}_{\text{I}} + \underbrace{\rho \int_{\text{top}} v_x v_y \, \mathrm{d}x}_{\text{II}}$$

$$\underbrace{-\rho \int_{\text{left}} v_x^2 \, \mathrm{d}y}_{\text{III}} + \underbrace{\int_{\text{right}} p \mathrm{d}y}_{\text{IV}} - \underbrace{\int_{\text{left}} p \, \mathrm{d}y}_{\text{V}},$$

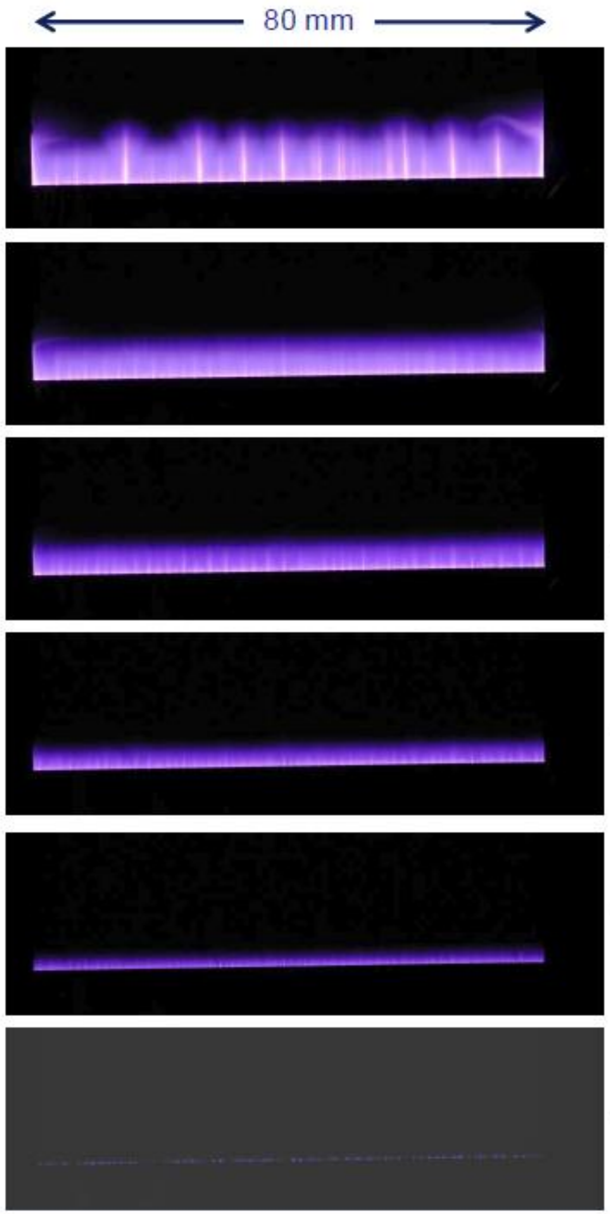
Thrust ≈ Momentum

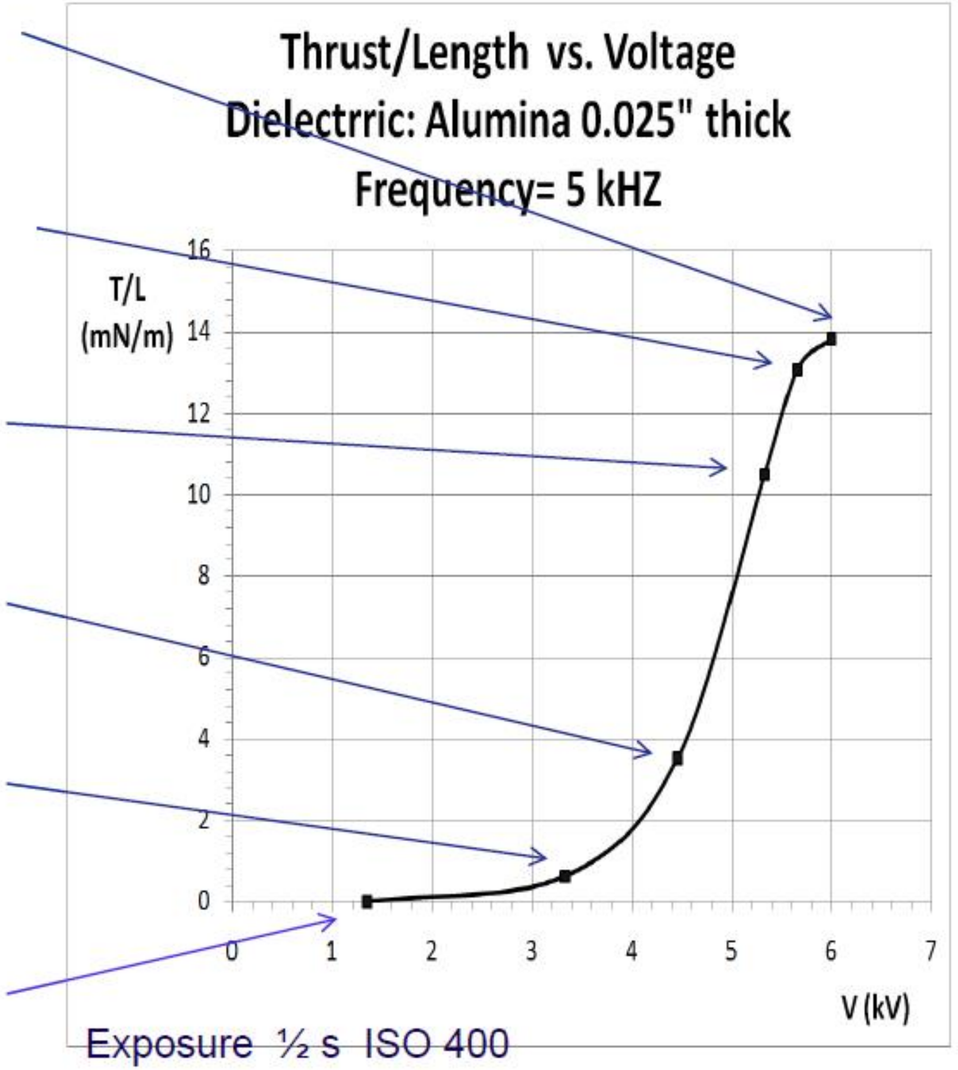
If wall shear is negligible

- Supported by calculation based on Glauert self-similar wall jet - Opaits et al 2010[1] data
- Contradiction with Durscher & Roy 2012[2]

[1] Opaits, D. F., et al, "Surface Plasma Induced Wall jets," AIAA-2010-469
[2] Durscher, R., and Roy, S., "Evaluation of Thrust Measurement Techniques for DBD Actuators," Exp. Fluids 53, 2012, pp. 1165–1176

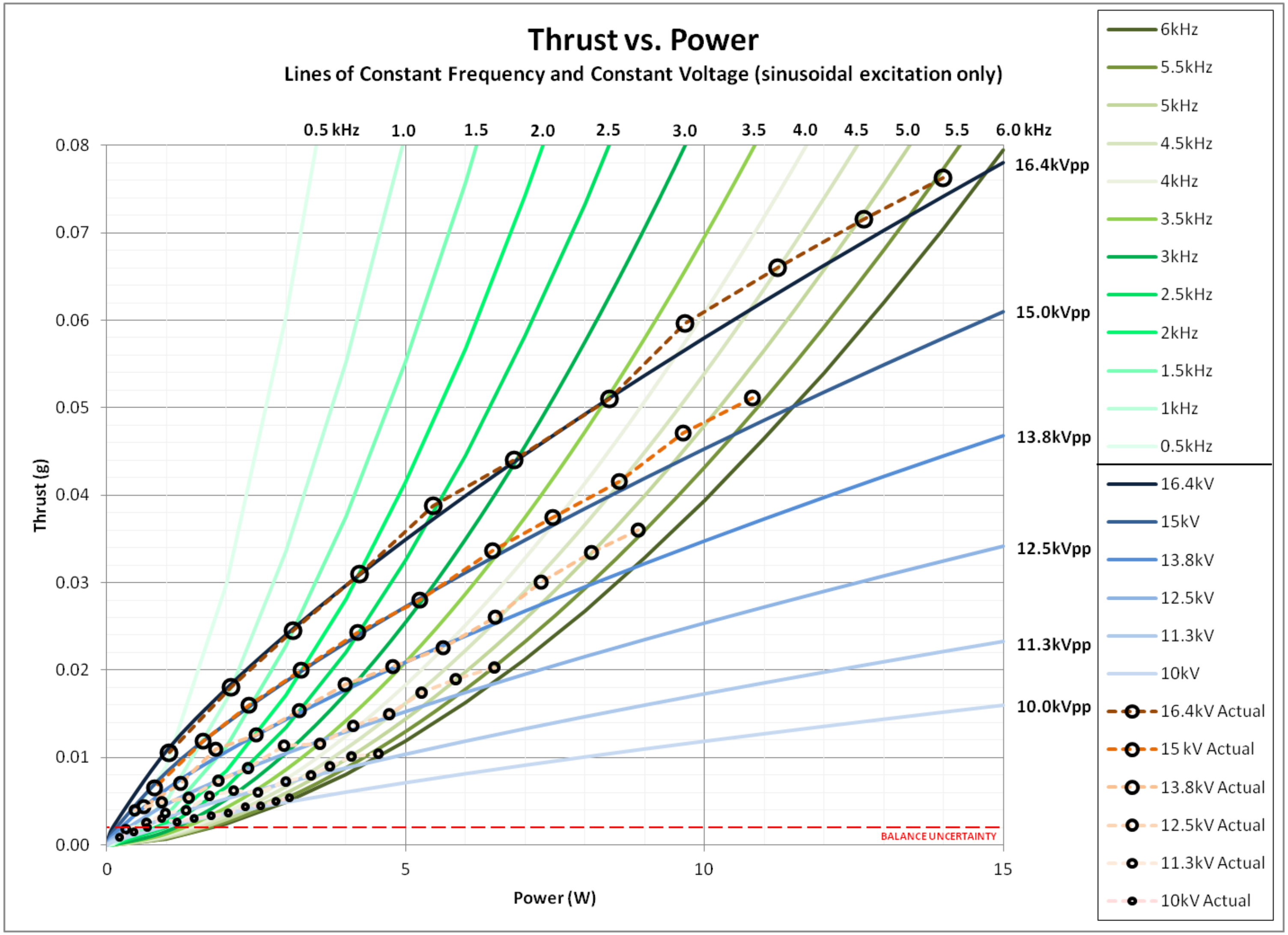
SAMPLE MEASUREMENT





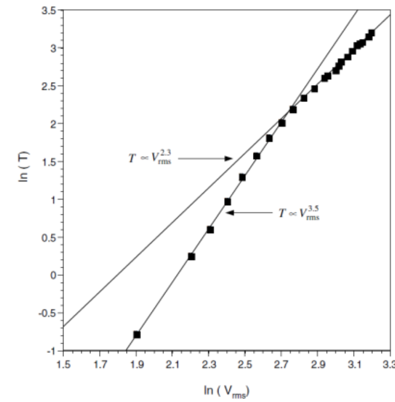
Exposure ½ s ISO 400

Sample Performance Map



Thrust- Voltage relationships

Power law $T \propto V^{m}$ at const. frequency.



