# Characterization of Radiation Heat Transfer in High Temperature Structural Test Fixtures

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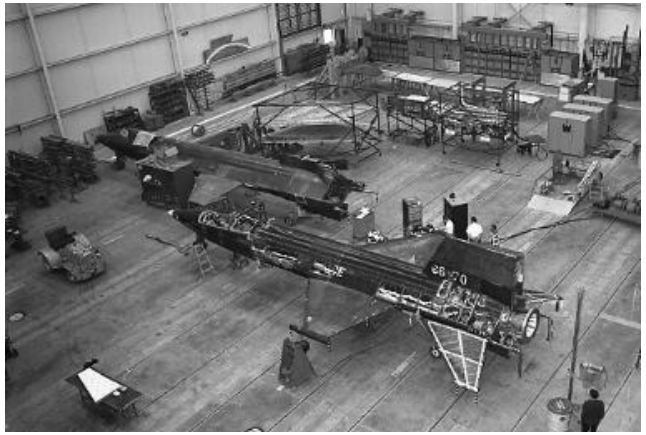
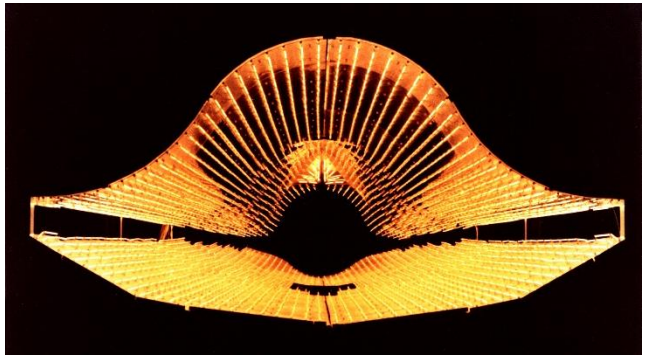
# Outline

- Background
- Planned Work
- Analytical Studies Completed To Date
- Test Fixture
- Test Data Comparison
- Conclusions
- Future Work

# Background: Motivation

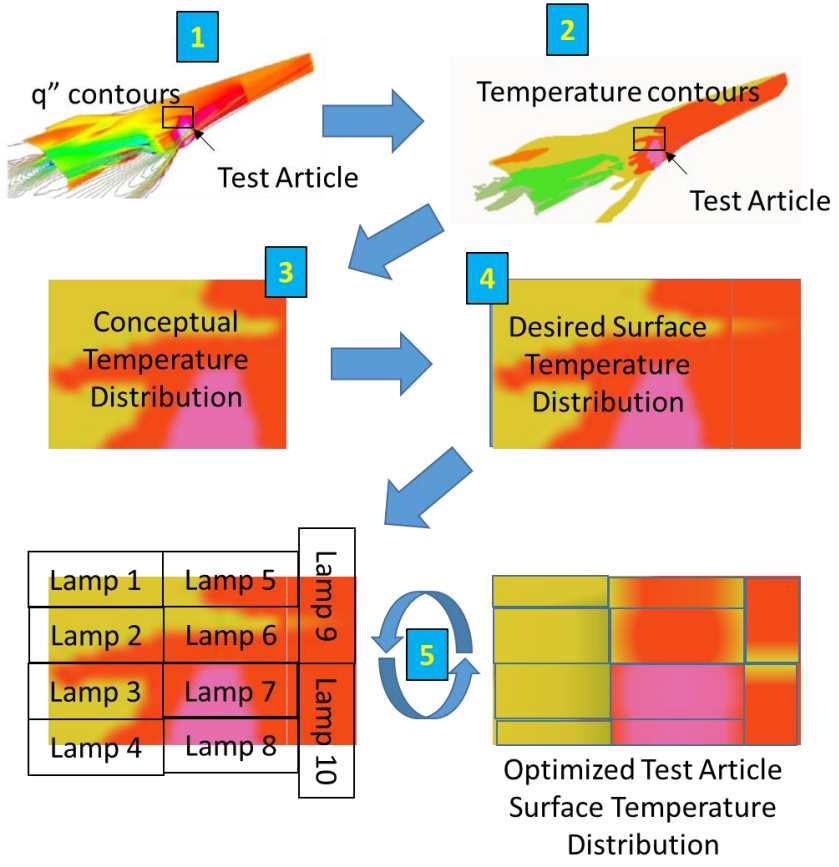
- Radiant heating of aircraft & spacecraft structures performed since early days of high speed flight (design, development, qualification)
- Common hardware: quartz lamps or graphite heater elements, certainly others do exist and are used
- Flight is analog (continuously varying heat flux profile around structures)
- Testing is digital (discretize heat flux profile two ways: thermal control zones, lamps)
- Lamps used for testing do not produce a uniform heat flux – lamp-specific
- **Design of lamp arrays** requires optimization of discretization of desired heat flux profile
- **Data interpretation** requires understanding of heat flux distribution created by lamps





# Background: Lamp Array Design Example

1. Run vehicle aero model to get surface fluxes
2. Map surface fluxes onto thermal model, include reradiation to space if significant, obtain nodal temperature distribution
3. Extract surface temperature distribution for test article region from vehicle thermal model ("Conceptual temperature distribution")
4. Design surface temperature distribution for actual test article heated surface ("desired temperature distribution") using the test article region extracted surface temperature distribution (knowing that test article is geometrically simplified/modified representation of actual vehicle geometry)
5. Design lamp layout and assess difference between optimized test article surface temperature distribution and "desired temperature distribution" using a single control TC in each zone (i.e. 1 point and surrounding region in each zone exactly meets the requirement…rest of region is at mercy of discretization)




**Current methodology more empirical, after very simplified analytical tool (several decades ago, FORTRAN4) proved inadequate**

