National Aeronautics and Space Administration

Ion Thruster Produced Roll Torque

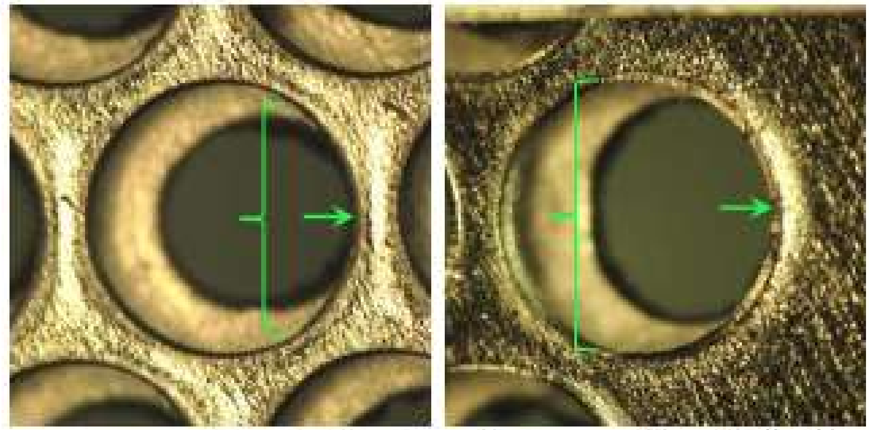
Neil Arthur
Vantage Partners LLC, Brook Park, OH, 44142

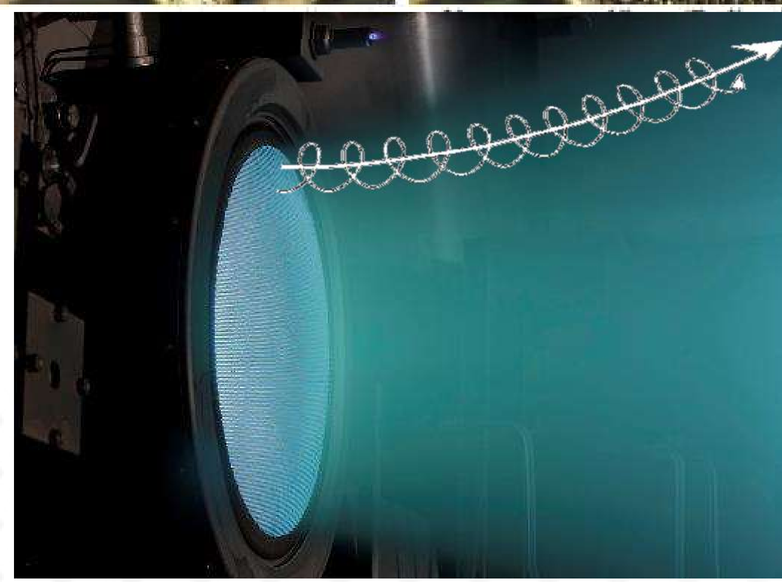
AIAA Propulsion and Energy Forum
8/21/2019
Indianapolis, IN

NEXT-C
NASA'S EVOLUTIONARY XENON THRUSTER–COMMERCIAL

Outline

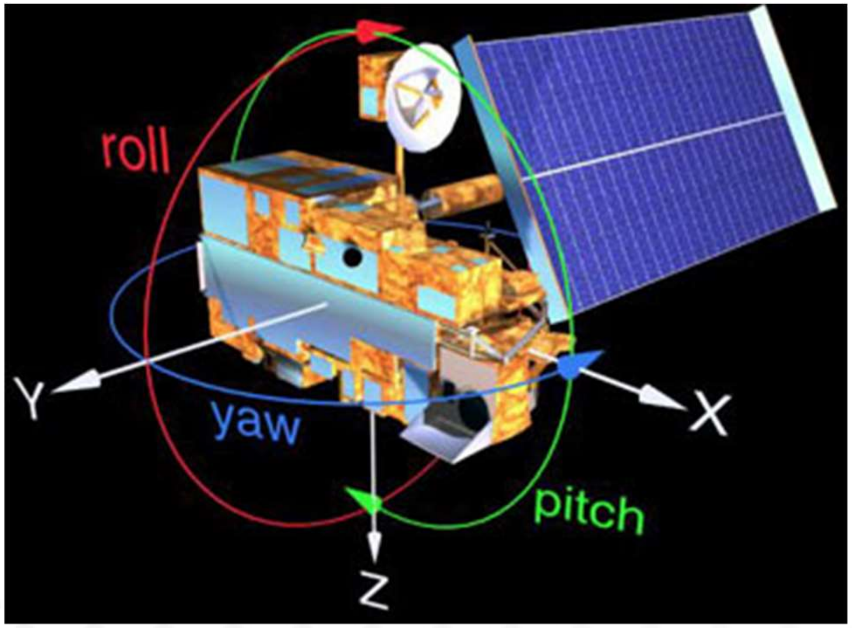
- Introduction
- Grid Misalignment
- Magnetic Field
- Flight Data
- Conclusion





Introduction

- Disturbances to an ion thruster's thrust vector will cause a spacecraft to spin about its axis if left unmanaged
- Spin about the yaw and pitch axis can be handled by a gimbal with enough authority
- The apertures of the ion optics are $\sim$1 mm^2 and must be aligned over the full $\sim$ 0.5 m diameter
  - Misalignment errors on the order of 10 μm can cause a large disturbance to the thrust vector

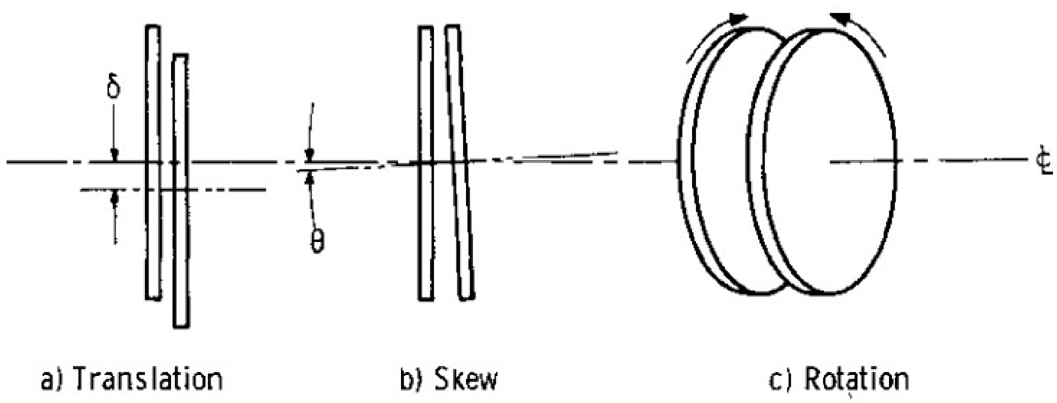


Why is Roll Torque Important to Understand?