Proposed m values :

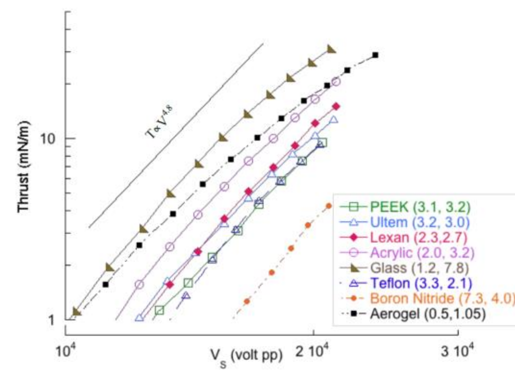
- *Thomas et al, 2009, AIAA Journal*

  m = 3.5 low voltage

  m = 2.3 high voltage

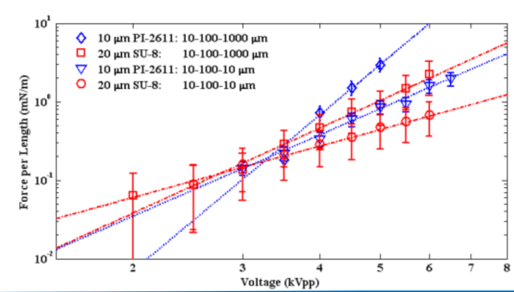
- Wilkinson et al AIAA-2014-2810

  m = 4.8



- Zito et al AIAA 2012-3091 micro-actuators

  m = 2.2, 3.4, 3.6, 6.6



We found a different relationship

Objectives

- Generate a quality data set for pure sine waves excitation
- Find thrust-voltage- frequency relations
- Provide bench mark data for numerical simulation
- Provide predictive capability

Thrust Measurement Approach

- Actuator construction
- Test setup
- Pure sine waves excitation
- Low humidity
- Burn-in procedure
- Anti thrust data correction

- Builds upon Ashpis & Laun AIAA Paper 2014-0486 (also NASA/TM—2014-218115)

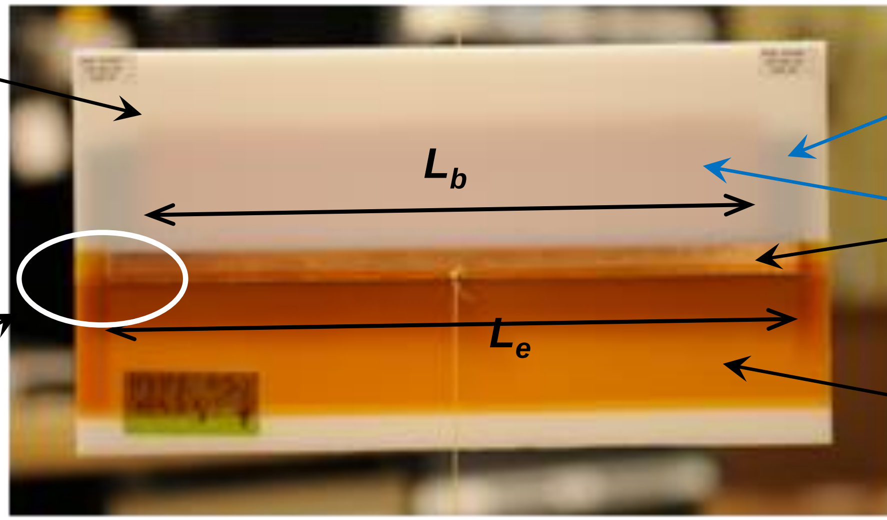
Actuator Test Articles

Nominal Thicknesses: 1/16”, 1/8”, 1/4”

Covered Electrode length ≈ 10”

HDPE
(High Density
Poly Ethylene)
Ɛ = 2.3

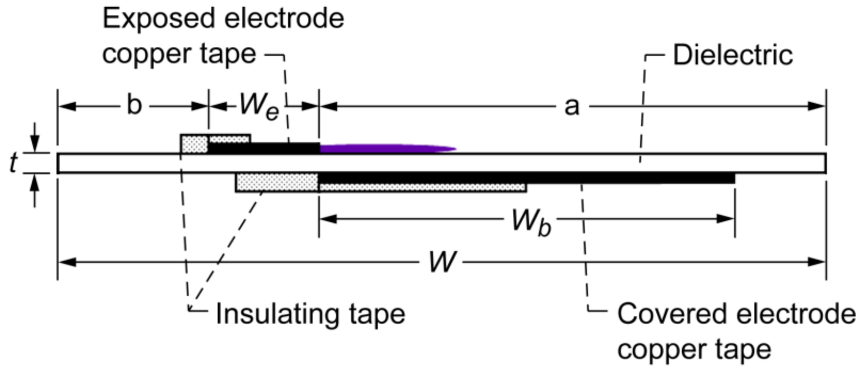
Super Corona
Dope®



3M Scotch-Seal
#229

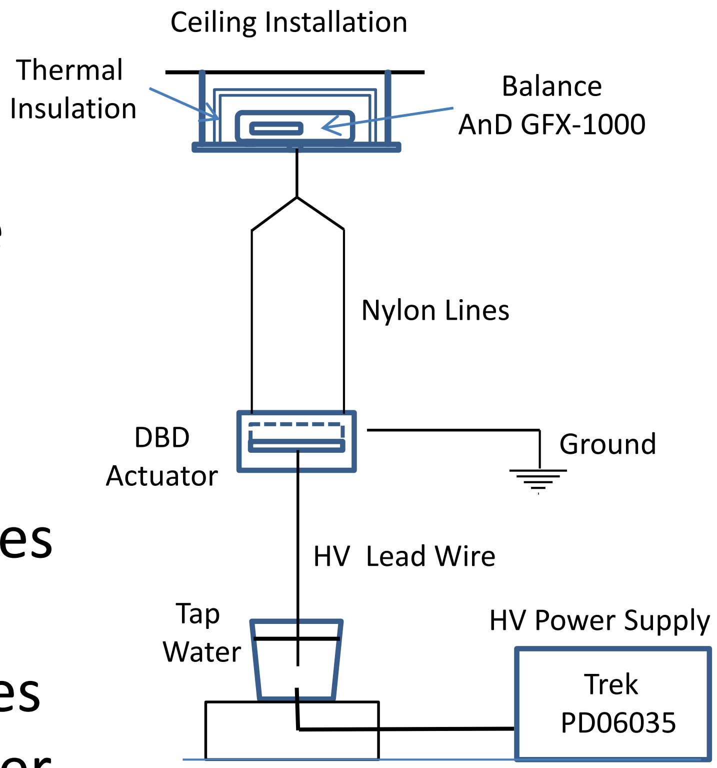
Copper tape
3M #1181

Kapton®
3M #5413

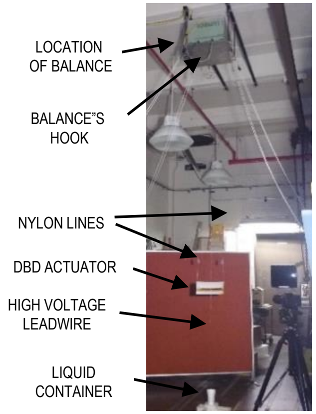


Exact dimensions and
details – see paper

TEST SETUP:

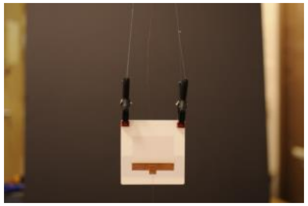


- Out in the room without enclosure
- Balance installed near ceiling
- Balance thermally insulated to eliminate temperature drift
- Test article suspended on nylon lines
- High voltage applied via a liquid interface eliminates lead wire forces
    - Lead wire immersed in tap water
    - Power supply charges tap water



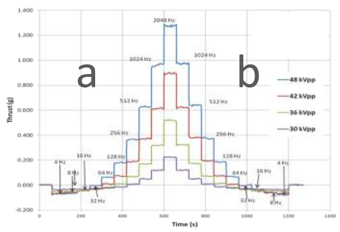
Excitation Voltage

- Waveform- Sine Wave
    - Distortion monitoring



Humidity effects

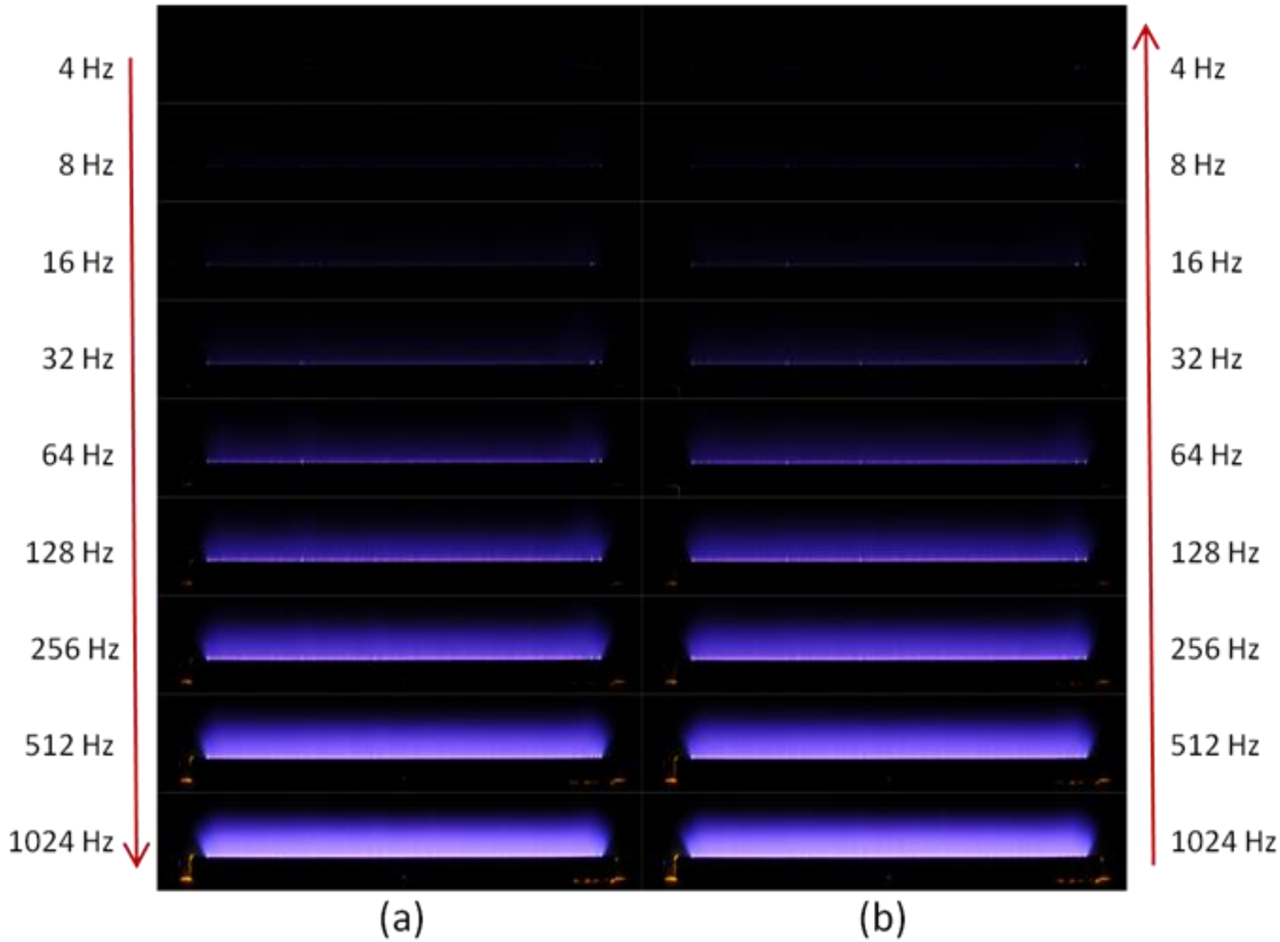
- Benard et al 2009 AIAA-2009-488
  - Peak wall-jet velocity decreases with humidity
- Ashpis & Laun AIAA-2014-0486
  - Thrust decreases with humidity (44%)
- Wilkinson et al AIAA-2014-2810
  - Material dependence – water retention