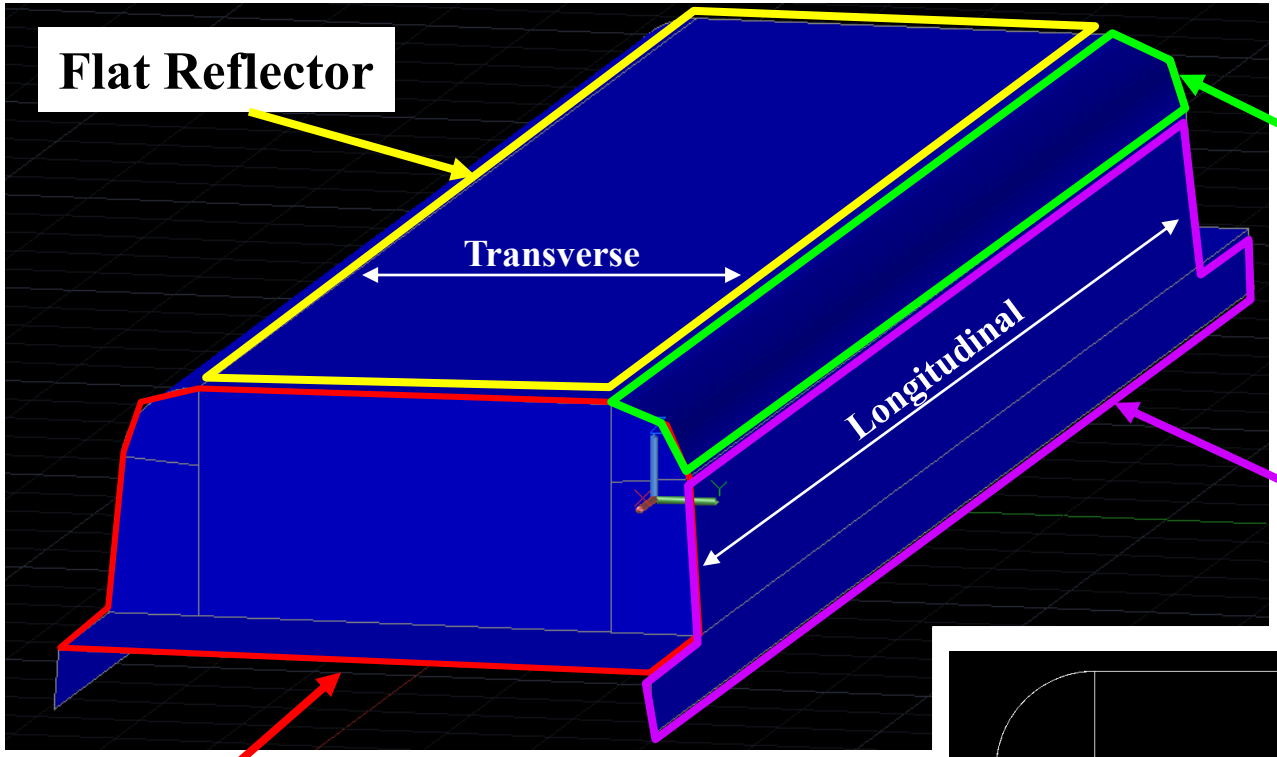
# Background: Previous Work

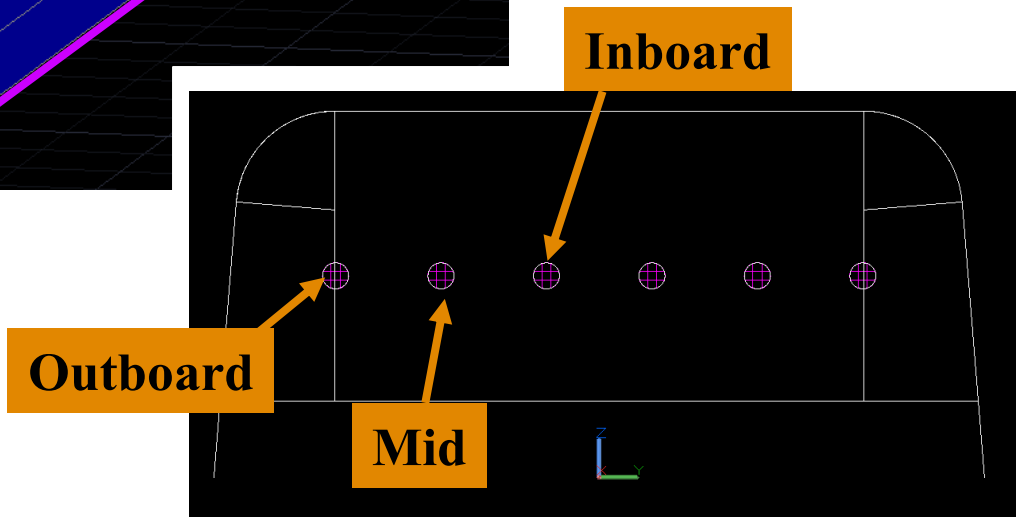
- Travis Turner/LaRC, Robert Ash/ODU (1988-1994)
- Y. Ohno, J.K. Jackson/NIST (1995/1996)
- Zalameda (2000)
- Undoubtedly countless industrial applications (in-house characterization for process control)
- Contrary to our purposes, most industrial applications are focused on uniformity (drying, curing, etc.) not on variation
- Our addition to the body of knowledge: data on our particular reflector, system level considerations (radiant exchange in different lamp configurations, influence of thermal control zone fences)

# Planned Work

- Use Thermal Desktop/RadCAD* to investigate the heat flux distribution contributions from:
  - Individual filaments (in different reflector locations)
  - Reflector components
  - Thermal control zone isolation fences (separation distance, angle, vertical clearance from test article, side-to-side power difference)
  - Lamp height
  - Lamp configuration (end-to-end, side-to-side, staggered vs aligned rows)
- Use existing student project (intern) developed test rig, collect heat flux distribution data on the variables identified above
- Compare pre-test predictions with data, refine model or test fixture if necessary
- Generate functional forms to describe heat flux distribution dependencies

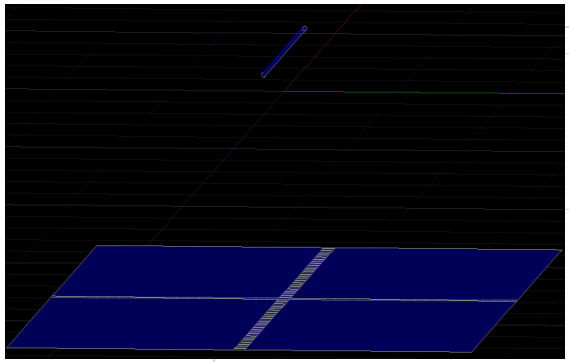
# Terminology

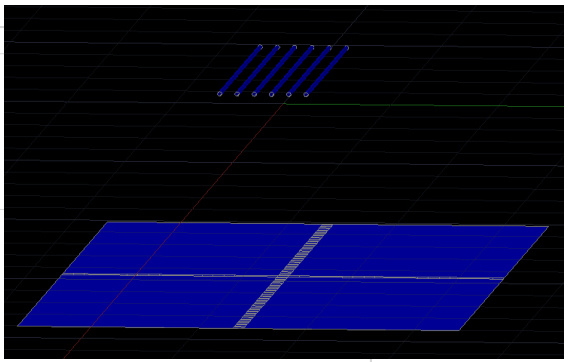


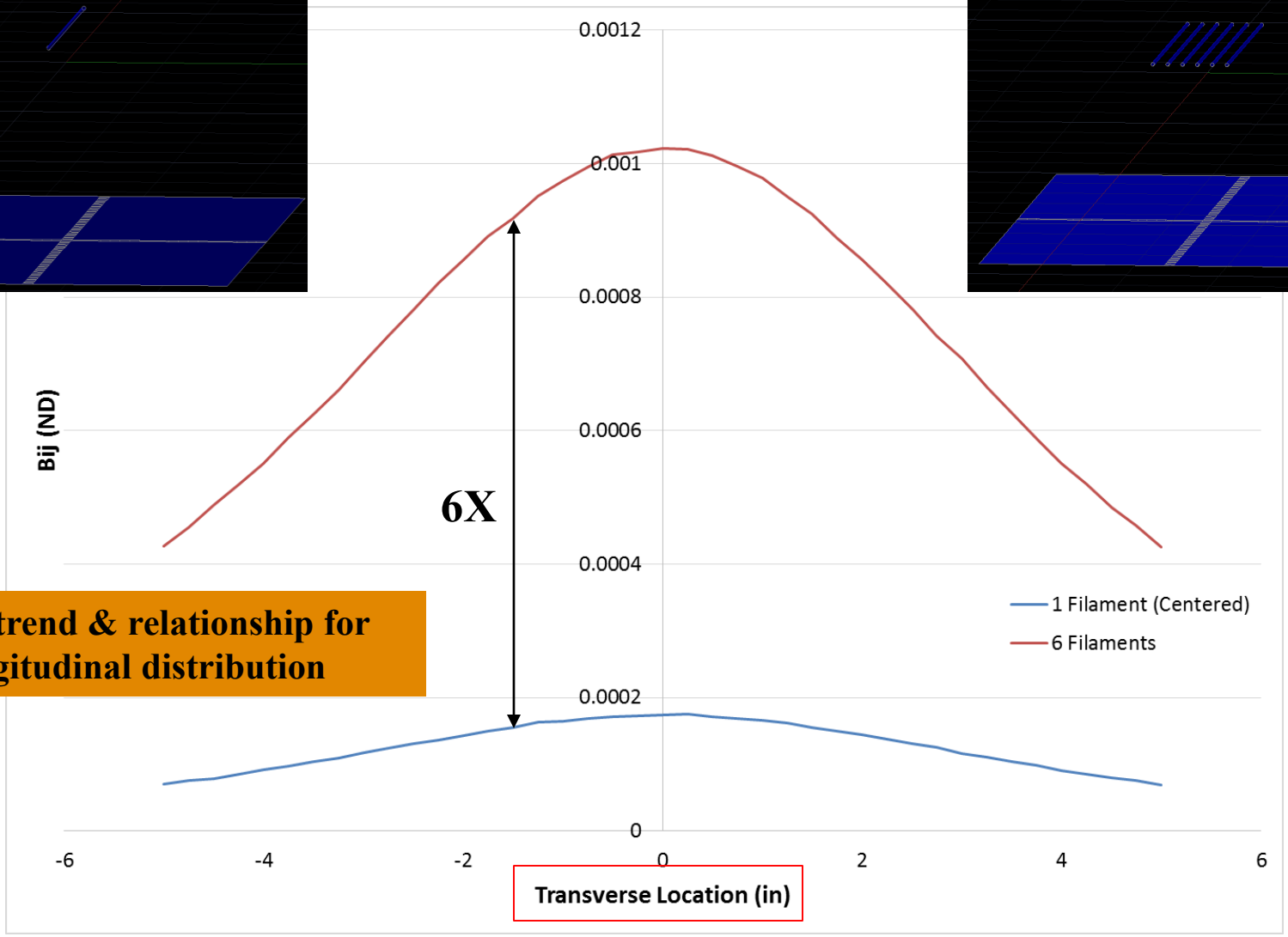




NB: Outboard filaments almost centered on edge of flat portion of reflector (+/-1.0025 vs +/-1.0062)