- Spacecraft utilizing EP are designed to thrust for very long times, so even small torque will accumulate over the mission
- Roll torque cannot be handled by the gimbal
- Chemical thrusters and/or reaction wheels are required to counteract roll torque
  - The quantity of hydrazine propellant carried by the spacecraft is in part determined by the expected roll torque
- DS1 took measures to conserve hydrazine because it was critical to maintain proper solar array and spacecraft pointing
  - Once the hydrazine was depleted the hyperextended mission was terminated
- Dawn used reaction wheels and hydrazine thrusters to unload the wheels
  - The Dawn extended mission ended in Nov 2018 when the spacecraft ran out of hydrazine
- The DART mission has requested updated roll torque predictions because it is the main driver of their hydrazine budget

Ion Optics Misalignments

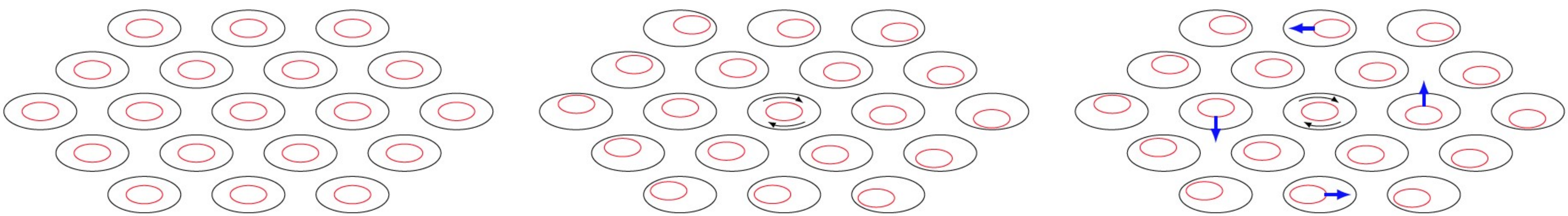
- Misalignment between the screen and accelerator grid distorts the electric field, causing beamlet deflection
  - Deflection direction is opposite of the misalignment direction



Lathem, *J. Spacecraft Rockets*, **5**, 6, 1968.

Ion Optics Misalignments

- A grid clocking error will cause beamlet deflections that produce a roll torque about the thrust axis
- Misalignment errors between hole pairs increases as a function of radius
- This clocking error will produce spin about the roll axis



Beamlet Deflection Angle – Theory

- The two grids can be modeled as a lens with linear optics theory where the deflection angle is proportional to the misalignment displacement over the focal length

$$\beta = -\frac{\delta}{f}$$

- The focal length of the lens is

$$f = \frac{4V_{\mathrm{T}}}{E_1 - E_2}$$

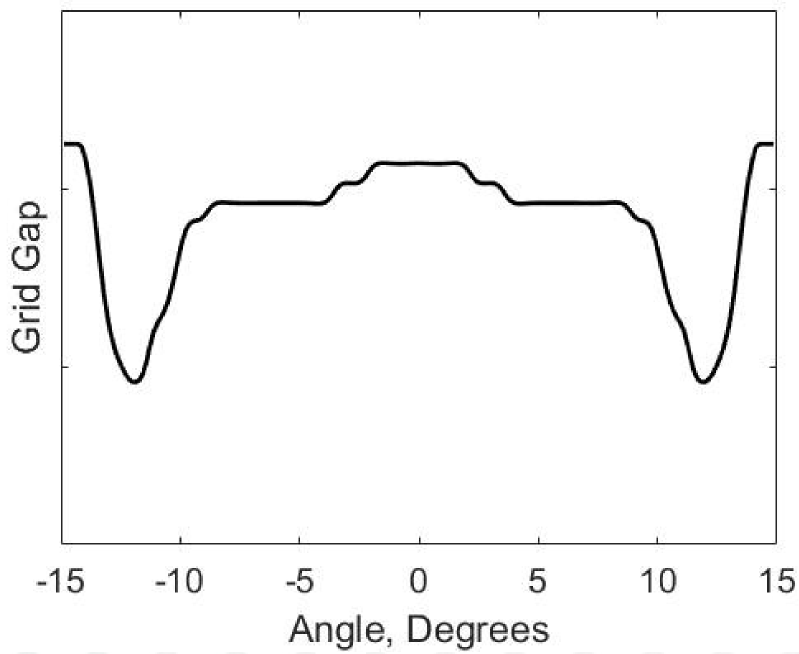
- Whealton provided a simple theoretical relation (Whealton, *Rev. Sci. Instrum*., **46**, 9, 1975):
  - Assume $|E_2| \ll |E_1|$ and $E_1 \approx V_{\mathrm{T}}/l_{\mathrm{g}}$

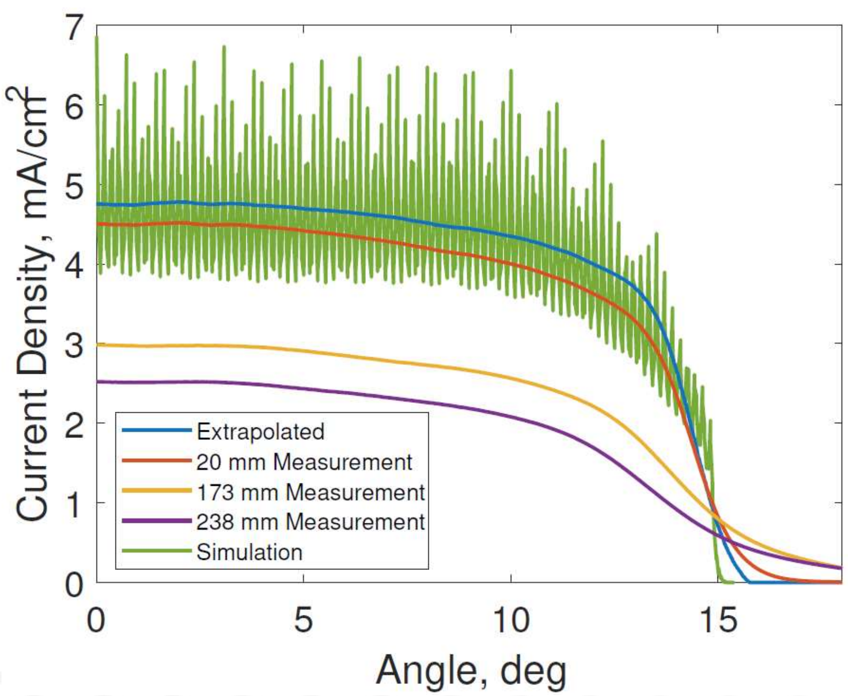
$$\beta = -\frac{\delta}{4l_{\mathrm{g}}} \quad \text{or} \quad \beta = -14.3^\circ \frac{\delta}{l_{\mathrm{g}}}$$

- Homa and Wilbur found experimentally that (Homa and Wilbur, AIAA-82-1895, 1982): $\beta = -15.8^\circ \dfrac{\delta}{l_{\mathrm{g}}}$

Grid Misalignment Produced Roll Torque

- Grid misalignment, grid gap, and the current density are a function of radius
- Roll torque can be found by integrating over the grid area