Humidity Effects

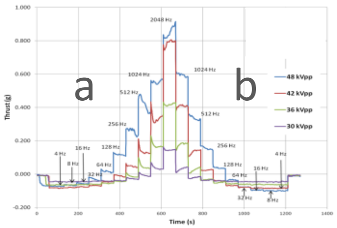
48 kVpp Frequency Sweep

“Dry” RH 18%, Dew Point 33 °F



10 s exposures F2.8 ISO 200

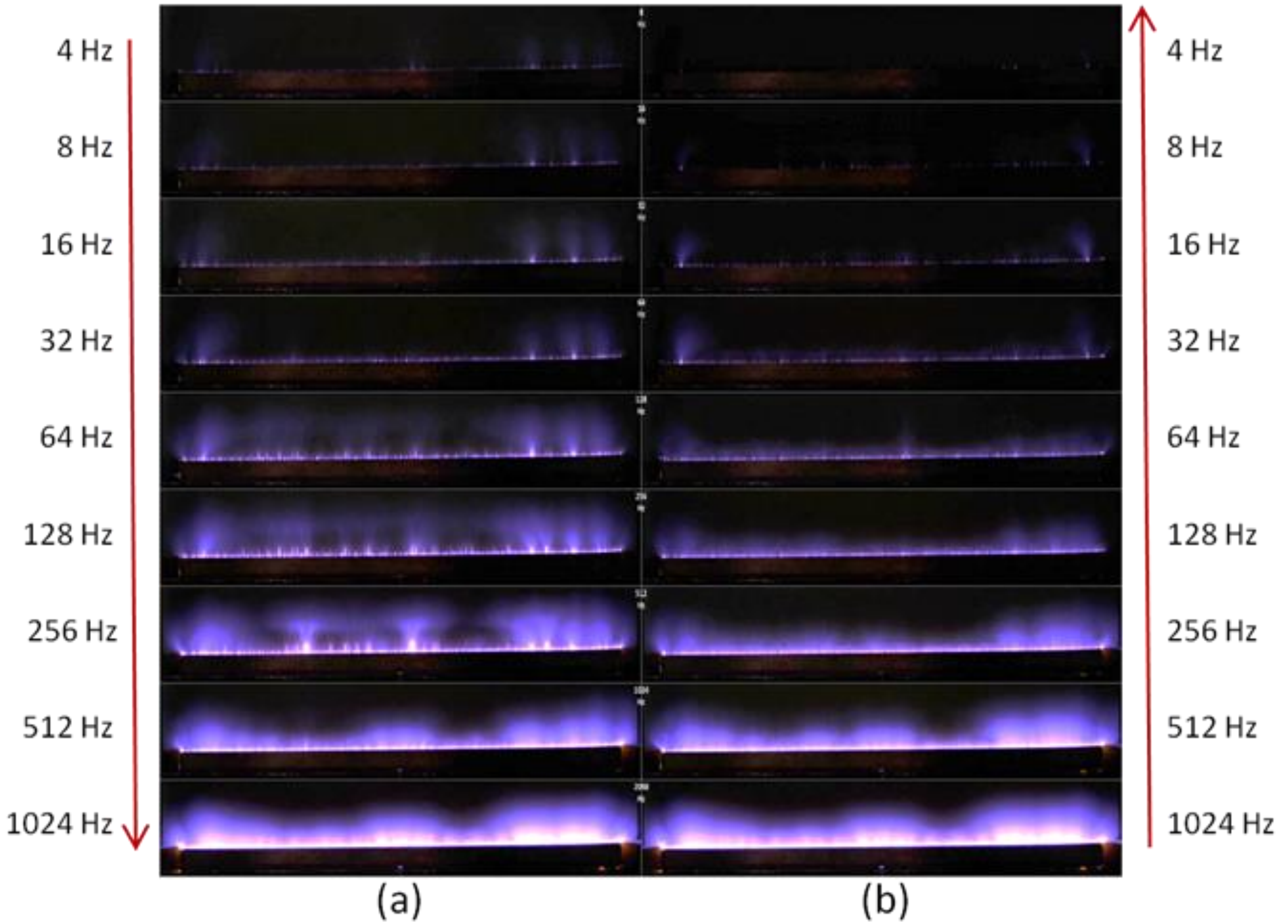
Ashpis & Laun AIAA-2014-0486



Humidity Effects – Cont.

48 kVpp Frequency Sweep

“Humid” RH 50%, Dew Point 57 °F



10 s exposures F2.8 ISO 200

Ashpis & Laun AIAA-2014-0486

Ambient Humidity Conditions

All tests in dry conditions

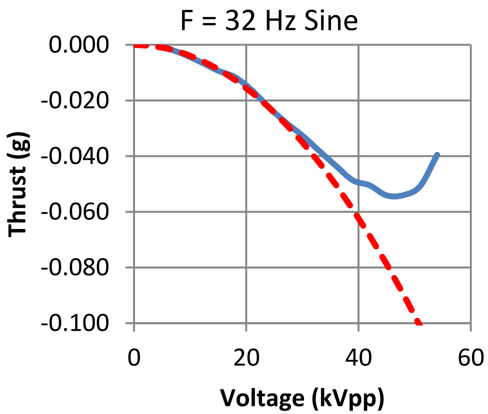
Actuator Nominal thickness	Dew Point (DP)	Relative Humidity (RH)	Temp
inch	° F	%	° F
1/16	39	22	81
1/8	37	26	74
1/4	37	26	74

Anti-thrust Data Correction

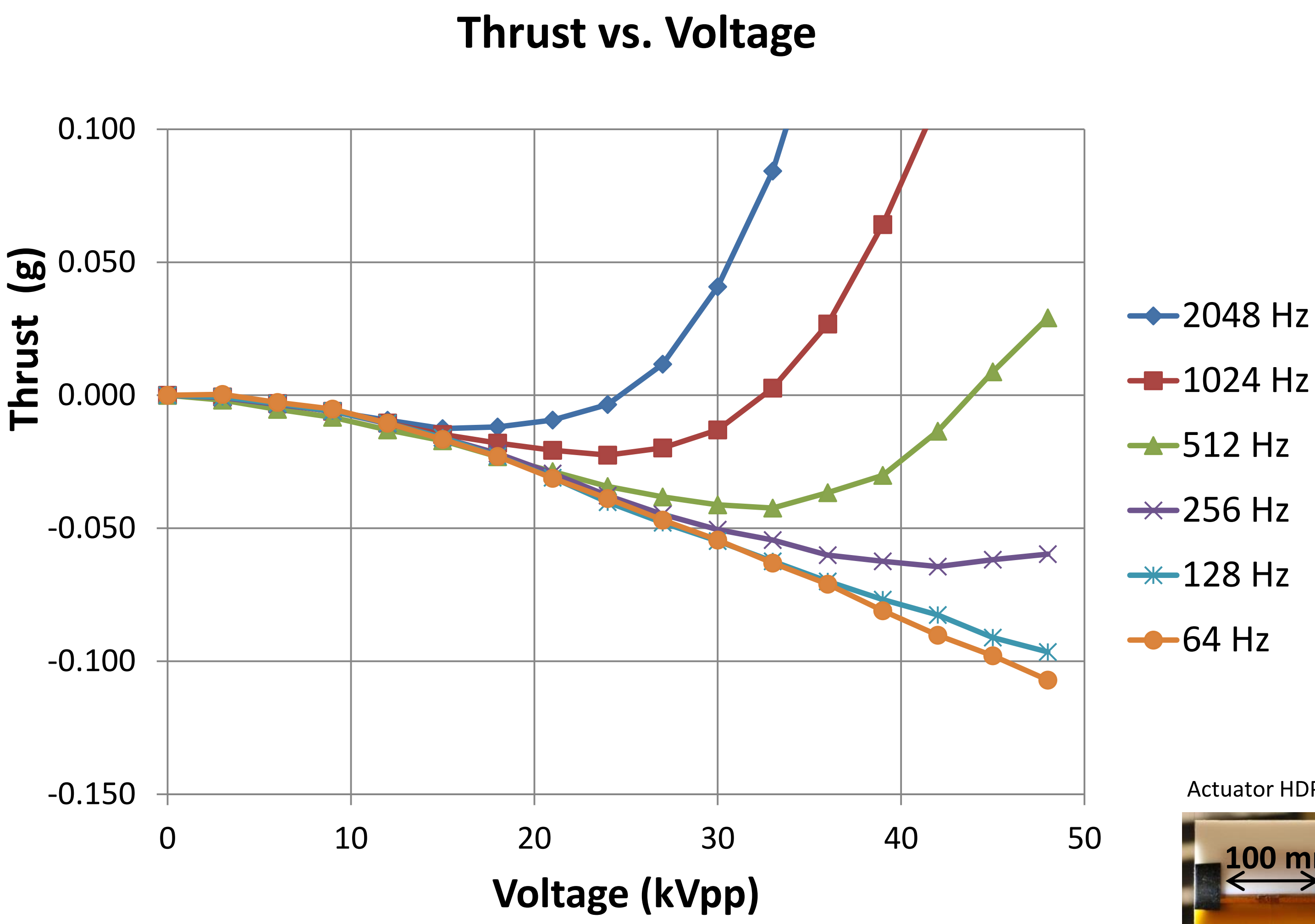
Anti-thrust Hypothesis (Ashpis & Laun AIAA-2014-0486):

Total Thrust = Plasma Thrust + Anti-thrust

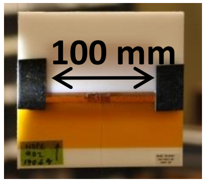
- **Plasma Thrust** is the quantity of interest for actuator performance
- It needs to be separated from the total thrust
- Anti-thrust ~ $-V^2$ (parabolic fit)
- Frequency independent
  - Observed from 4 to 64 Hz (at moderate voltages)
- Assumptions
  - Frequency independent at all frequencies
  - Extrapolated for higher voltages
- Depends on:
  - Actuator geometry & dielectric properties
  - Installation - proximity to surrounding objects and their grounding
  - Ambient conditions – Pressure, Humidity, etc. (?)
  - Actuator insulation (?)