# One or Six Filaments, Base, No Reflector

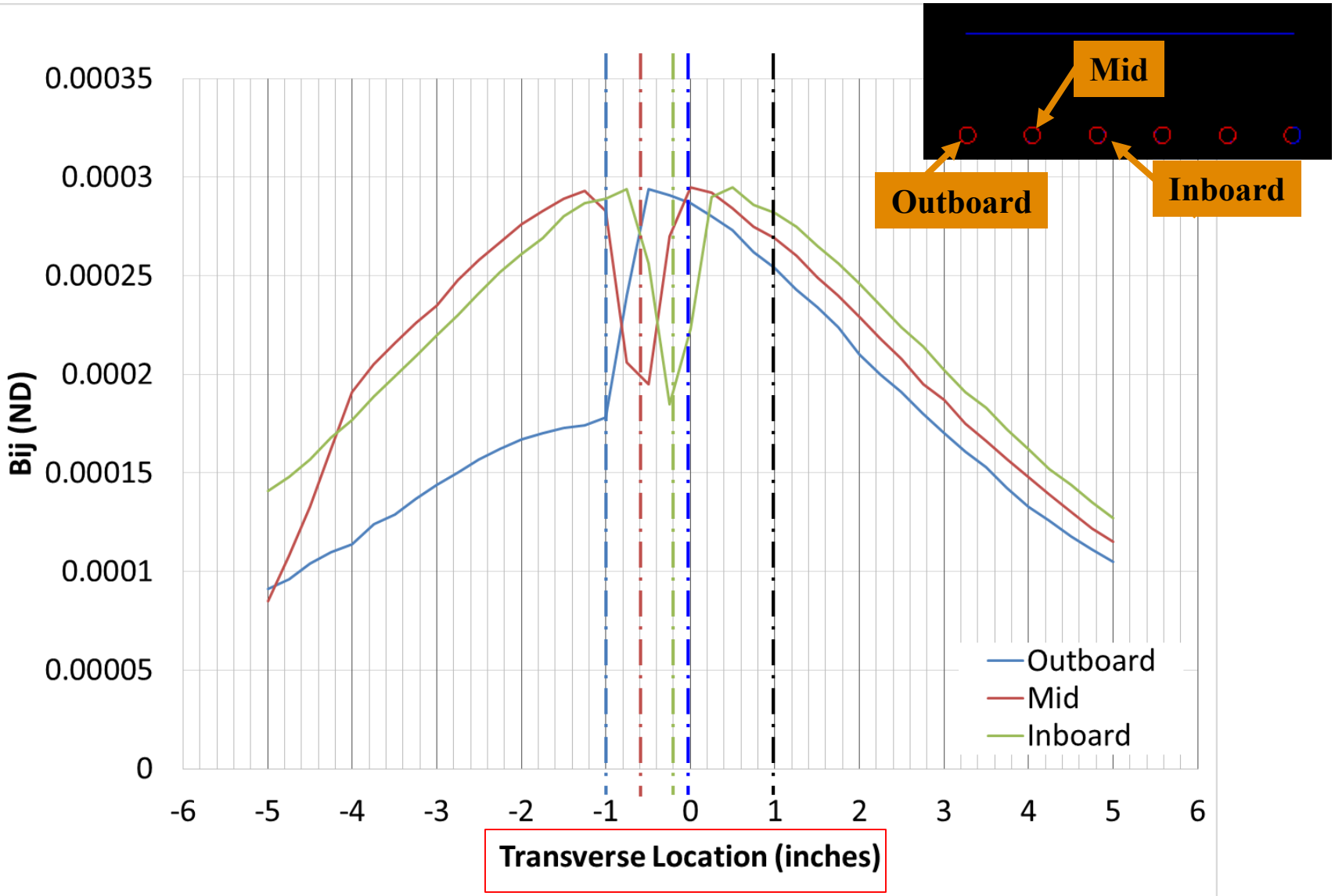






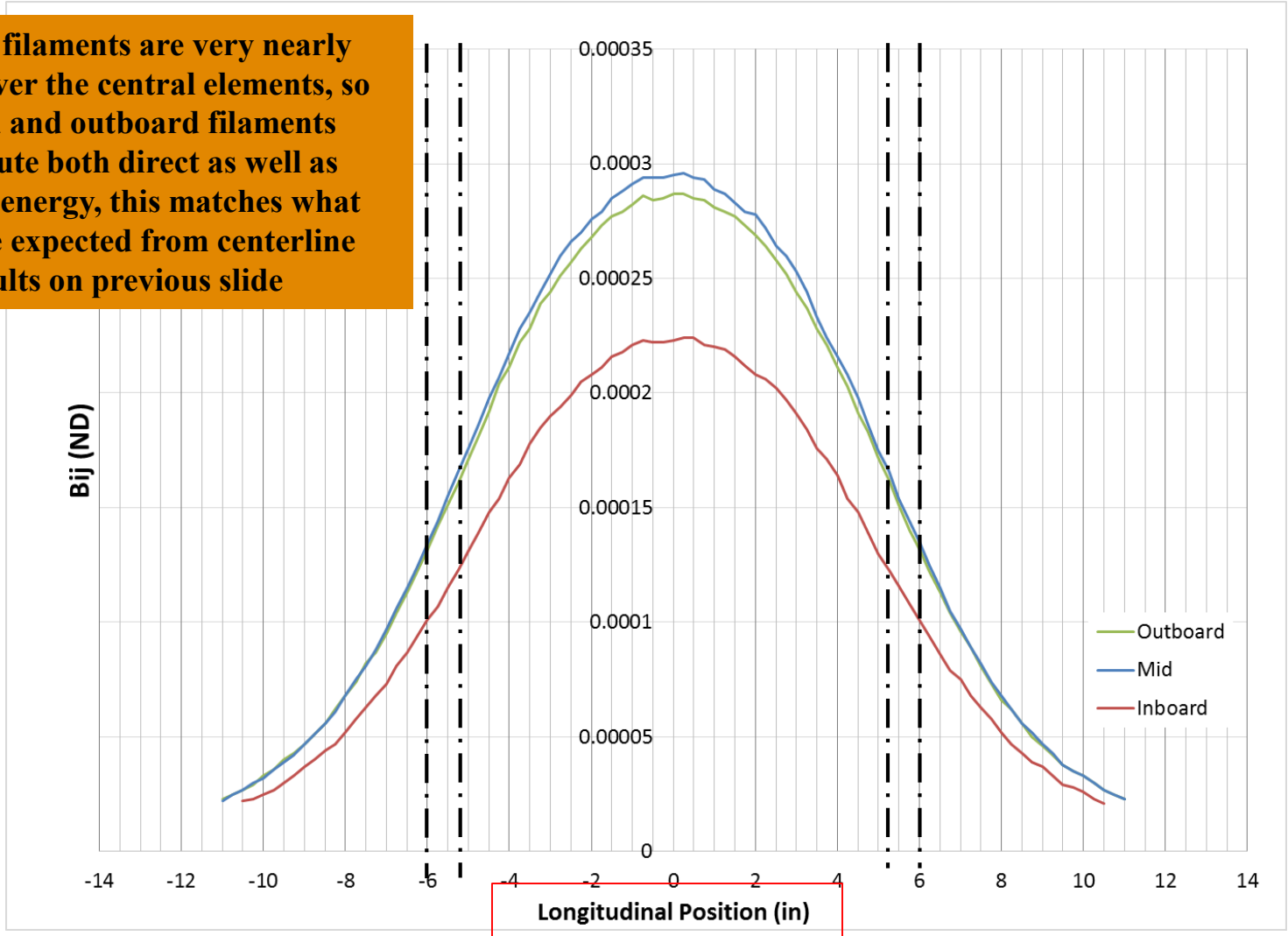

**Same trend & relationship for longitudinal distribution**

# One Filament at 3 Locations, Base, Flat Reflector

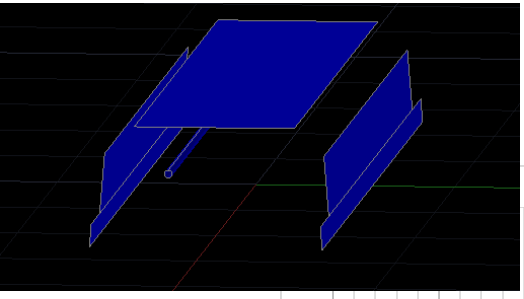


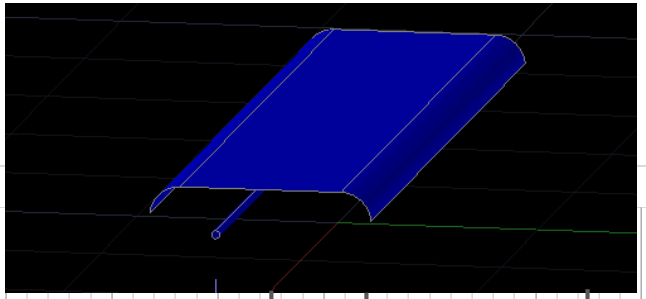
# 1 Filament @ 3 Locations, Base, Flat Reflector

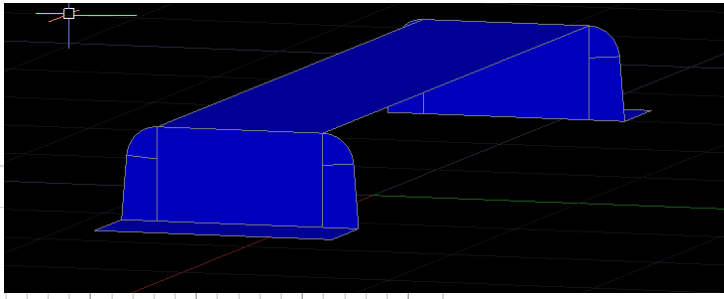
**Inboard filaments are very nearly directly over the central elements, so the mid and outboard filaments contribute both direct as well as reflected energy, this matches what would be expected from centerline results on previous slide**