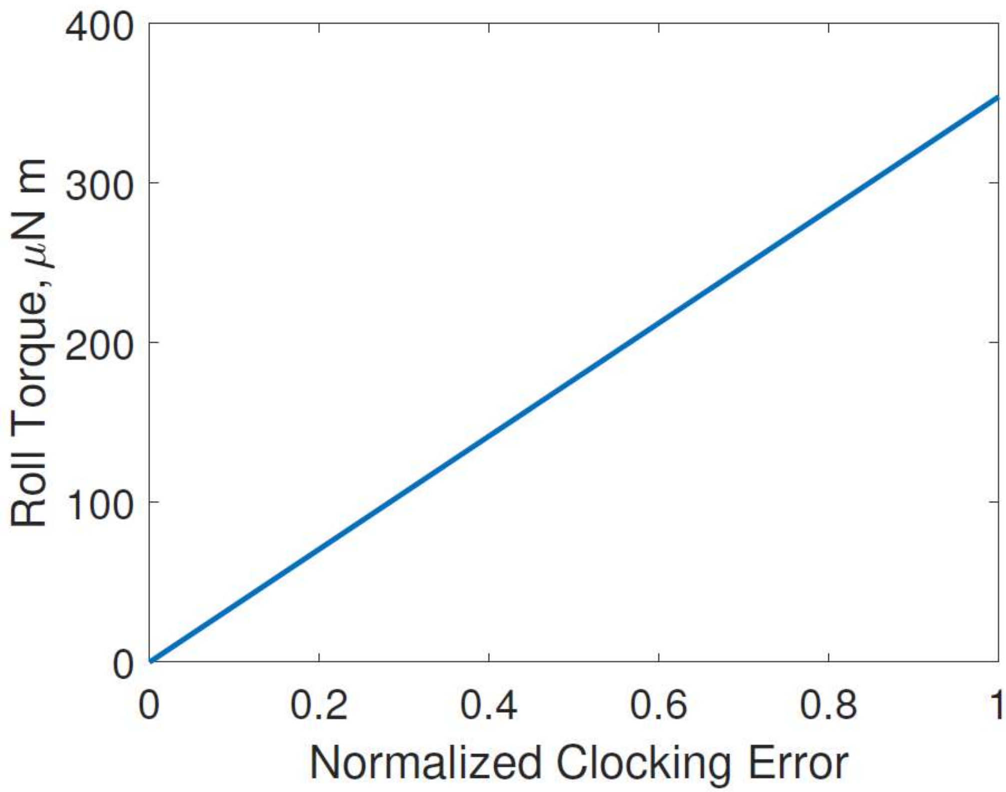




Grid Misalignment Produced Roll Torque

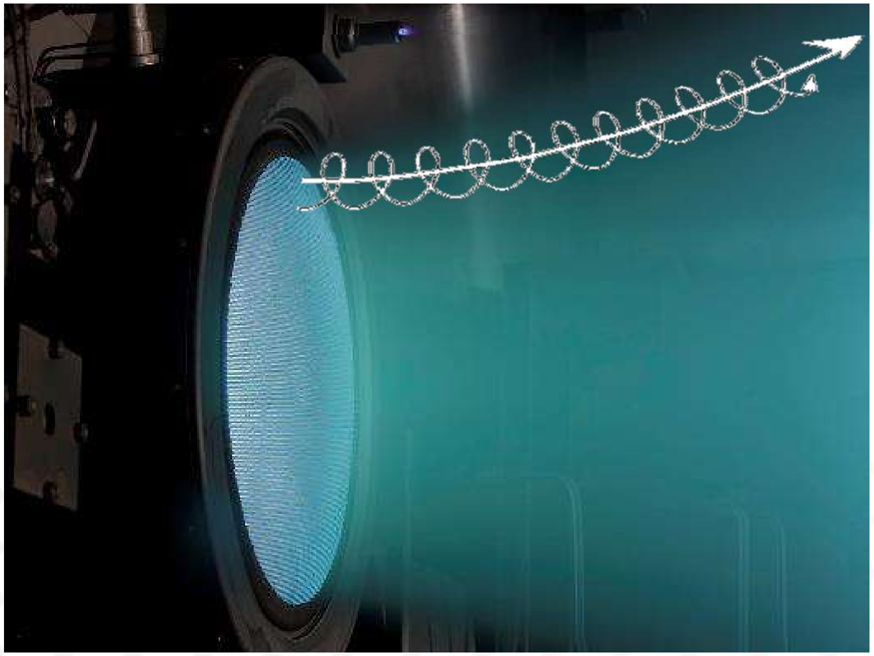
- The normalized grid clocking error is the distance between screen and accelerator aperture centers at the outermost hole pairs normalized to the NEXT-C specification
  - This is how alignment of flight optics is specified, e.g. misalignment shall be ≤ X.X mm at the beam periphery
- The values in the figure can be roughly scaled to any throttle level by multiplying by ratios of

$$j_b\sqrt{V_b}$$



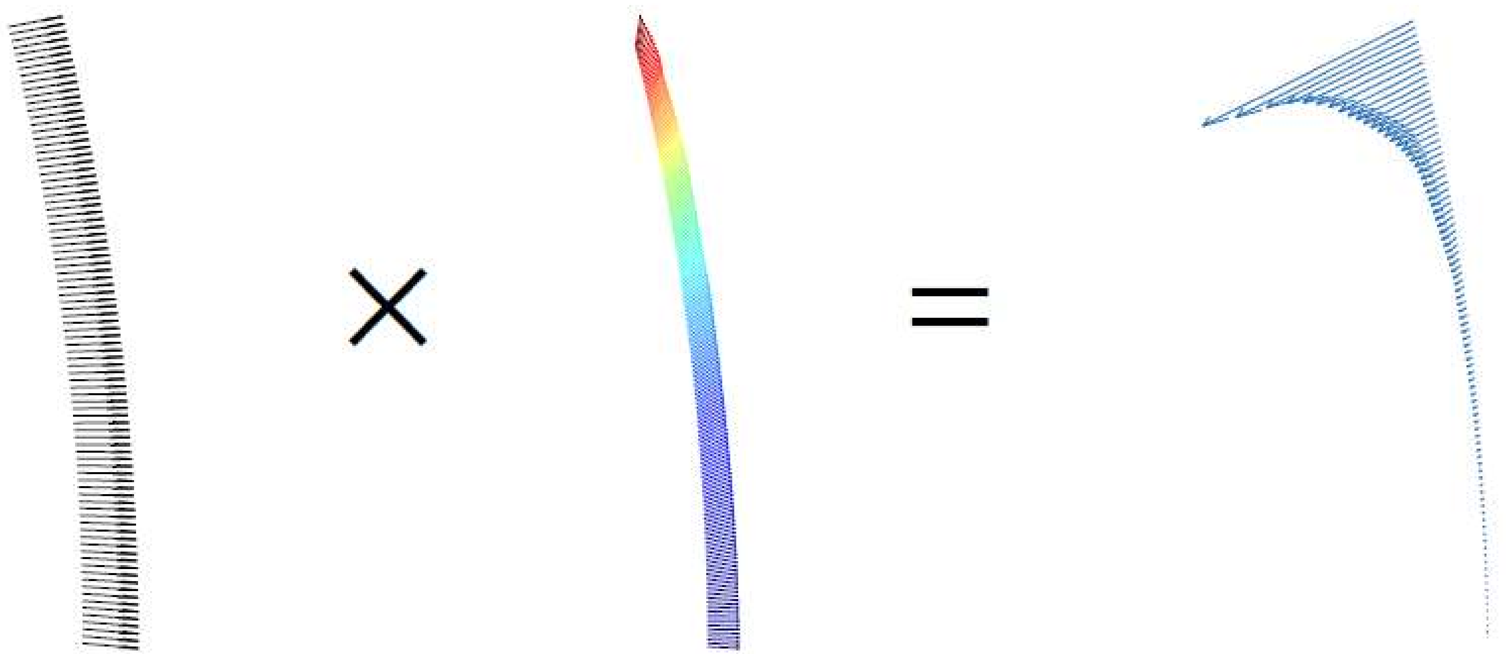
Magnetic Field – Beam Ion Interactions

- The magnetic field within the discharge chamber 'leaks' into the plume
- Ions will gyrate around the field producing a force perpendicular to the beam propagation direction