Anti-thrust:



Actuator HDPE #2

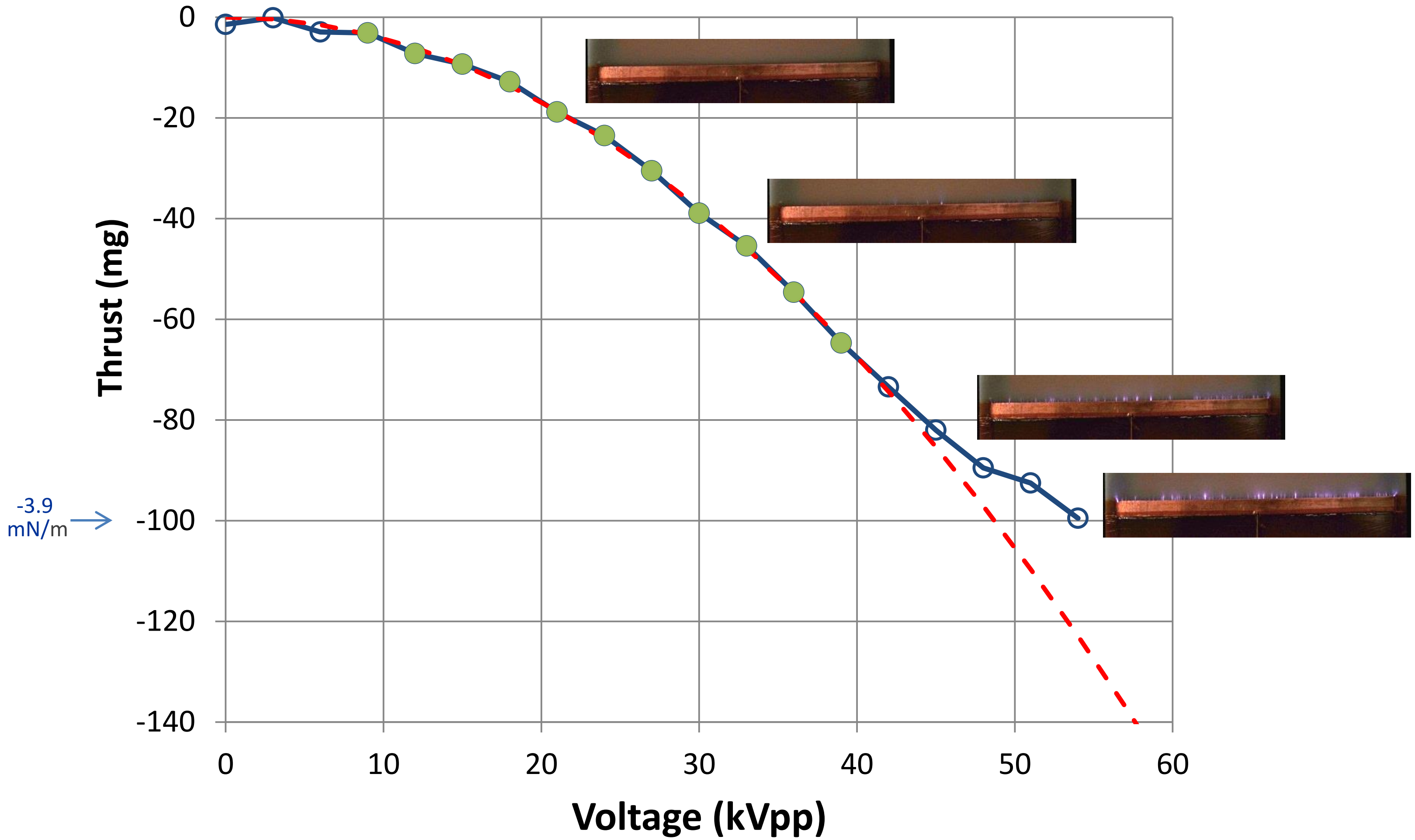


Ashpis & Laun AIAA-2014-0486

Anti-thrust:

Actuator HDPE #3

Thrust vs. Voltage @ 4Hz



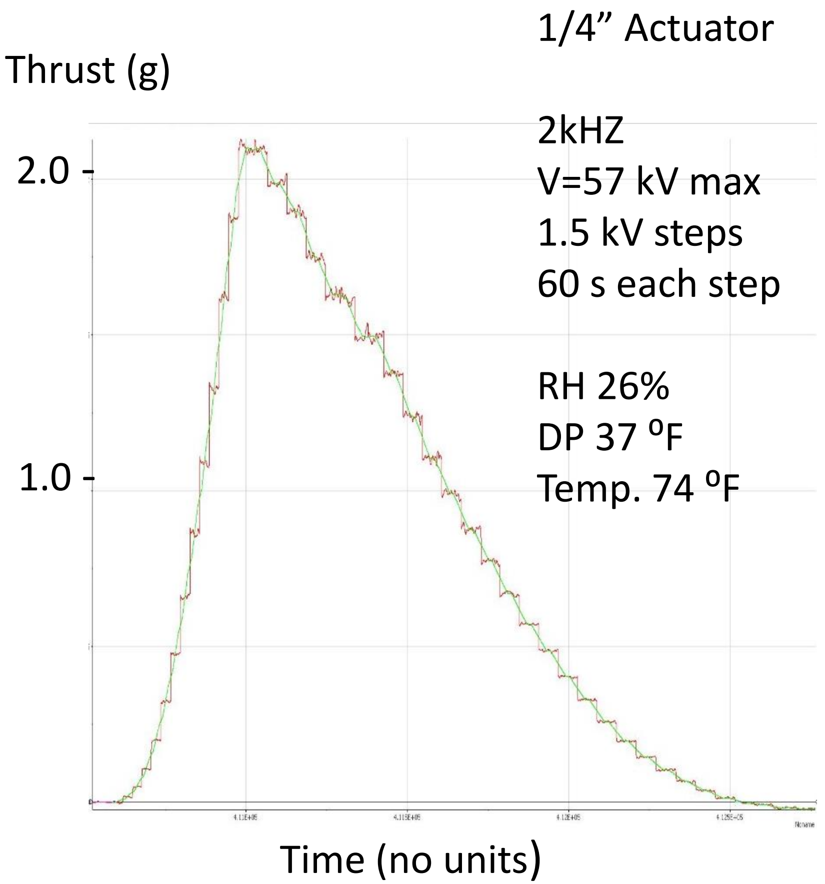
Ashpis & Laun AIAA-2014-0486

Burn-in and testing

- Set max frequency & voltage
- Step up gradually to max values
- Dwell ≈ 10-20 min
- Return gradually to zero

Perform a series of tests:

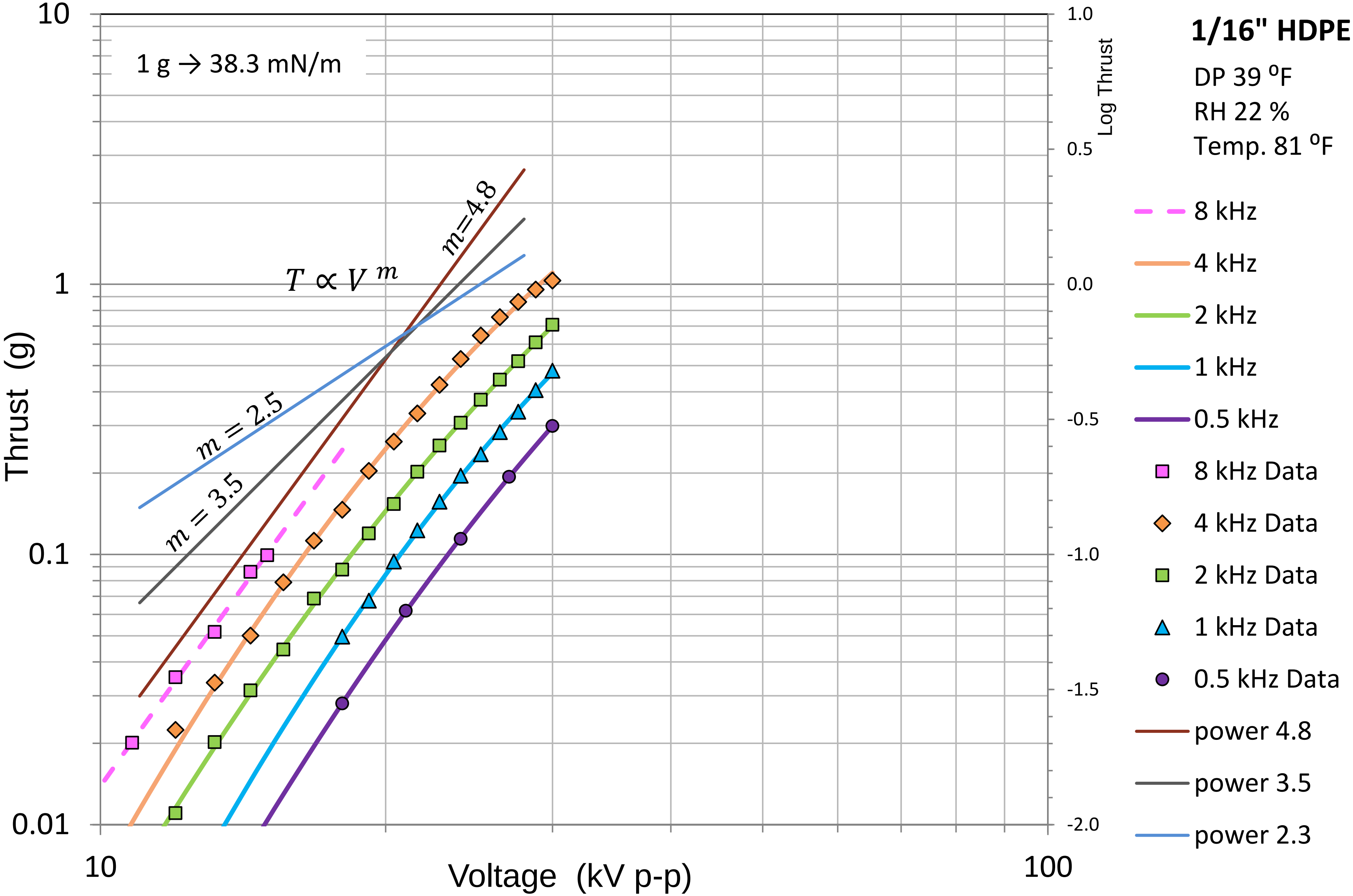
- Set frequency
- Step to max voltage,
- Step down in voltage, 60 sec at each voltage.