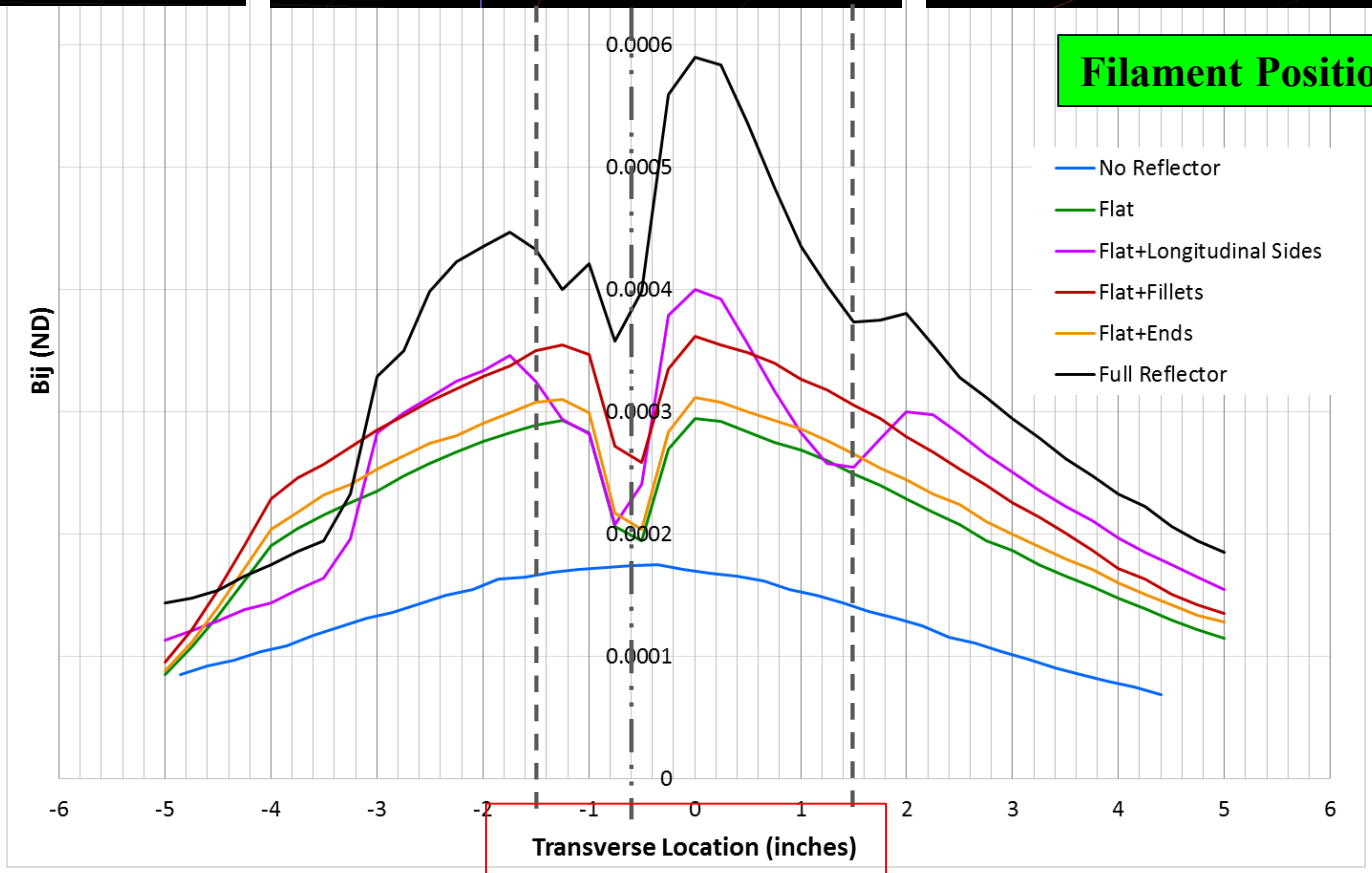


# One Filament, Base, Reflector Component Combinations

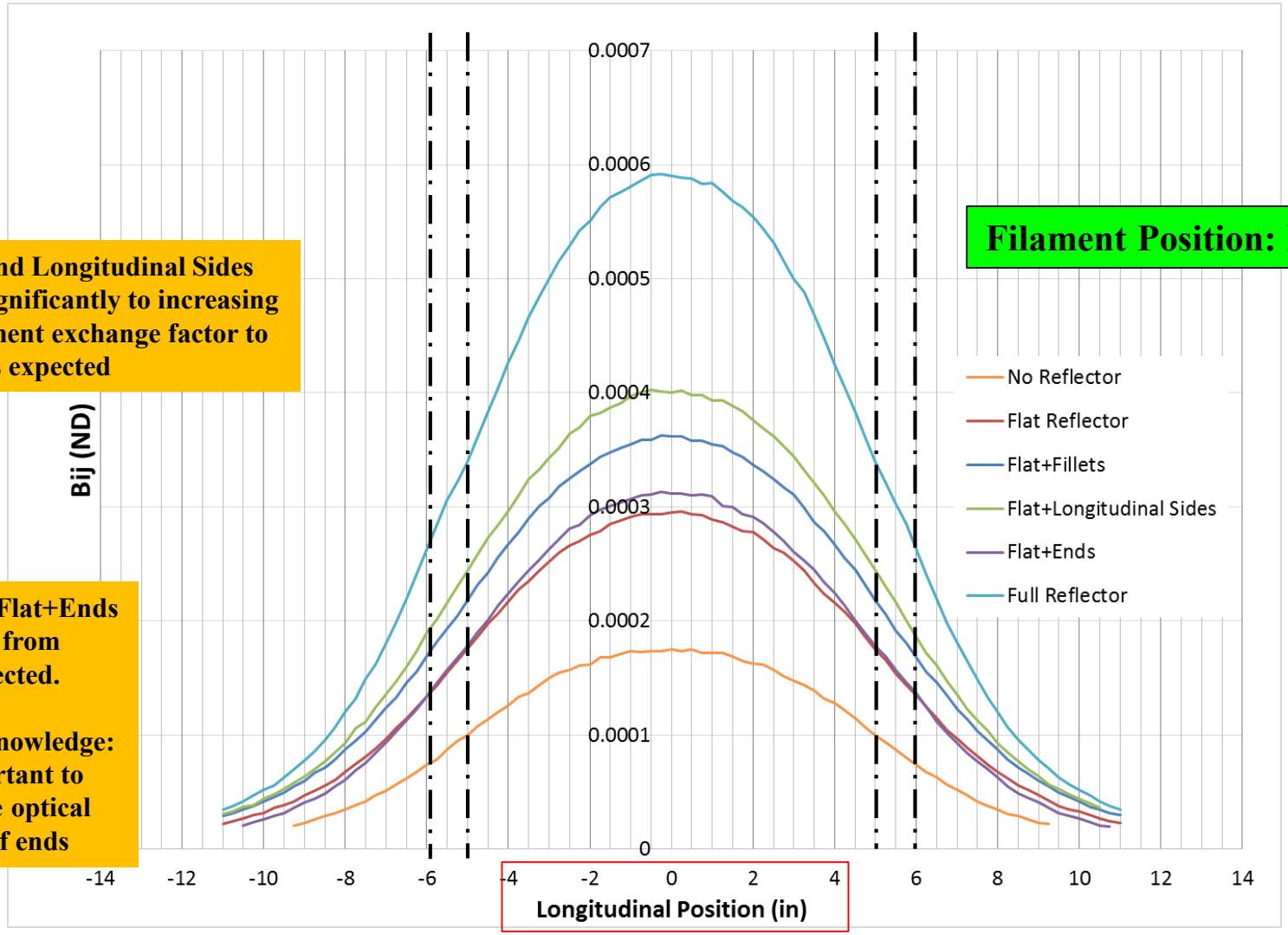