Magnetic Field – Beam Ion Interactions

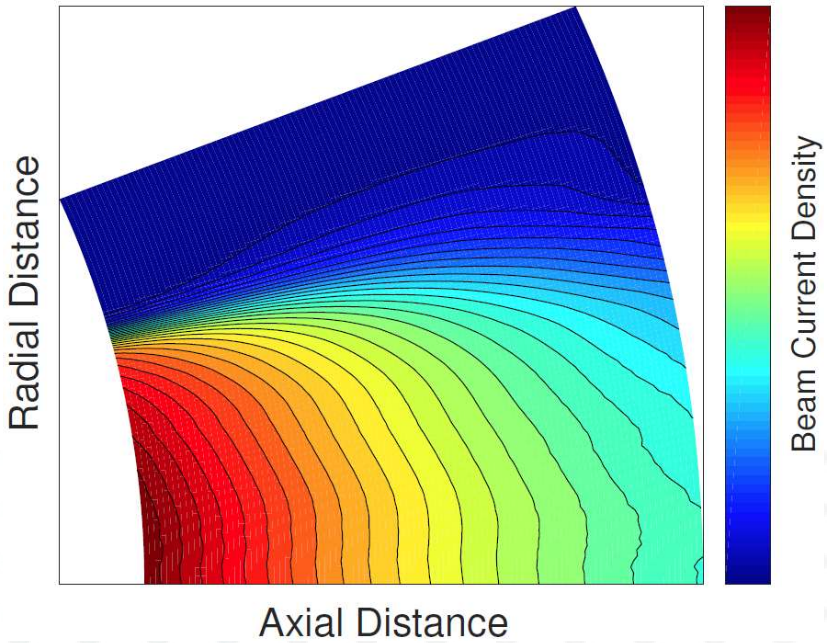
- The roll torque is found by integrating the Lorenz force throughout the entire plume

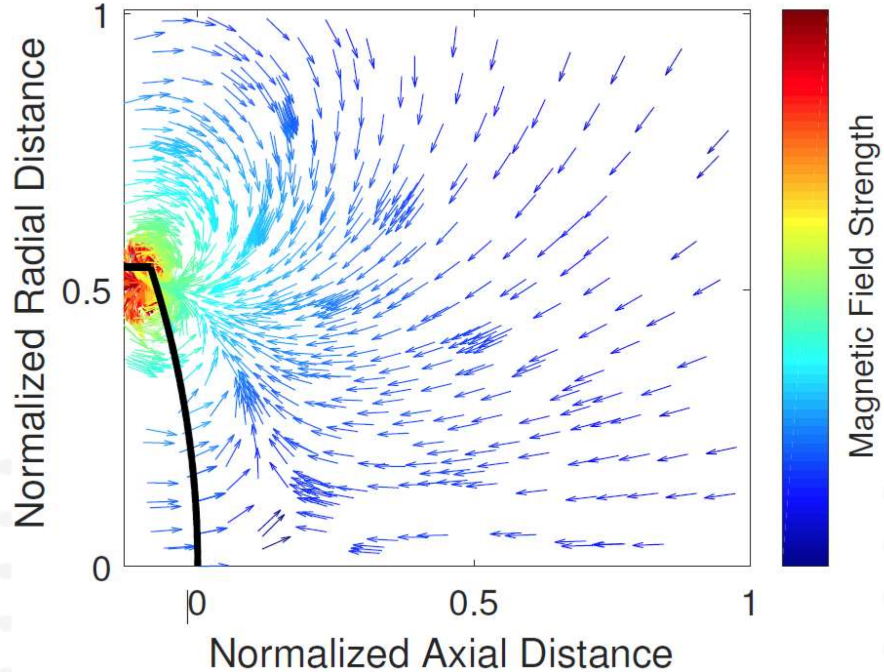


$$\vec{\mathbf{v}} \times \vec{\mathbf{B}} = \vec{\mathbf{F}}$$

Magnetic Produced Roll Torque

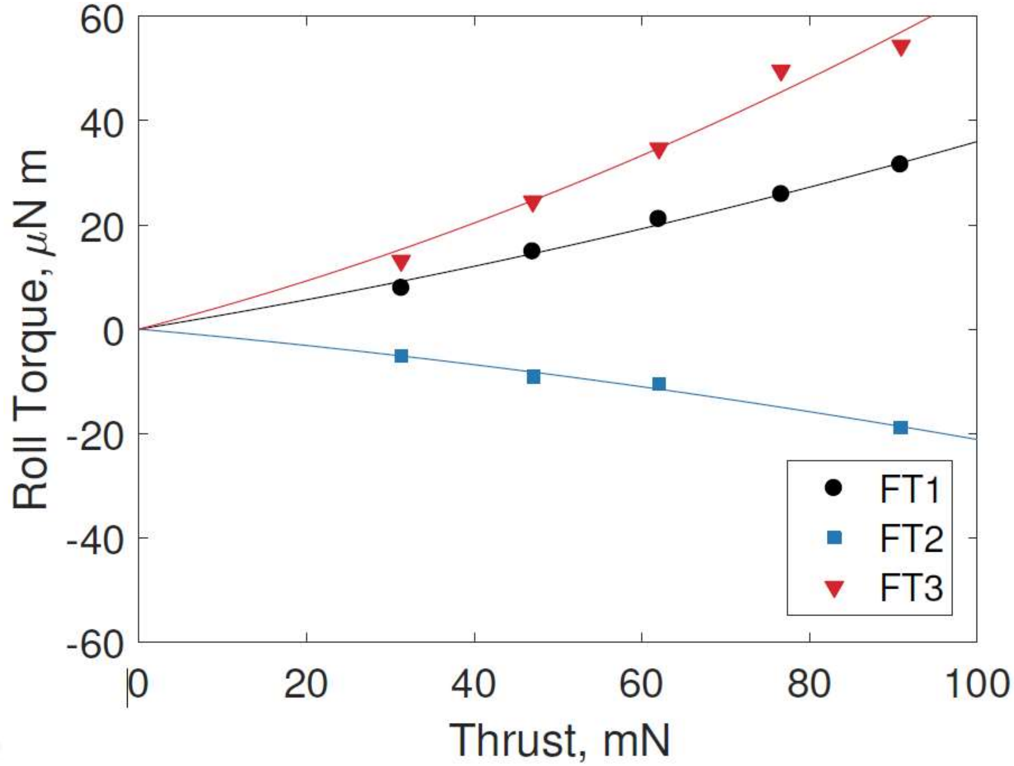
- The magnetic field and the ion plume theoretically extend to $r \rightarrow \infty$ but fall off according to r^{-3} and measurement data is only available up to a finite distance
- Magnetic field produced roll torque is estimated to be ~30 μN m
  - An order of magnitude less than the grid misalignment produced torque