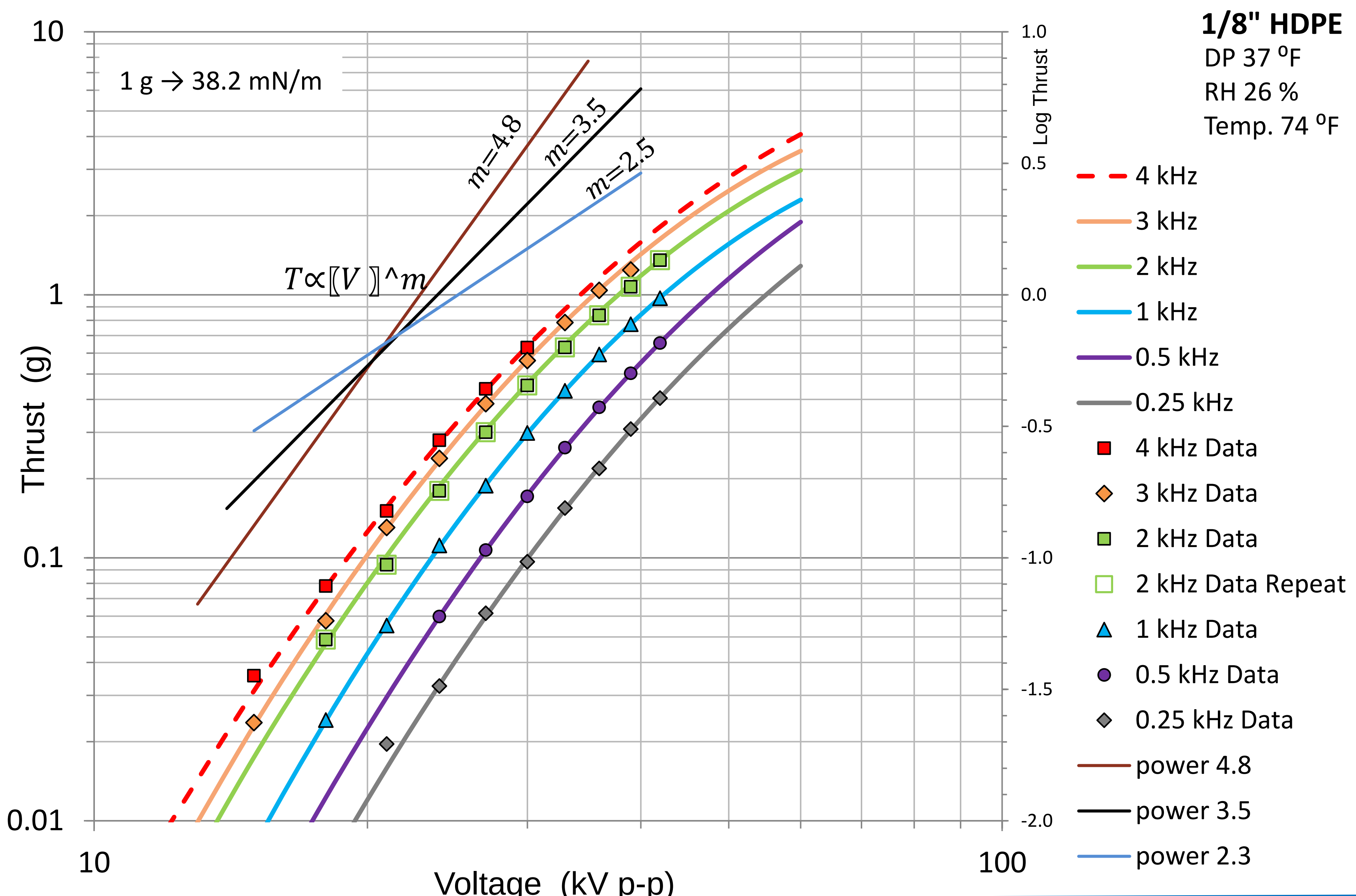
Typical test profile

RESULTS

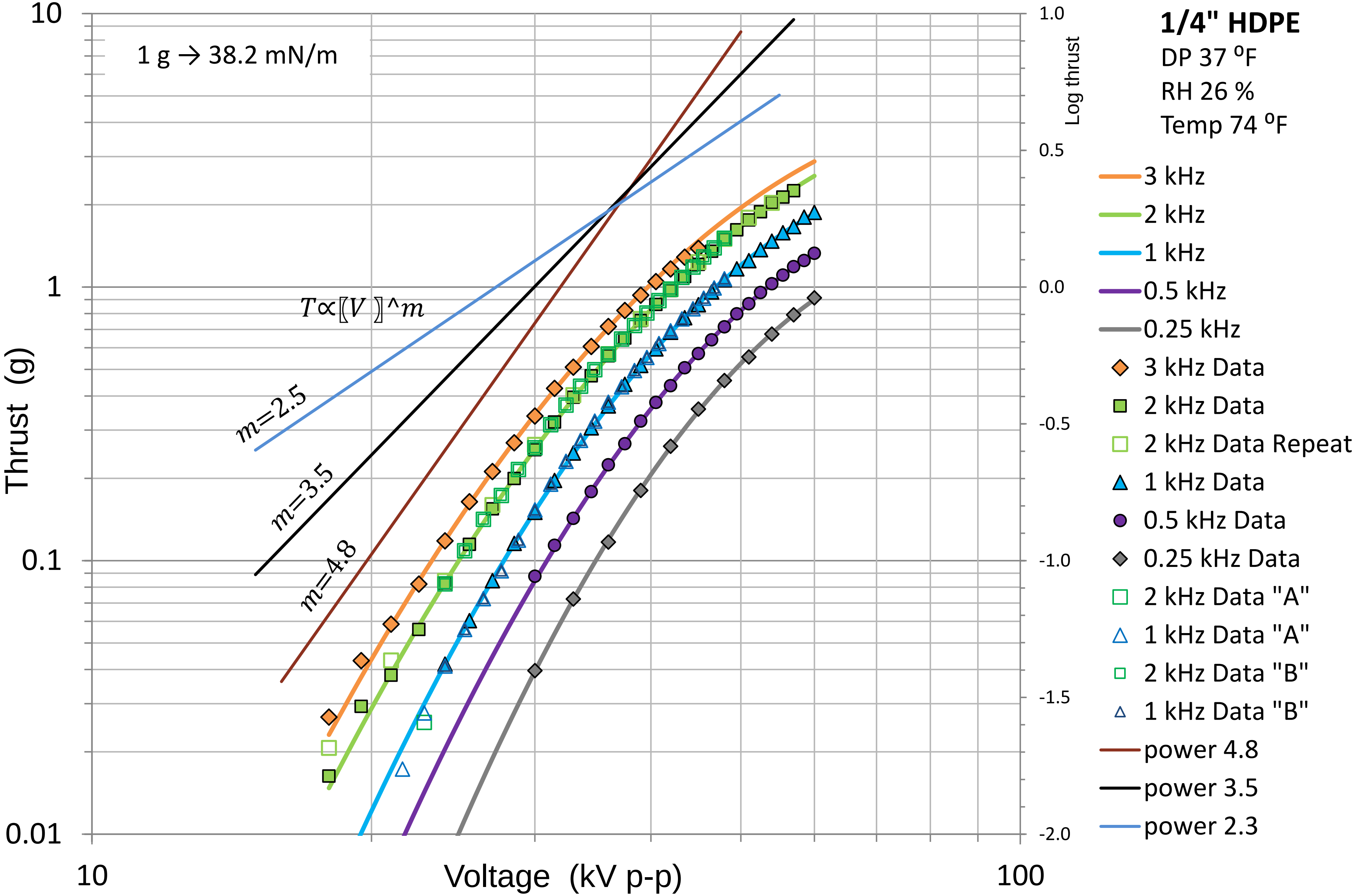
Results - 1/16" actuator



Results - 1/8” actuator



Results - 1/4” actuator



Quadratic curve fit coefficients

$$\log(\boldsymbol{T}) = \boldsymbol{a}\,[\boldsymbol{log}(\boldsymbol{V})]^2 + \boldsymbol{b}[\log(\boldsymbol{V})] + \boldsymbol{c}$$

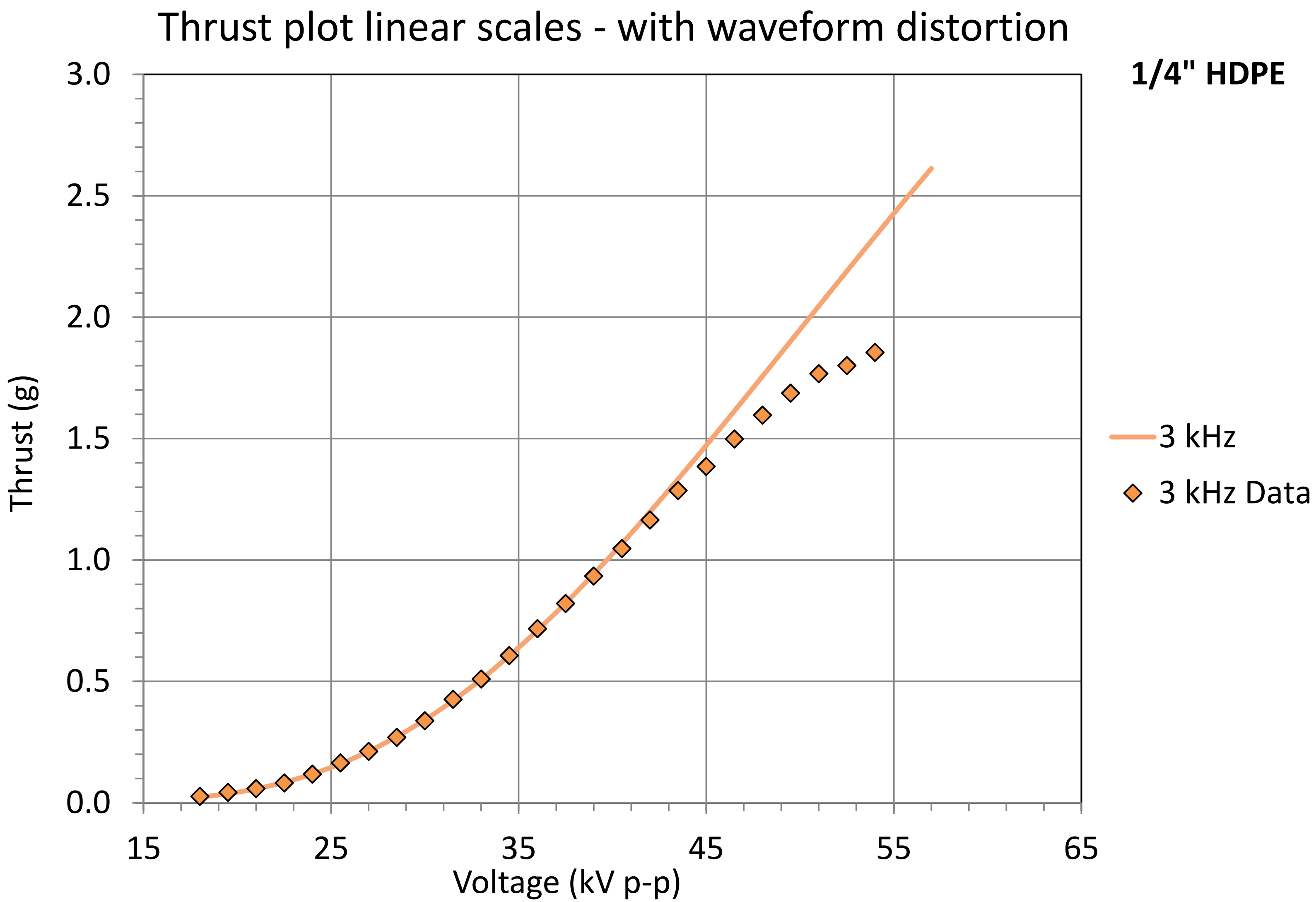
Actuator	f (kHz)	a	b	c
1/16"	0.5	-2.820	12.328	-12.583
	1	-3.483	13.919	-13.287
	2	-2.688	11.352	-11.059
	4	-3.300	12.869	-11.767
	8	-0.236	5.410	-7.031
1/8"	0.25	-3.158	13.977	-14.759
	0.5	-3.307	14.217	-14.546
	1	-3.766	15.211	-14.780
	2	-3.349	13.636	-13.182
	3	-3.358	13.628	-13.141
	4	-3.281	13.324	-12.769
1/4"	1	-8.785	32.672	-30.248
	2	-6.282	23.973	-22.520
	3	-6.054	23.035	-21.509
	4	-4.626	18.321	-17.553
	8	-7.313	26.571	-23.800

Observed relationships:

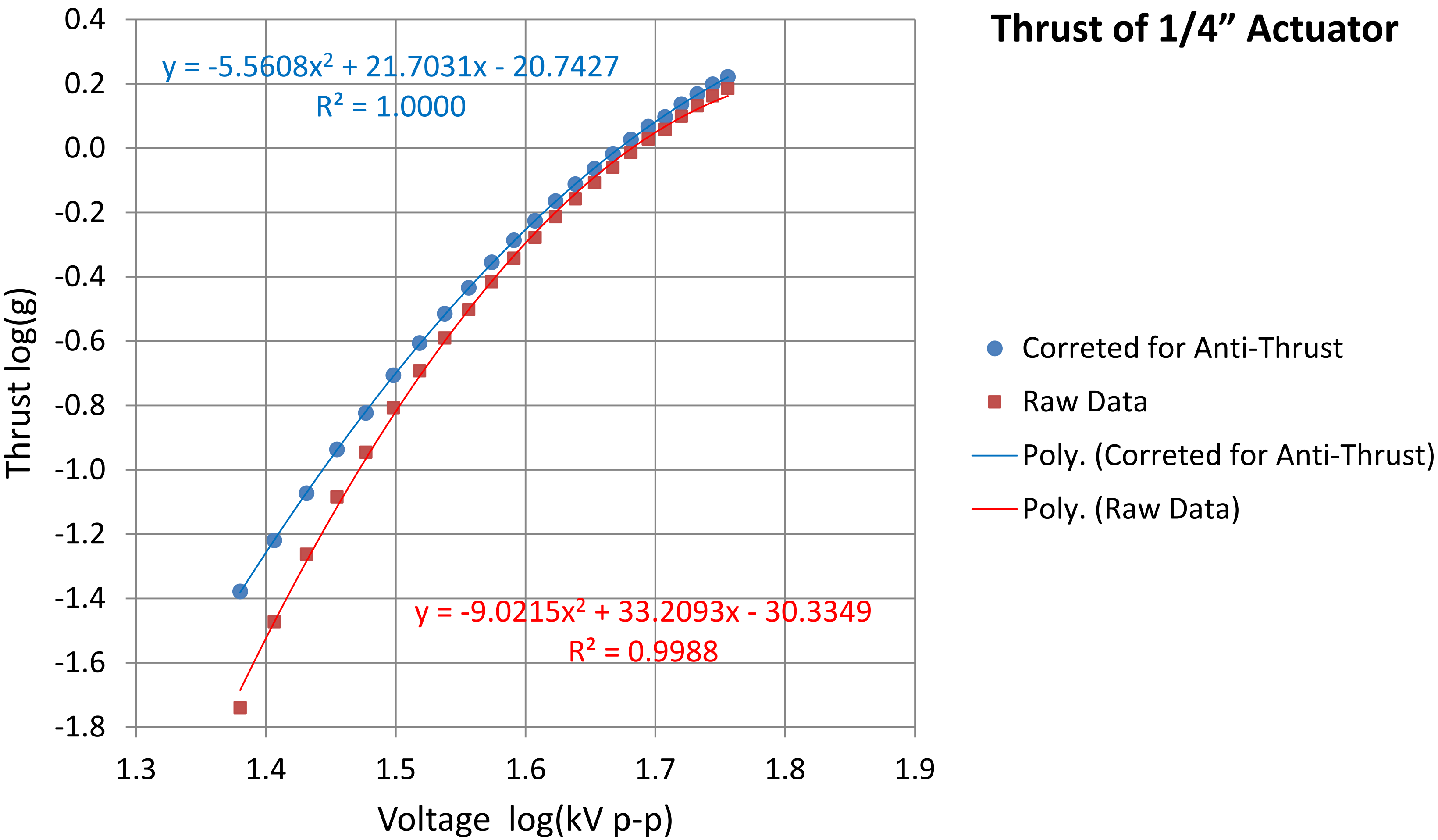
(b-c)/a ≈ const.

b ≈ - c

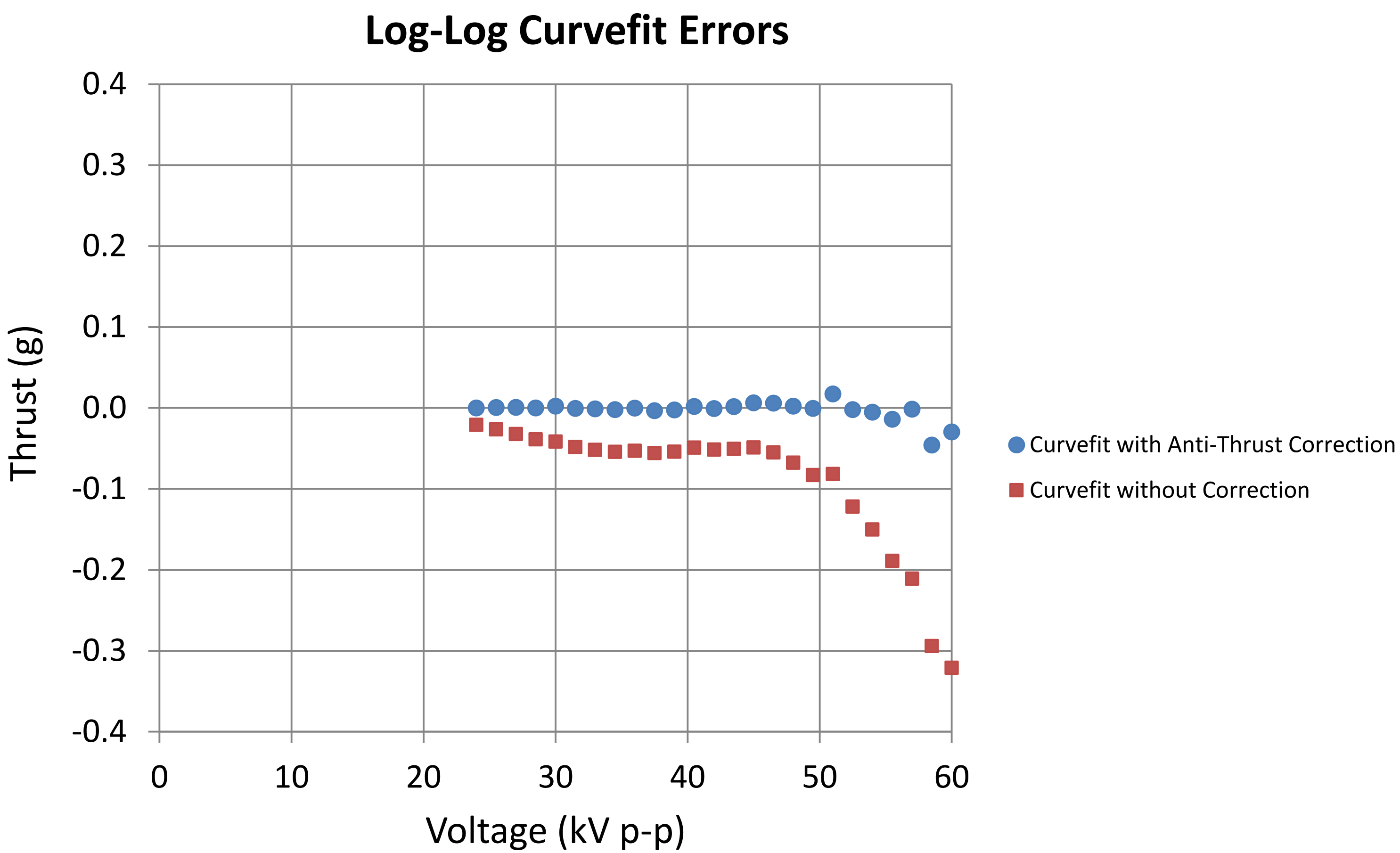
Effect of Including waveform distortions



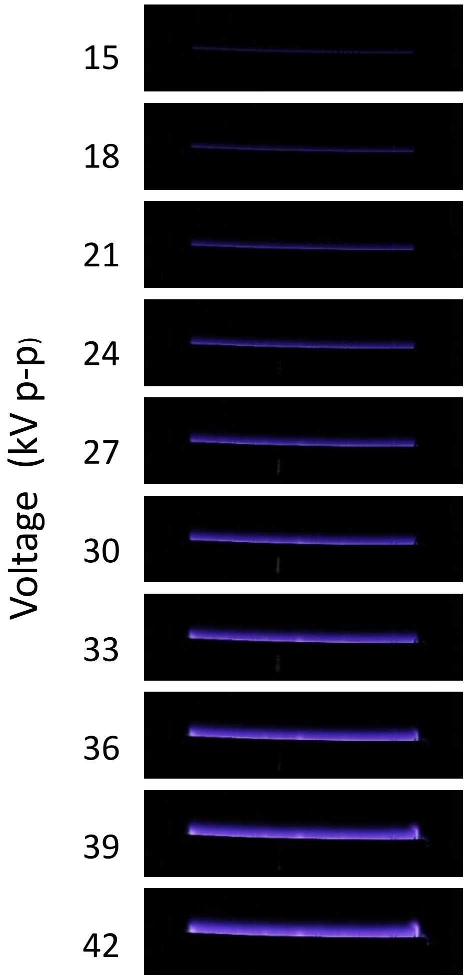
Effect of anti-thrust correction
Log-Log scale

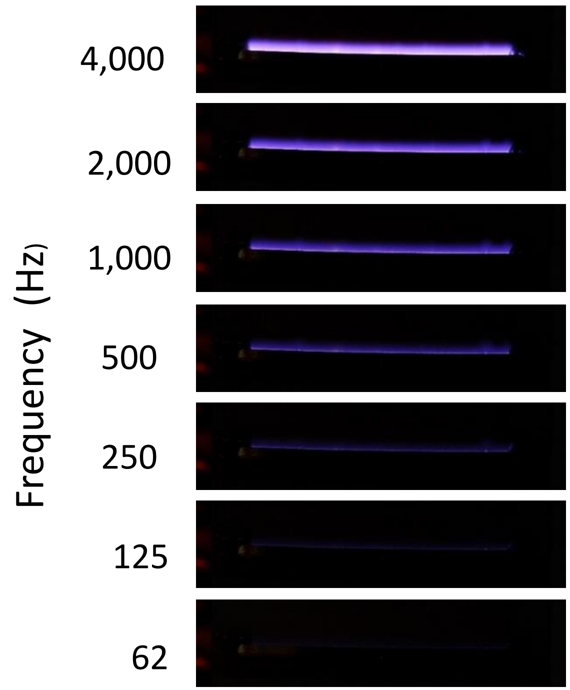


Effect of anti-thrust correction
Curvefit errors



Discharge Images - 1/8” Actuator



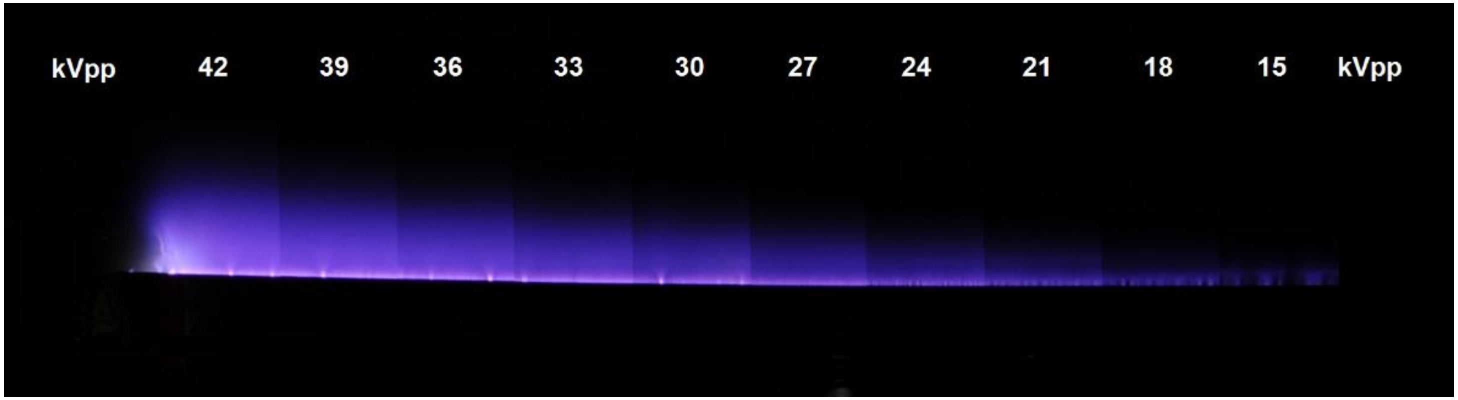


No saturation filaments observed

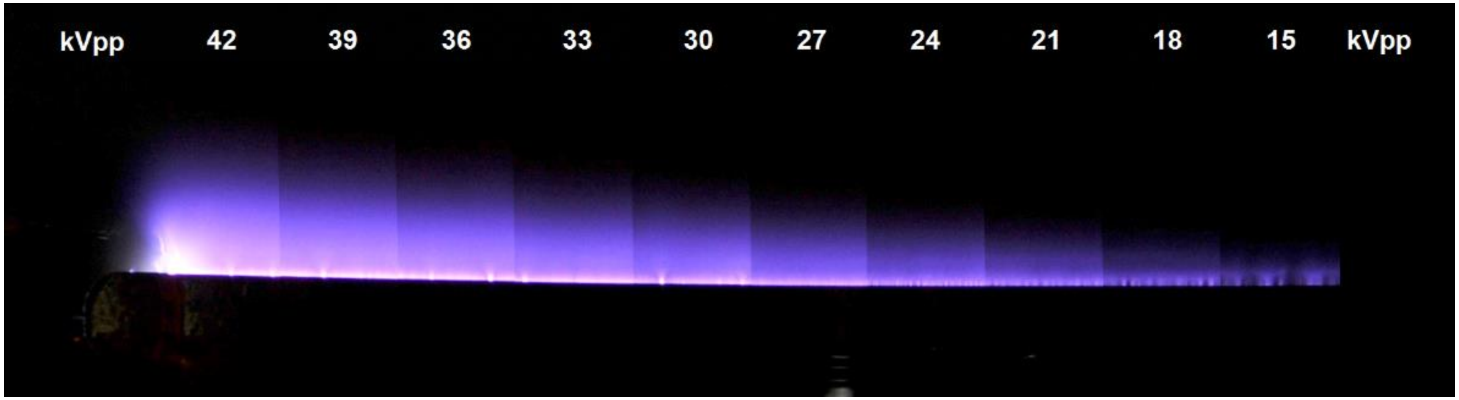
(a) Constant Frequency 2 kHz
5 s exposure