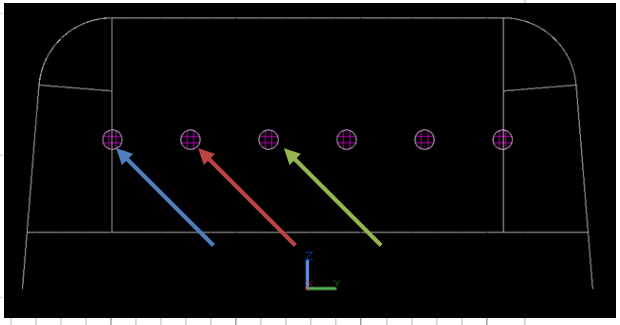


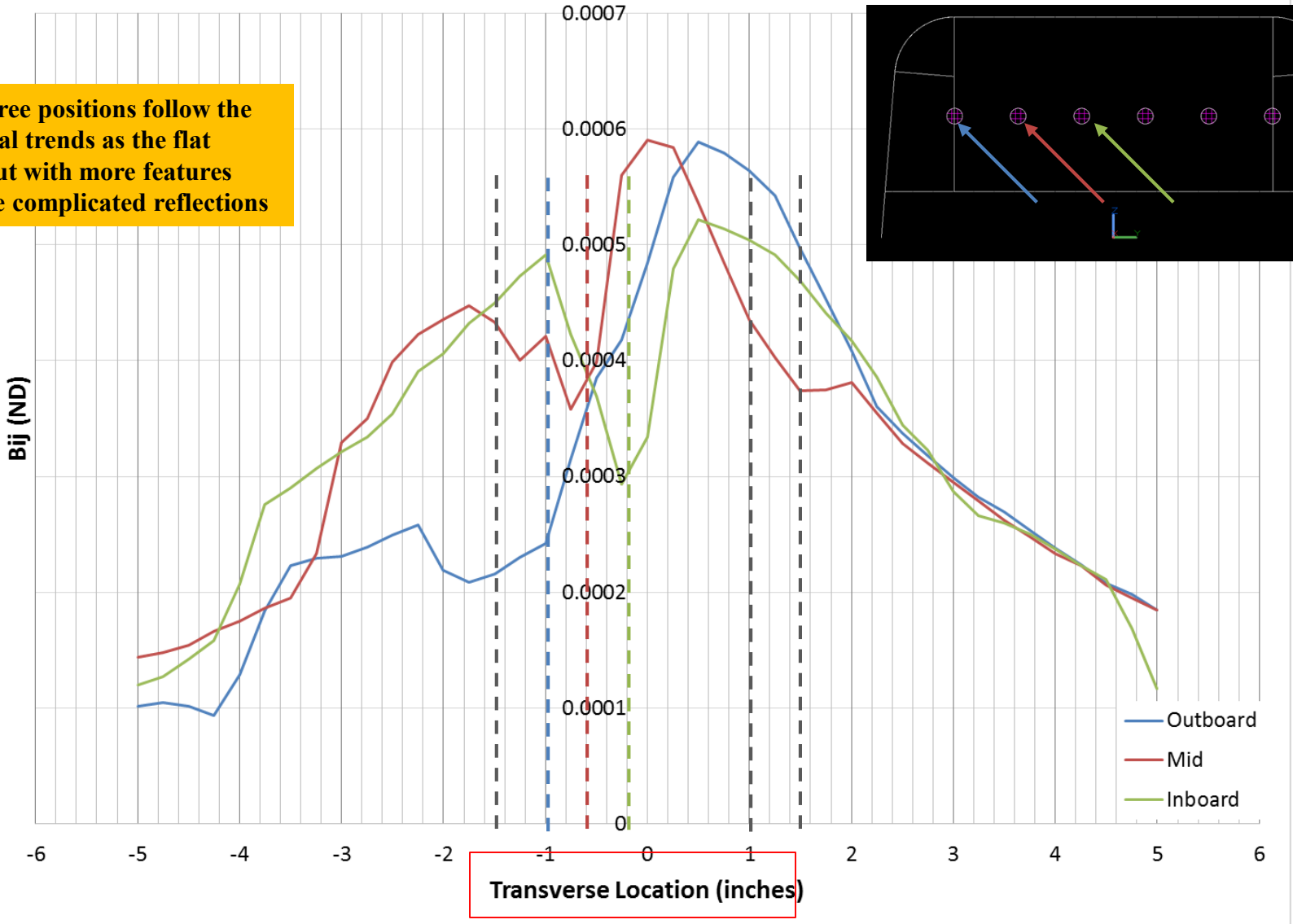
# 1 Filament, Base, Reflector Component Combinations