Flight Data – Dawn NSTAR Thrusters

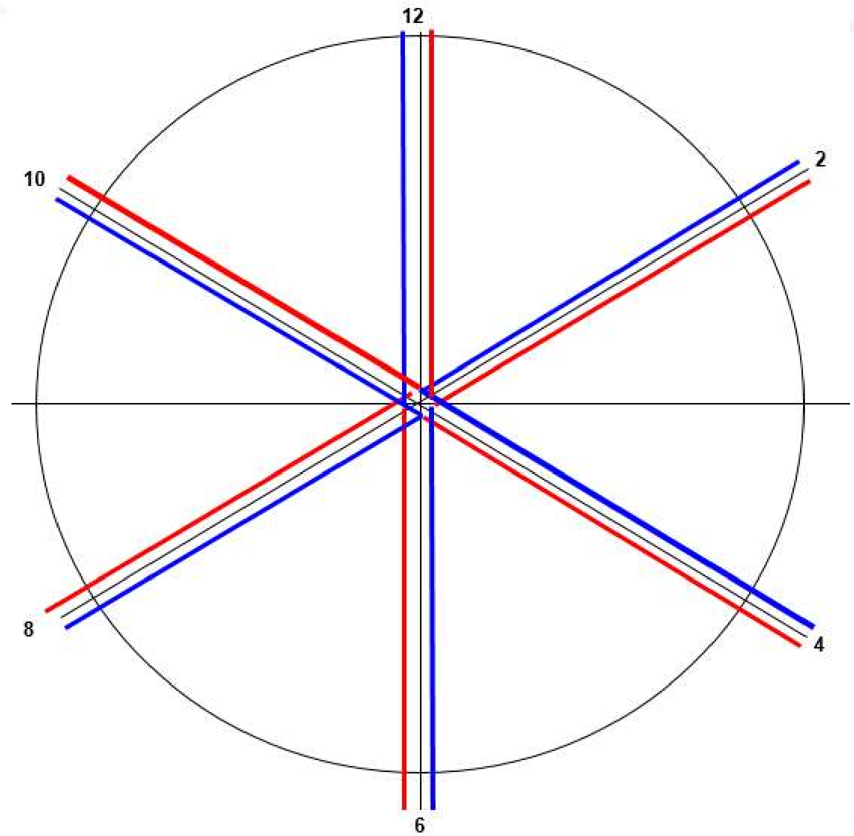
- Dawn measured the roll torque of the 3 flight thrusters using the momentum building up the reaction wheels
  - FT1: 32 μN m
  - FT2: -25 μN m
  - FT3: 54 μN m



Brophy, et al., *J. Propul. Power*, **25**, 6, 2009.

Flight Data – Dawn NSTAR Thrusters

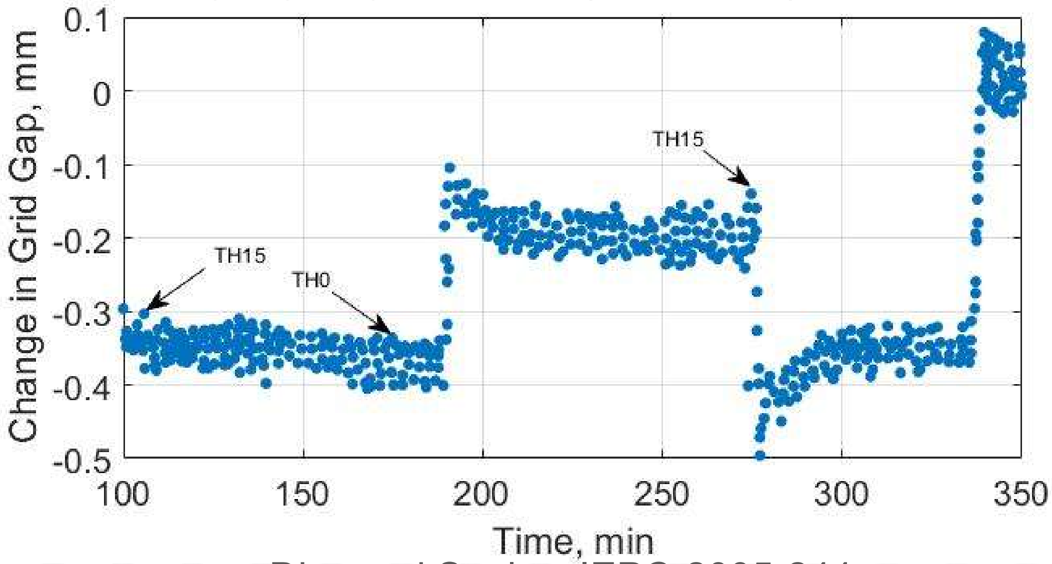
- Pre-flight alignment of 25 apertures along 3 radii was measured to predict roll torque
  - FT1: 16 μN m
  - FT2: -15 μN m
  - FT3: 23 μN m
- Underprediction of 40%-60%
- Why?



Boeing and NASA JPL, "Dawn Flight Grids Assembled Alignment Data," 2007.

Flight Data – Dawn NSTAR Thrusters

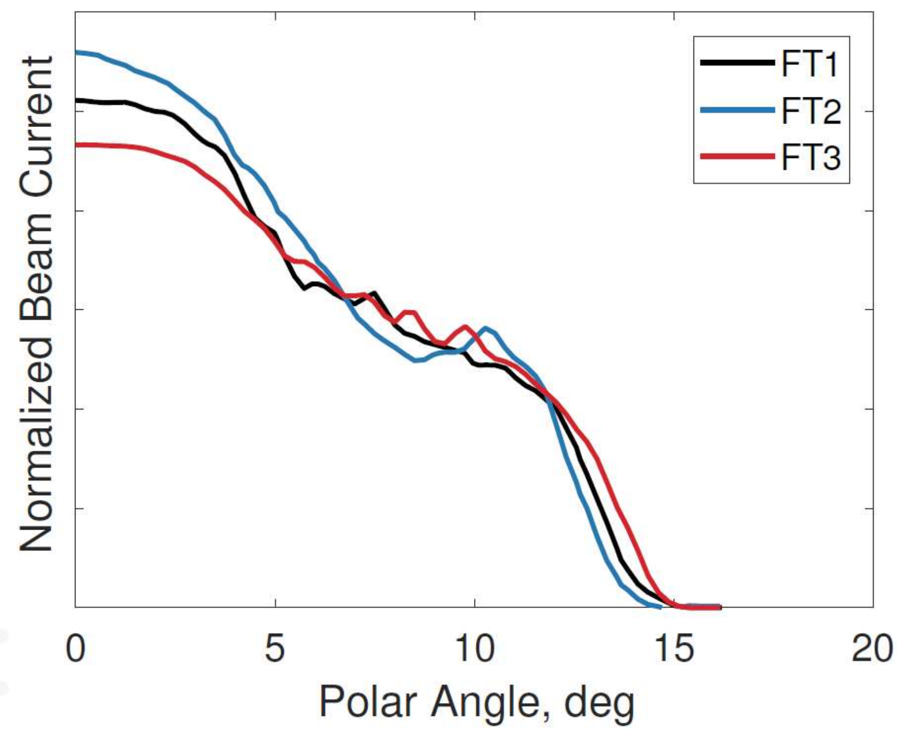
- Prediction assumed grid gap of 0.48 mm
  - Estimated from Haag's translated accelerator grid study
  - Agreed with thermal model
- Diaz measured a smaller hot grid gap
  - Leads to increase in roll torque of 45% to 65%
- Prediction assumed constant grid gap vs. radius
- Using the measured preflight grid gap profile ('W' shape) can lead to an increase in roll torque of 25% to 30%