(b) Constant Voltage 27 kV p-p
30 s exposure

Discharge Images Composites- 1/8" Actuator Constant frequency 2 kHz

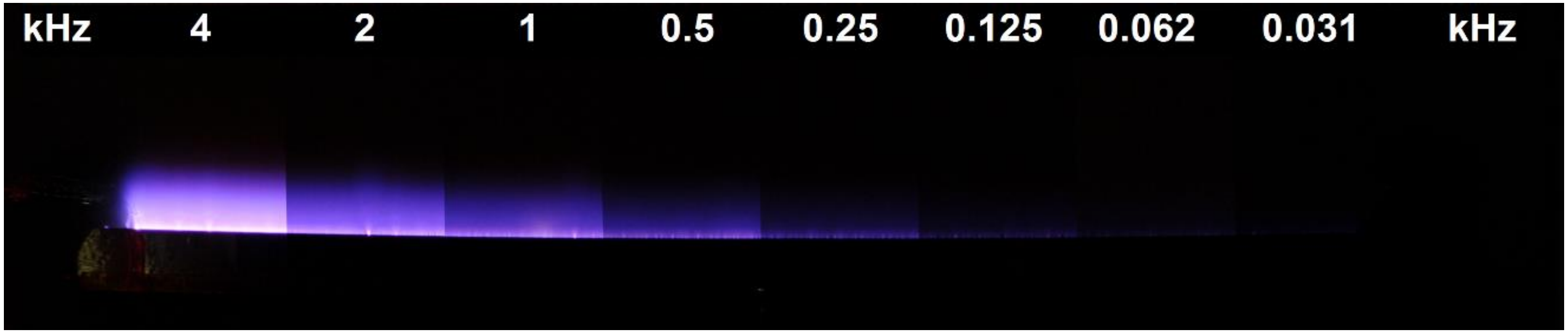


(a) Fixed exposure. f = 2 kHz

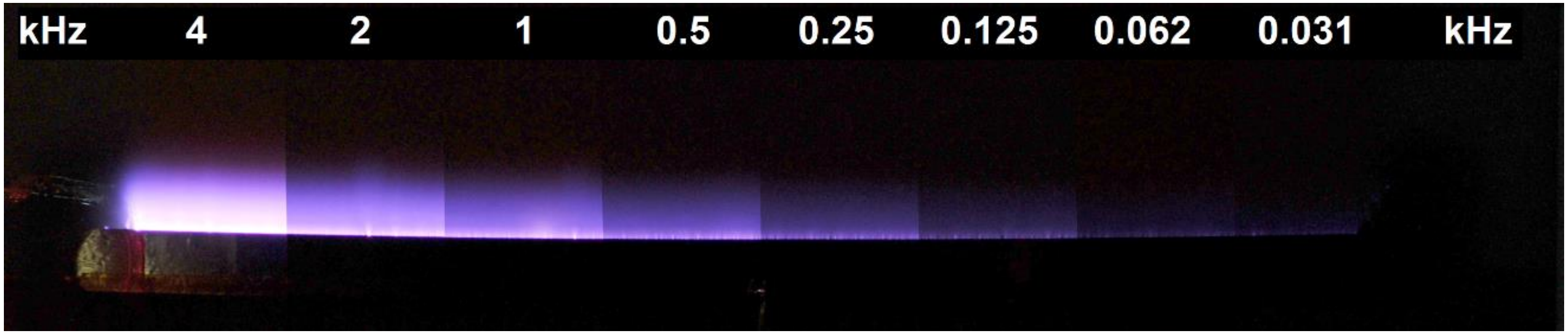


(b) Gamma enhanced. *f* = 2 kHz

Discharge Images Composites- 1/8" Actuator Constant Voltage 27 kVp-p

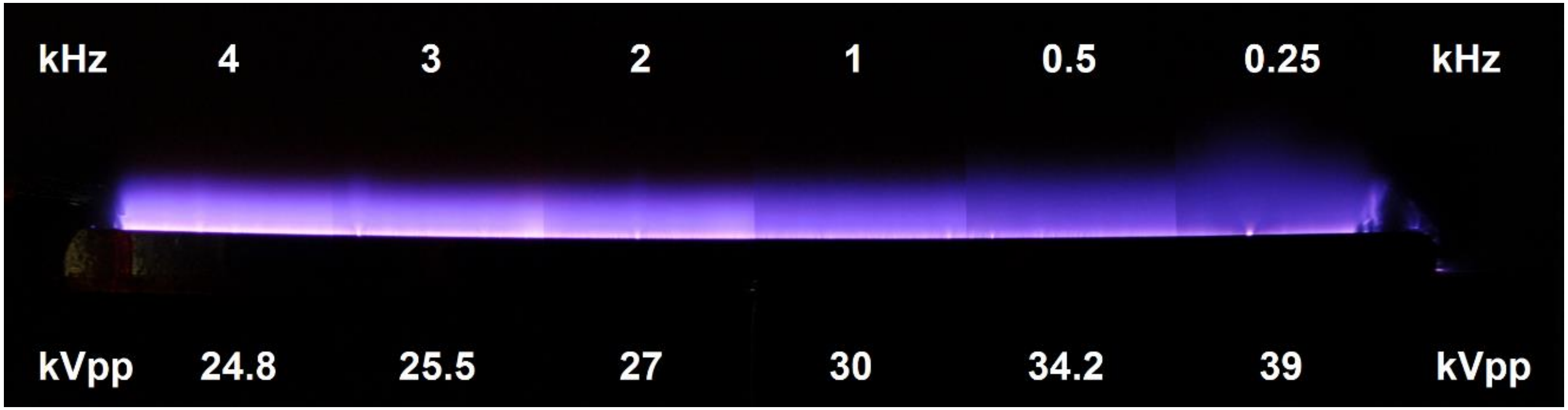


(a) Fixed exposure. V = 27 kV p-p

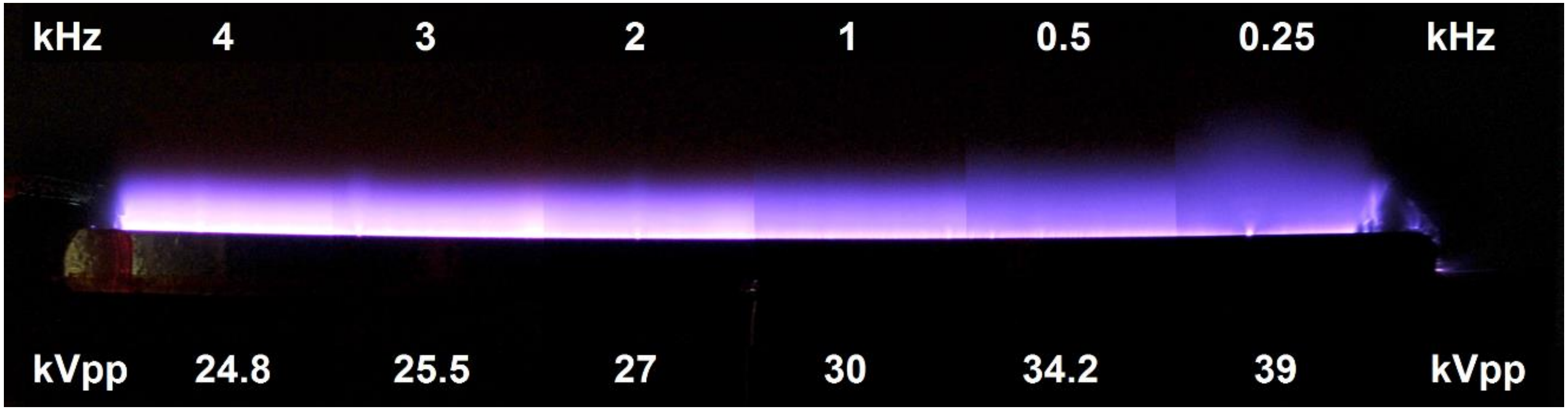


(b) Gamma enhanced. V = 27 kV p-p

Discharge Images Composites- 1/8” Actuator Constant Thrust 300 mg



(a) Fixed exposure. T = 300 mg



(b) Gamma enhanced. T = 300 mg

Summary and Discussion

For pure sinusoidal excitation waveform:

- Thrust vs voltage at fixed frequencies can be correlated via quadratics on log-log scales
- The fit is very good, $R^2 = 0.9993$ to 0.9999
- Smooth, orderly curves, nested, no overlap.
- Power law $T \propto V^{m}$ is not a good representation over the full voltage ranges.
    - *m* = 3.5, 2.3, 4.8, were proposed, *m* = 2.2, 3.4, 3.6, 6.6 for micro-actuators
- Logarithmic terms plausible - appear in electric field solutions
- Deviations from quadratics in log space can be due to
    - Non-sinusoidal wave forms, harmonics, edge, humidity
    - No compensation for anti thrust
    - No separation of plasma of interest from parasitic plasma

Discussion – Cont.

- Curve fits will not be quadratic or have large deviations if distorted waveform thrust data is included, or if anti-thrust correction not performed.
- Humid conditions increases the randomness in the data.
- Thrust-Frequency at constant voltage relations seems also to follow quadratic
- Quadratic thrust-voltage relationship in log space for sine waveforms and dry environment can be considered as measure of quality of the test.

Conclusion

- Proper approach is needed to obtain benchmark data for DBD actuators
  - Actuator construction
  - The test setup and measurement system
  - Proper isolation of plasma thrust generated by the spanwise edge
  - Low ambient humidity
- The benchmark results can be used for numerical validation and development of models
- Accurate extrapolation of data for power supply and components design.