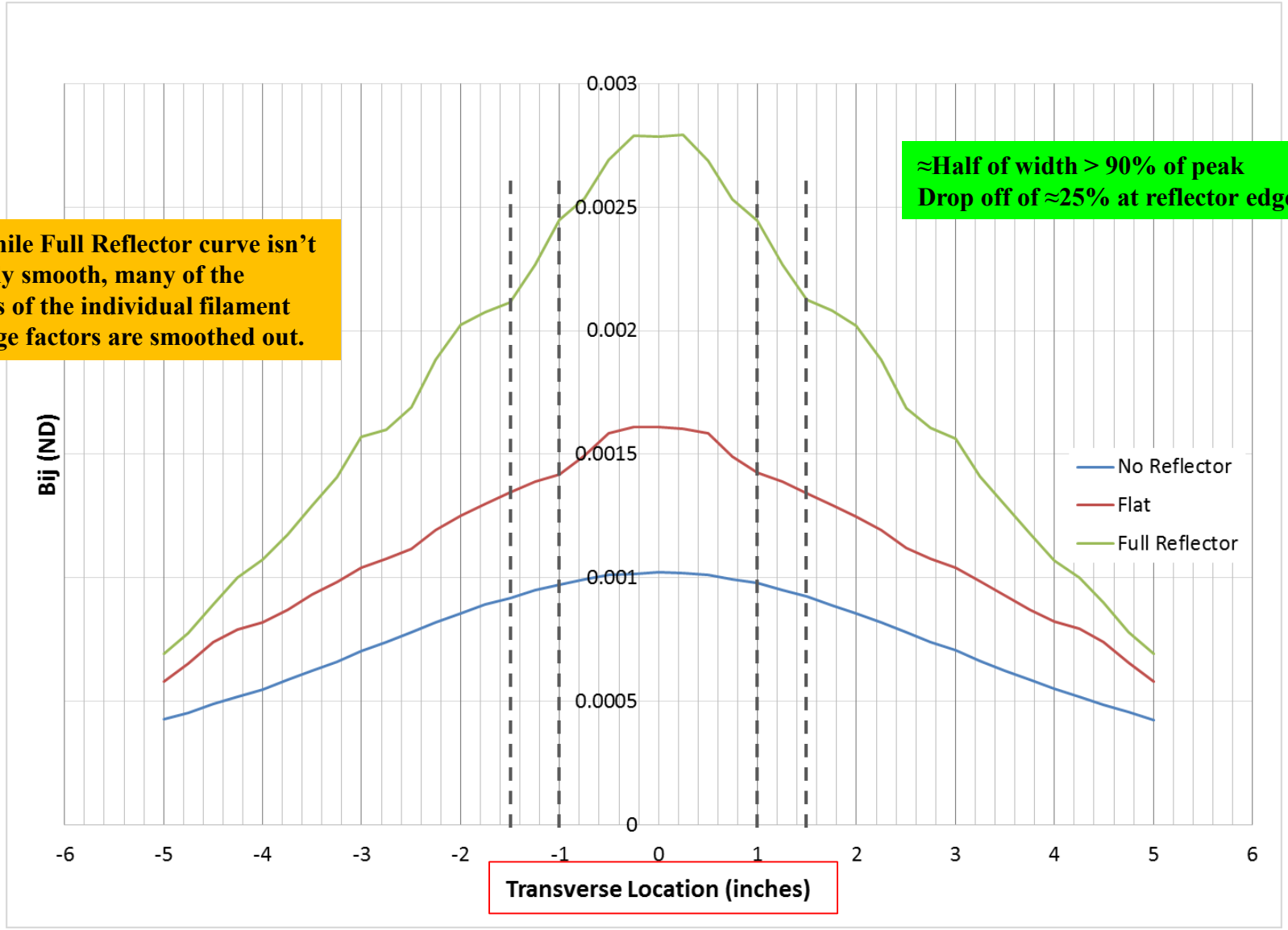
# 1 Filament @ 3 Locations, Base, Full Reflector

**NB: The three positions follow the same general trends as the flat reflector, but with more features due to more complicated reflections**





# 6 Filaments, Base, Flat & Full Reflectors

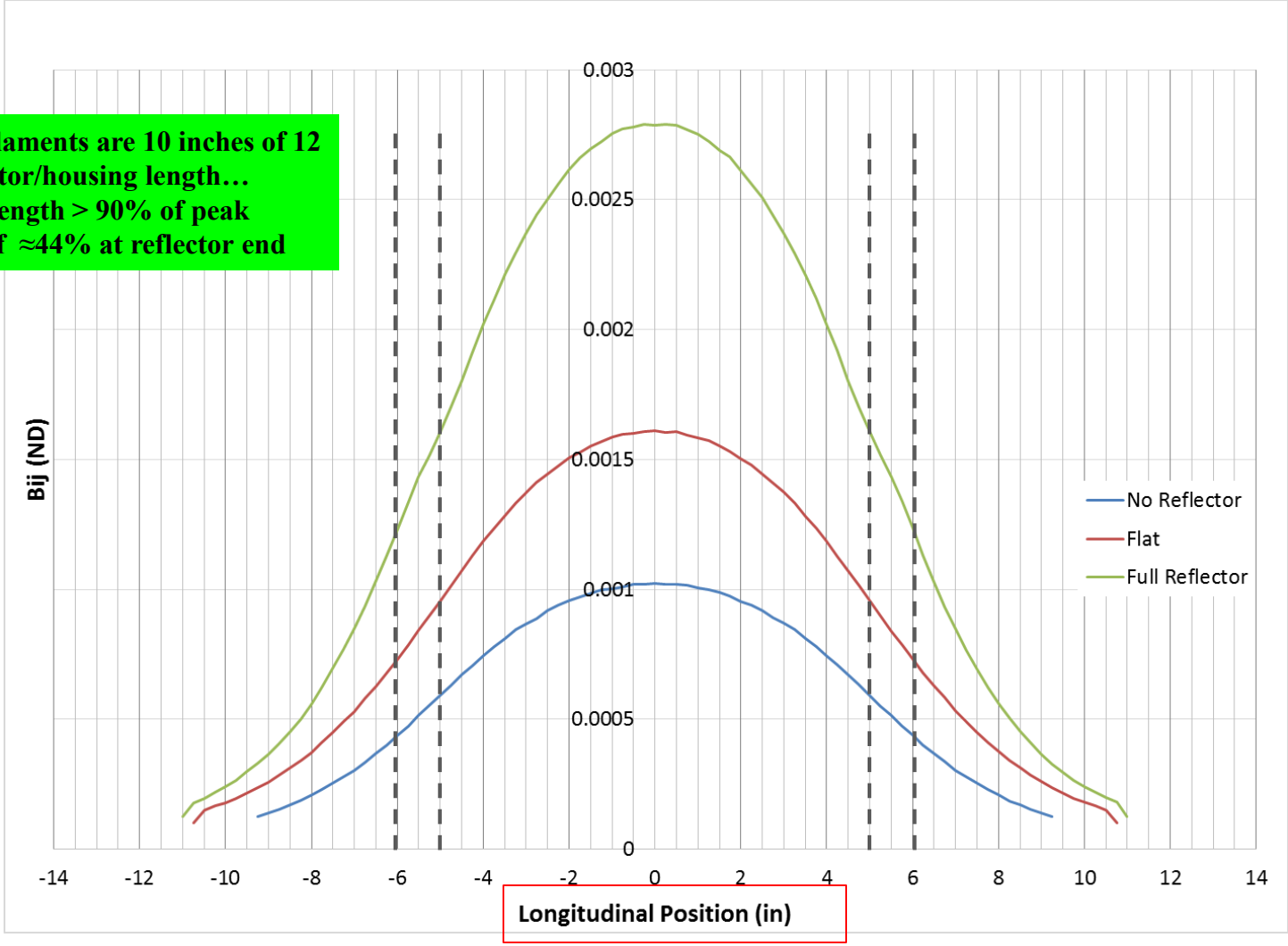



**NB: While Full Reflector curve isn't perfectly smooth, many of the features of the individual filament exchange factors are smoothed out.**

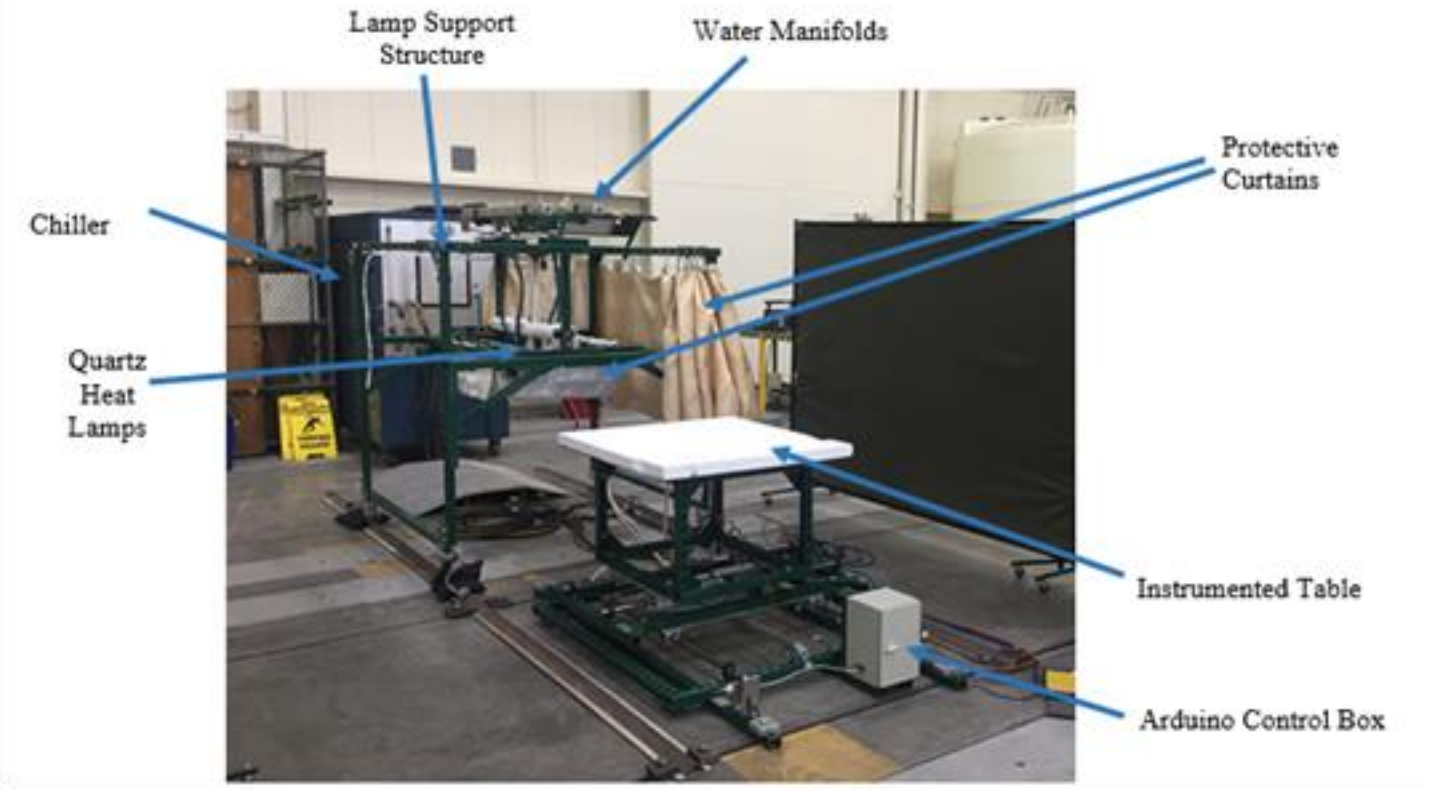
**≈Half of width > 90% of peak**
**Drop off of ≈25% at reflector edge**