Diaz and Soulas, IEPC-2005-244

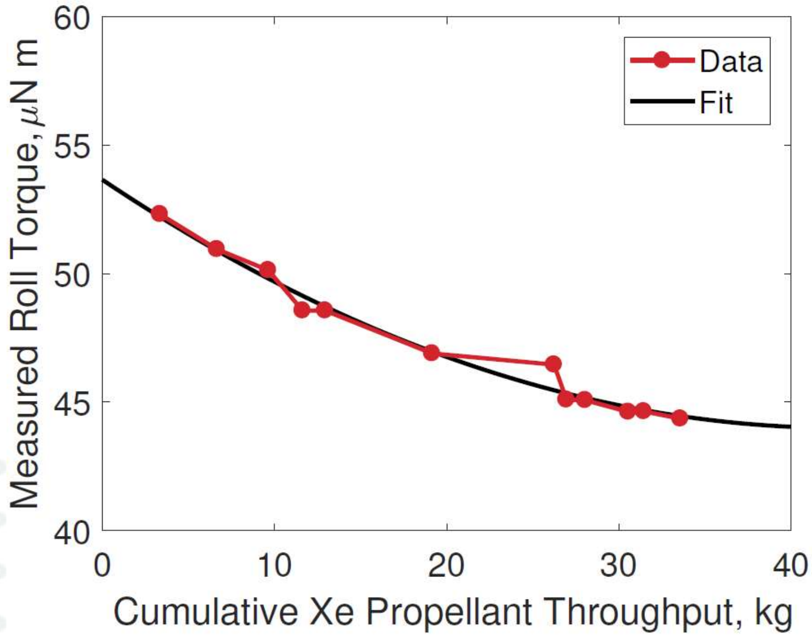
Flight Data – Dawn NSTAR Thrusters

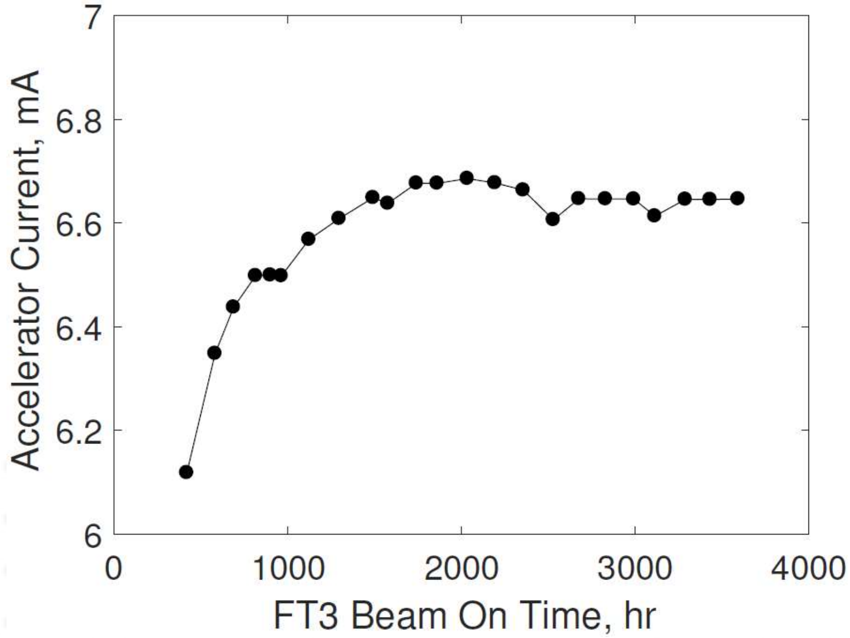
- Variation in beam profile leads to >15% variation between FT2 (most peaked) and FT3 (least peaked)
- Magnetic field produced roll torque for NSTAR has been estimated as 2 to 7 μN m
- NSTAR electric field correction at full power is 1.23
- Taking all these into account:
  - FT1: 34 μN m (25 to 45 μN m)
  - FT2: -29 μN m (22 to 40 μN m)
  - FT3: 48 μN m (36 to 63 μN m)
- Flight values
  - FT1: 32 μN m
  - FT2: -25 μN m
  - FT3: 54 μN m



Flight Data – Dawn NSTAR Thrusters

- FT3 showed a roll torque that decreased the longer the thruster was operated
- Garner proposed that there is systematic thrust vector error that results in a torque, which is changing as Xe is used and the SC's CoM changes
- Did grid misalignment improve, as badly misaligned apertures were severely eroded?
  - Documented processes referred to as 'notching' (Not supported by J_a trend)