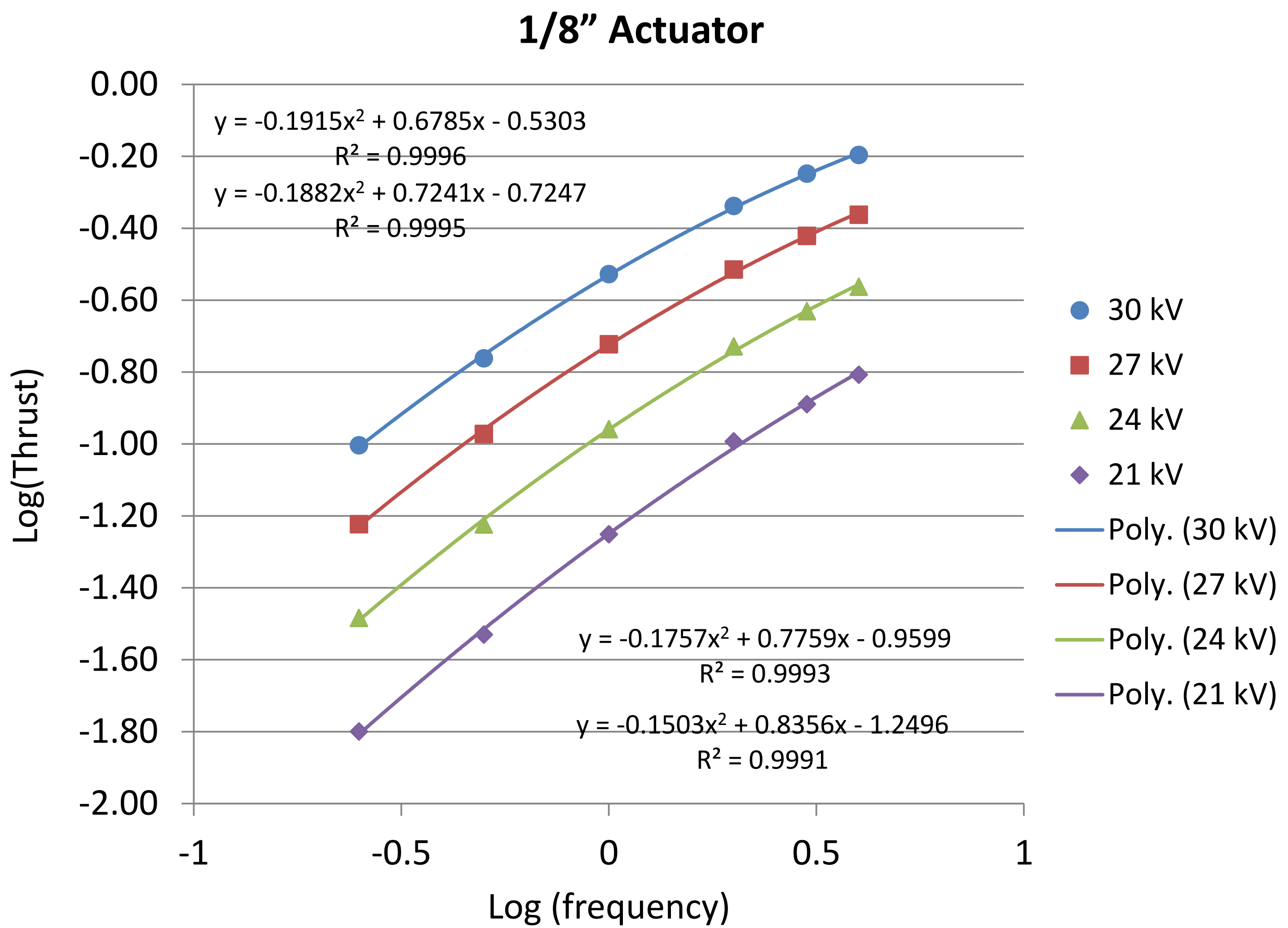
Thank You

Questions ?

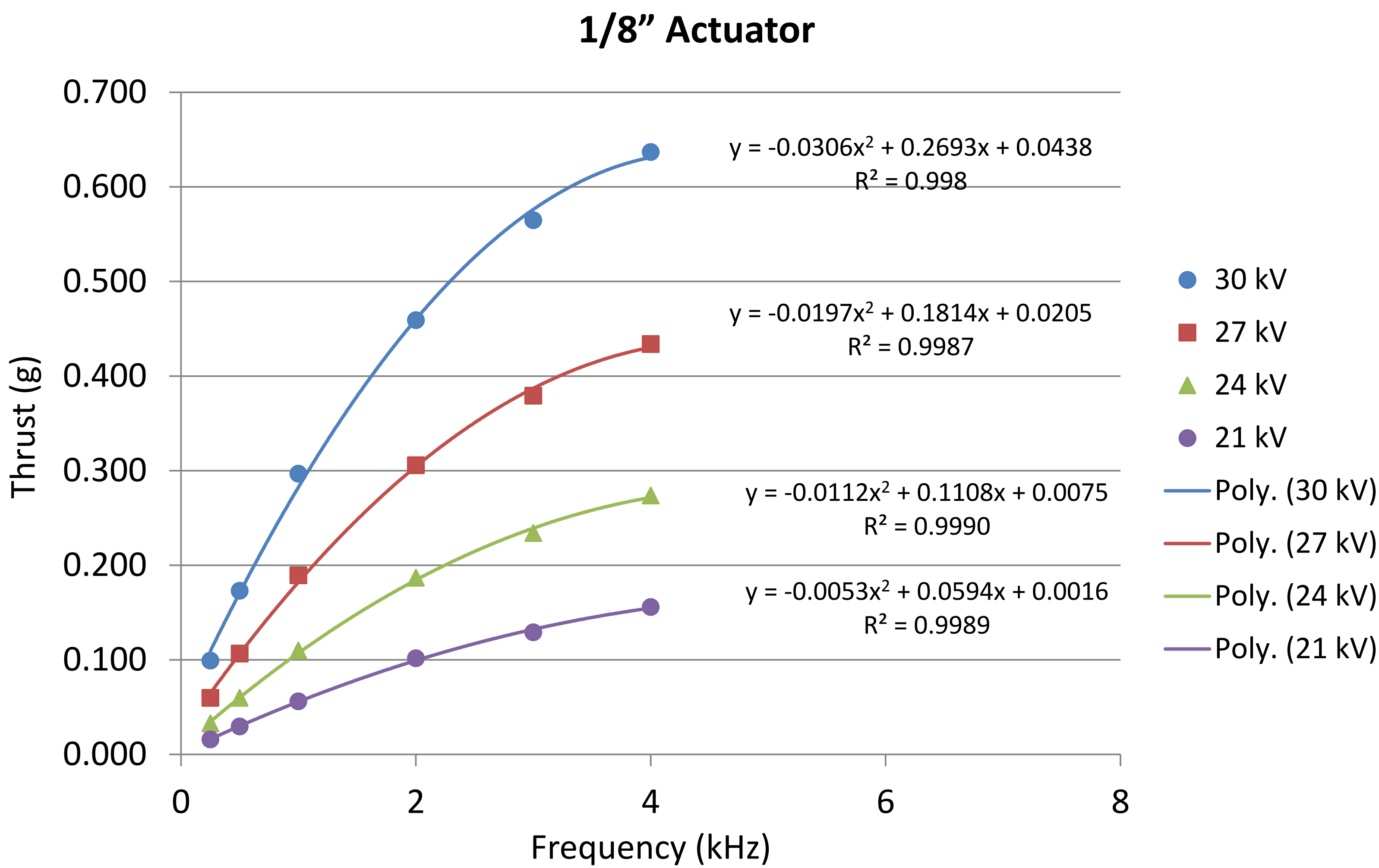
BACKUP CHARTS A

- Thrust-Frequency at const. Voltage
- Actuator detailed dimensions
- Normalization lengths
- Unit conversions

Thrust – frequency at const. voltage
Log-Log scale

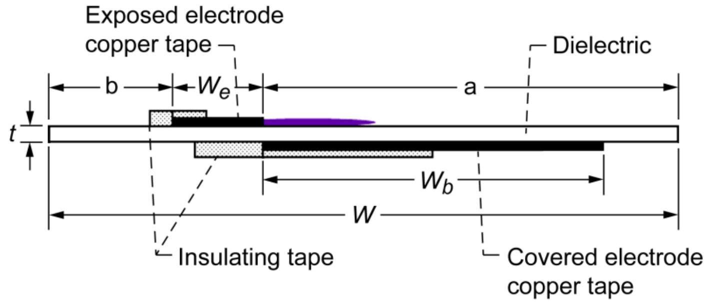


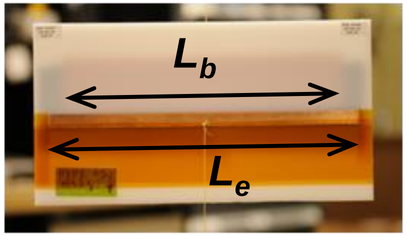
Thrust – frequency at const. voltage Linear scale



Actuator Test Articles

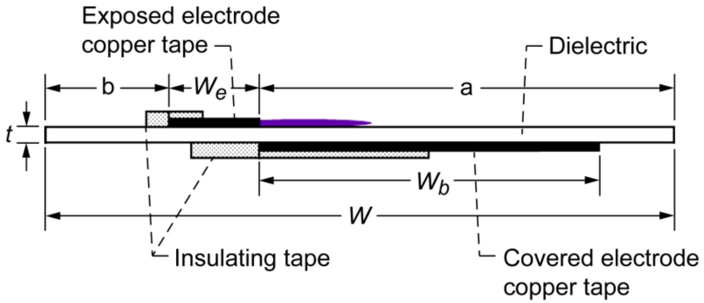
- HDPE - High Density Poly Ethylene
  - Dielectric Constant: 2.3 at 1 kHz
  - Dielectric Strength: 22 MV/m
  - Dissipation Factor: 0.0005 at 1 kHz
- 3M #1181 Copper tape w/ conductive adhesive
  - Copper thickness: 0.04 mm (1.4 mil)
  - Adhesive thickness: 0.03 mm (1.2 mil)
- Super Corona Dope®: MG Chemicals Inc. Cat. No. 4226-1L
  - Used for edge Insulation buildup
- Kapton® 3M #5413, 0.08 mm (3 mil) thick
  - Used for upstream edge insulation
- 3M Scotch-Seal No. 229 pads
  - Used for covered electrode insulation

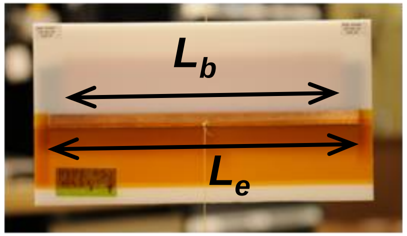




Designation	t (Nominal)	t	W_e	W_b	L_e	W	a	b
	inch	mm	mm	mm	mm	mm	mm	mm
HDPE #5	1/16	1.53	12.7	51	282	154	86.5	54.0
HDPE #7	1/8	3.16	12.0 12.8	48	283	164	81.0	59.0
HDPE #3	1/4	6.09	12.0	48	254	154	76.5	64.5

Thrust Normalization Length





Designation	*t* (Nominal)	L_e (exposed electrode)	L_b (covered electrode)	$L_{e\text{-}}$ *uninsulated* (exposed electrode)	Thrust *T* to T/L_e conversion factor	Thrust *T* to T/L_b conversion factor	Thrust *T* to $T/L_{e\text{-uninsulated}}$ conversion factor
	inch	mm	mm	mm	g to mN/m	g to mN/m	g to mN/m
HDPE #5	1/16	282	256	218	34.78	38.31	44.98
HDPE #7	1/8	283	257	249	34.65	38.16	39.38
HDPE #3	1/4	254	256.5	259	38.61	38.23	37.86

conversions

- 1 g = 9.80665 mN
- 1 mg = 0.00980665 mN
- 1 mN = 0.101971621298 g
- 1 mN = 101.971621298 mg