# 6 Filament, Reflector Study

**Because filaments are 10 inches of 12 inch reflector/housing length…**
**≈ 42% of length > 90% of peak**
**Drop off of ≈44% at reflector end**



# Test Fixture




**Two linear actuators (upper in transverse direction, lower in longitudinal direction)**

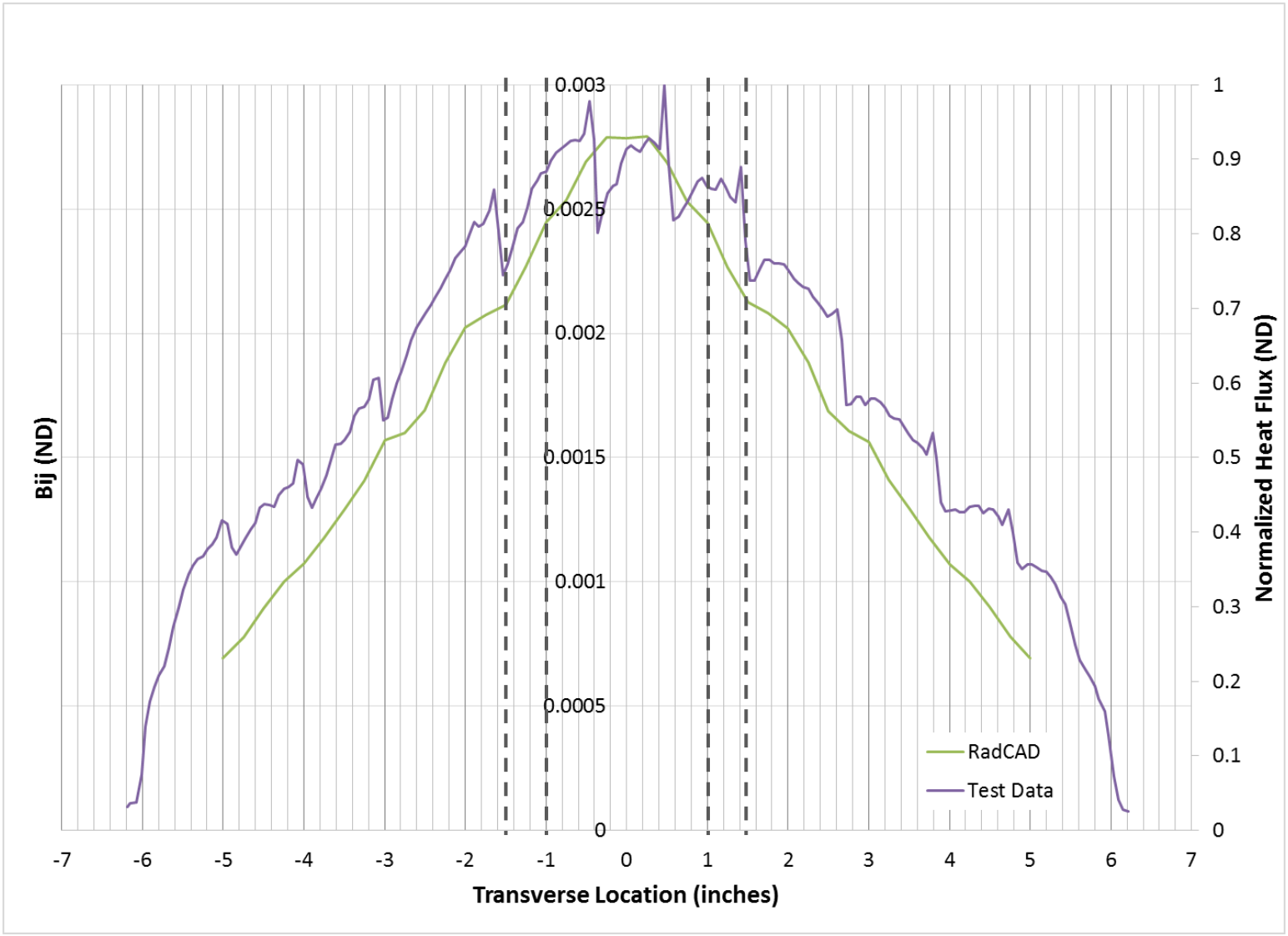
**String potentiometers for position control and recording**

**Water-cooled Vatelle heat flux gage**

**Air- and water-cooling lines with inlet and outlet TCs**

**Light sensor, voltage and current sensors for each lamp (characterization of lamp flashing)**

# Test Data Comparison



# Conclusions

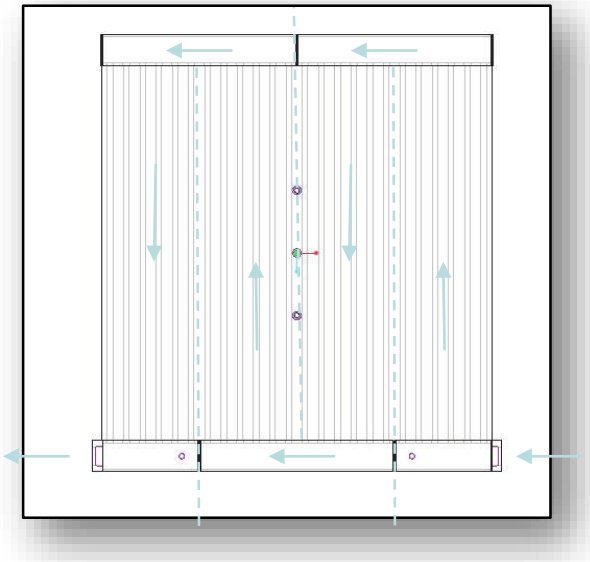
- RadCAD MCRT provided fast, easy method of obtaining heat flux distribution estimates via exchange factors
- Reflector with non-primitive geometry produces relatively complex heat flux distribution for each filament in transverse direction
- Summation of heat flux distributions from each filament results in relatively smooth transverse heat flux distribution
- Predicted drop-off in heat flux near lamp edges is much more significant in longitudinal direction (44%) than transverse (25%), as expected
- Elliptical footprint > 90% peak flux characterized by ≈50% of transverse direction, ≈42% of longitudinal direction