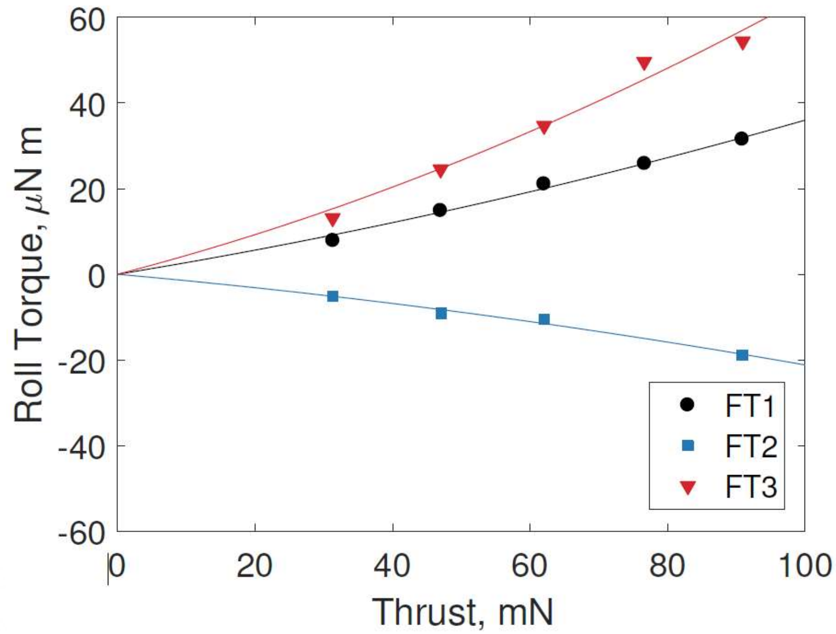




Garner, et al., AIAA-2015-2771

Dawn Roll Torque – Direction

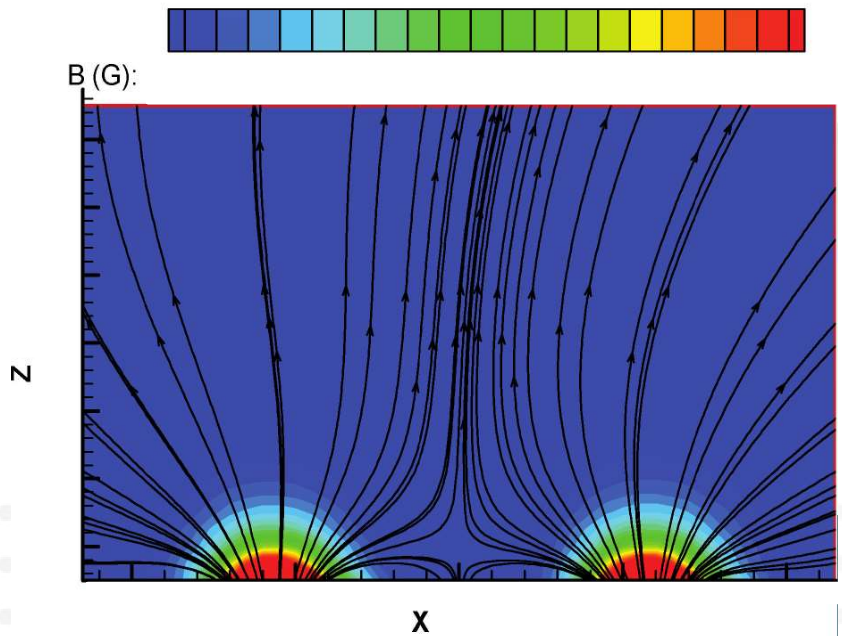
- From Brophy, et al., *J. Propul. Power*, **25**, 6, 2009.
  - "**The direction of the roll torque produced by FT2 corresponds to the right-hand rule with your thumb pointing in the direction of the ion beam propagation**."
  - "However, calculations of the roll torque for each thruster based on careful measurements of the grid clocking errors made during thruster assembly do not agree with the data [in the figure]. These calculations do not correctly predict the magnitudes or even in some cases the directions of the measured roll torque"



- Boeing's grid clocking alignment measurement documents
  - "A positive value for the above roll torque indicates that the beamlets are deflected in the clockwise direction as determined when facing upstream toward the accelerator grid. **The torque on the spacecraft, then, is in the 'positive' direction according to the right-hand-rule with your thumb pointing in the direction of the ion beam propagation**."

Hall Thruster Roll Torque

- Hall thrusters have larger current densities and magnetic field strengths at the exit plane leading to roll torque
- Manzella estimated SPT-100 roll torque to be 60 μN m or 2-8% of thrust (AIAA-94-3141)
- Ashkenazy estimated roll torque was 20-40 μN m for a 0.5-0.8 kW Hall thruster (IEPC-99-183)



Beal, B. E., et al., *J. Propul. Power*, **20**, 6, 2004.

Conclusion

- Roll torque is important to quantify due to the length of the missions utilizing EP and the impact it has on the hydrazine budget/reaction wheels
- There are two sources of roll torque: Grid misalignment errors and magnetic field – beam ion interactions
- The grid misalignment produces the bulk of the roll torque, which for NEXT is on the order of 300 to 400 μN m
- The magnetic field produced roll torque is about 30 μN m
- Measuring grid alignments prior to flight *can* effectively predict both the magnitude and direction of roll torque
- Dawn’s FT3 showed a decreasing roll torque as a function of operating time

Thank you to Chuck Garner at JPL for providing the Dawn flight thruster documentation.

This work was completed as part of the NEXT-C project, which is supported by the Planetary Science Division of the Science Mission Directorate, NASA Headquarters and awarded to Aerojet Rocketdyne and ZIN Technologies.

Backup Slides

Beamlet Deflection Angle – Theory

- Beamlet deflection angle

$$\beta = \frac{\delta(E_1 - E_2)}{4V_T}$$

- Accelerating and decelerating fields

$$E_1 = \frac{V_T}{\ell_a} \qquad E_2 = \frac{V_T - V_N}{\ell_d}$$

- Whealton provided a simple theoretical relation (Whealton, *Rev. Sci. Instrum*., **46**, 9, 1975):
  - 1.5 – 40 kV ion beams, in a three grid ion accelerator
  - So in the case that $|E_2| \ll |E_1|$ and $E_1 \approx V_T/l_g$

$$\beta = \frac{\delta}{4l_g} \qquad \beta = 14.3^\circ \frac{\delta}{l_g}$$

Beamlet Deflection Angle – Experimental

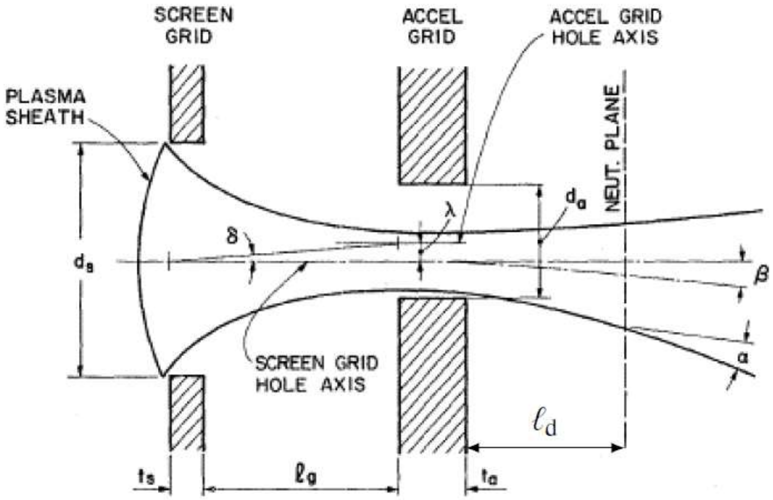
- Let κ be the constant of proportionality
  - κ = 14.3° from theoretical expression
  - Stewart included space-charge effects and found κ = 19.1°
- Homa and Wilbur found experimentally κ = 15.8°
- Haag found for NSTAR 16.5° $\leq \kappa \leq$ 22.8°
- Okawa and Shagayda used 3D simulations and found 19° $\leq \kappa \leq$ 20°
- Homa suggests that the reason for this variation is that the assumption $|E_2| \ll |E_1|$ is not valid
- As the ratio $|E_2|/|E_1|$ increases, the value of β increases

Beamlet Deflection Angle – Deceleration Electric Field

- The deceleration electric field is:

$$E_2 = \frac{V_T - V_N}{\ell_d}$$

- The deceleration length in a two-grid system is not easily defined
  - Can be estimated from an expression provided by Kaufman
- Homa and Wilbur estimate that the correction $(1 - E_2/E_1)$ for their grid geometry was 1.14
  - Their experimentally determined value of 15.8° was 10% higher than 14.3°
- For the NEXT grid geometry the correction factor ranges from 1.07 to 1.19



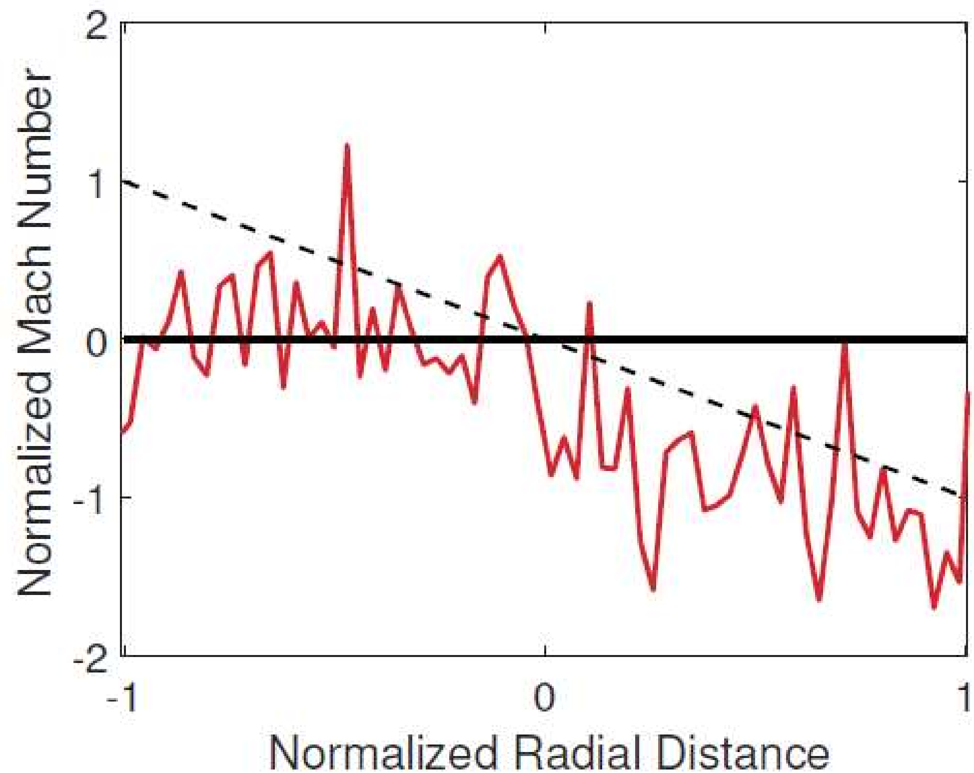
Homa and Wilbur, AIAA-82-1895, 1982

Roll Torque Measurements – Roll Torque Probe

- Probe is scanned across the thruster face and the current to the top and bottom probes is compared

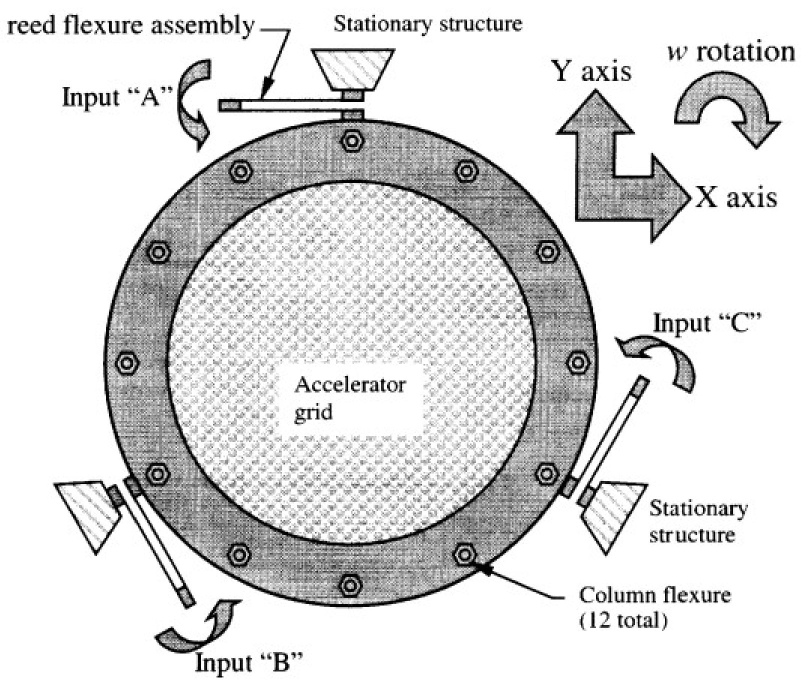
$$\frac{I_\mathrm{t}}{I_\mathrm{b}} = e^{-kM} \qquad M = \frac{v_\mathrm{i}}{c_\mathrm{s}}$$

- The dashed line represents the expected shape assuming the grid set only has rotational misalignment
- The data suggests there is a translational misalignment directing the beam downwards
  - This agrees with thrust vector taken with this thruster with 2 different TVPs in 2 different facilities
- Detailed grid misalignment measurements are not available for this engineering model thruster

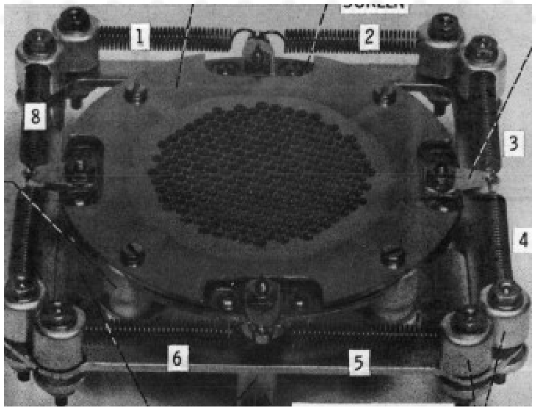


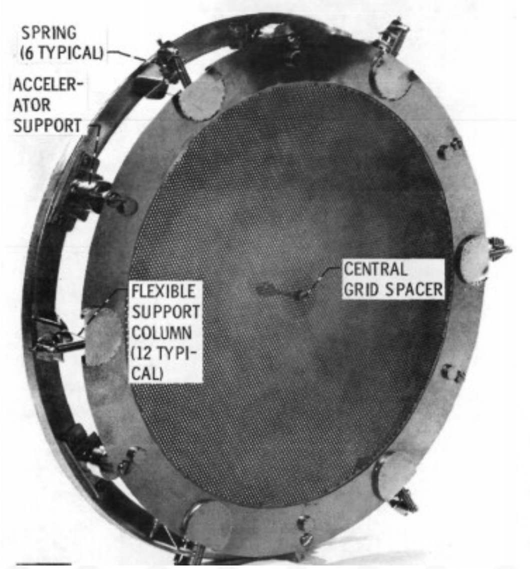
Ion Beam Deflection

- Grid translation was explored as an alternative to a gimbal for thrust vectoring



Haag, IEPC-01-116, 2001.





Lathem, AIAA-72-485, 1972.

Magnetic Field – Beam Ion Interactions

- The ions are subject to the Lorenz Force

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

- The ion velocity is ~normal to the grid surface ($\hat{r}$-direction)
- Ring-cusp thrusters have an azimuthally symmetric $\vec{B}$-field
  - $\vec{B}$ is in the $\hat{r}$ and $\hat{\theta}$ -directions
- The force increases exponentially towards the edges of the grid because the magnets are located around the circumference of the thruster