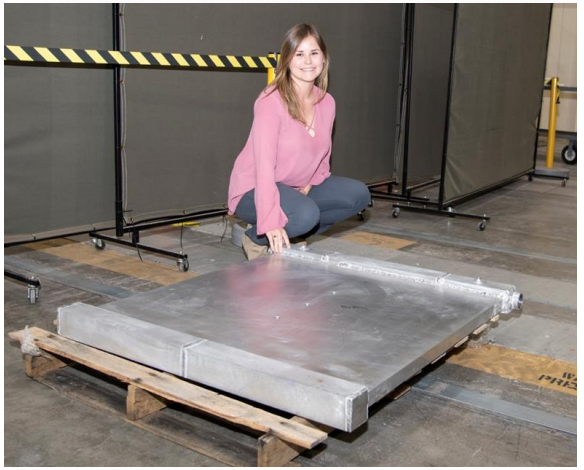
# Future Work

- Complete modeling studies (all test conditions)
  - Outboard and Inboard filament exchange with different reflector components
  - Fences (vertical offset, angled)
  - Multi-lamp configurations
  - Sensitivity studies (surface optical properties, spectral distribution of optical properties and lamp emission spectra)
- Obtain optical property measurements for fences, reflector
- Complete testing
  - Cold plate integration [next slides]
  - Single lamp fence studies
  - Multi-lamp configurations

# Components of the Cold Plate

- 3’ x 3’ x 1.5” 6061-T6 Aluminum
  - Weld-able, stock material
- 24, 0.5” diameter channels through plate
- Manifolds connecting to channel openings on either end of plate
  - Welded fittings to connect supply and return hoses, instrumentation
- Drilled and tapped central holes for heat flux gauge installation
- Wattage capacity: ≈80 W/cm$^2$
- Current and envisioned operating levels:
  - Current: 20 W/cm$^2$
  - Envisioned: up to 80 W/cm$^2$
- Fabricated by Megan Waller (spring 2018 intern)

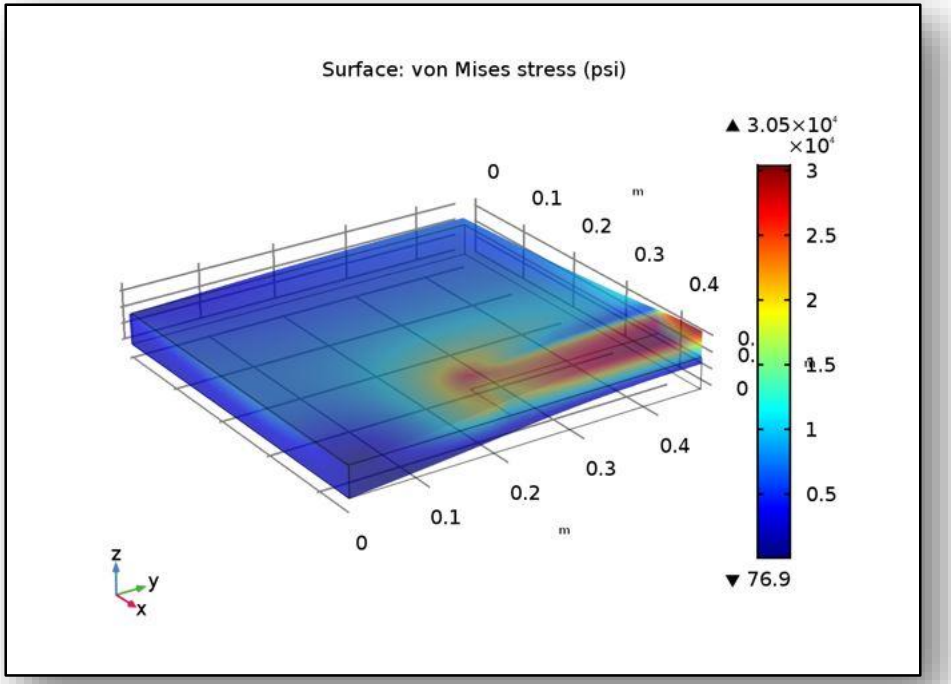


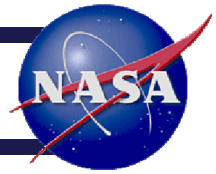


**Fabricated, pre-painting, no instrumentation**

# Thermal Stress Analysis

- Modeled thermal and mechanical loads
  - Gus Kendrick (Intern, Summer 2017)
  - 24 channels, 0.5-in diameter
  - Pressure drop, flowrate, temperature, and stresses were considered
- Applied heat flux of 80 W/cm$^2$
  - Vertical displacement (warping): 0.131 in
  - Max stress (von Mises): 30446 psi
  - Max Temperature: 474.26 Kelvin

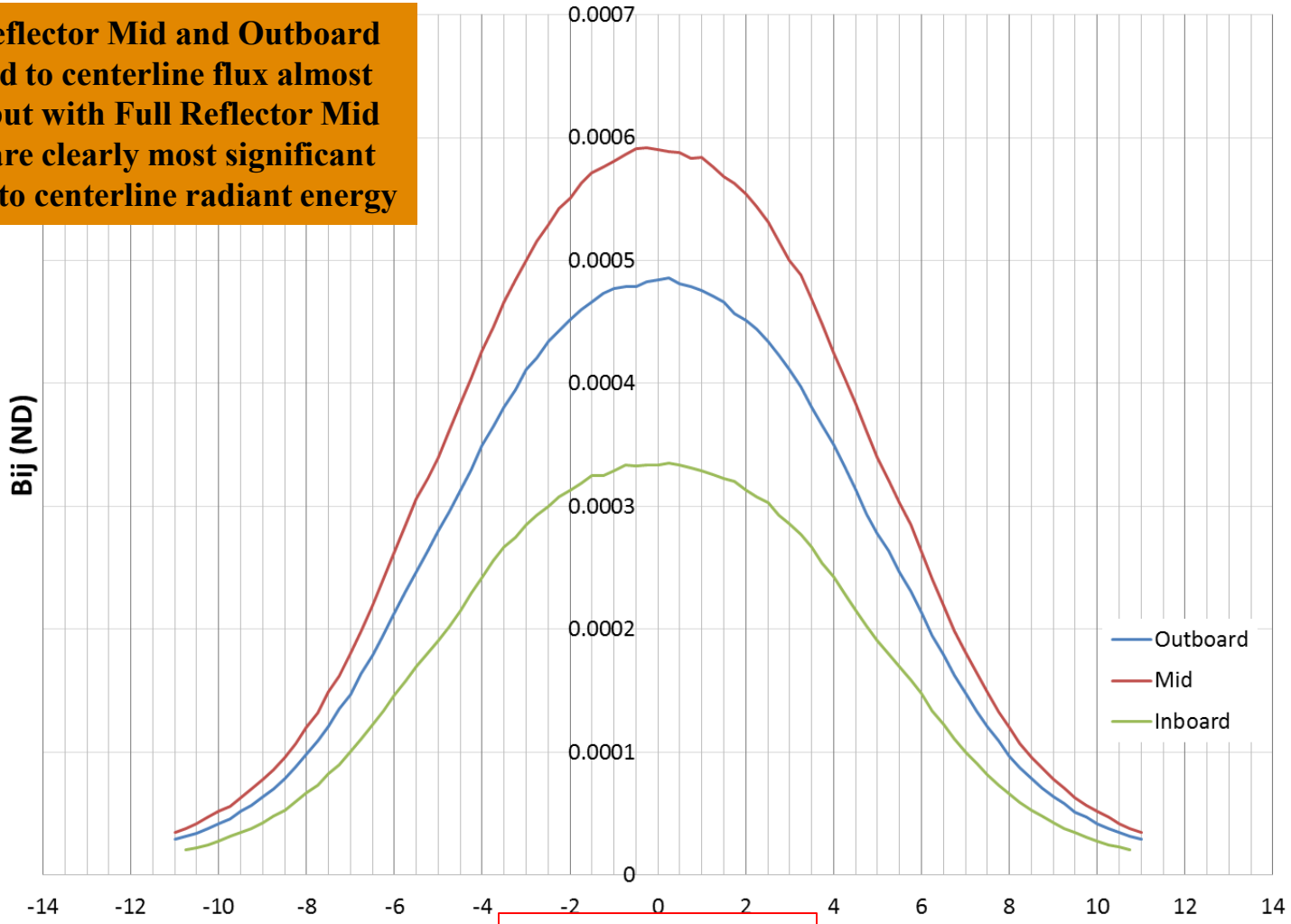





# Questions

# 1 Filament @ 3 Locations, Base, Full Reflector

**For Flat Reflector Mid and Outboard contributed to centerline flux almost the same, but with Full Reflector Mid filaments are clearly most significant contributor to centerline radiant energy**



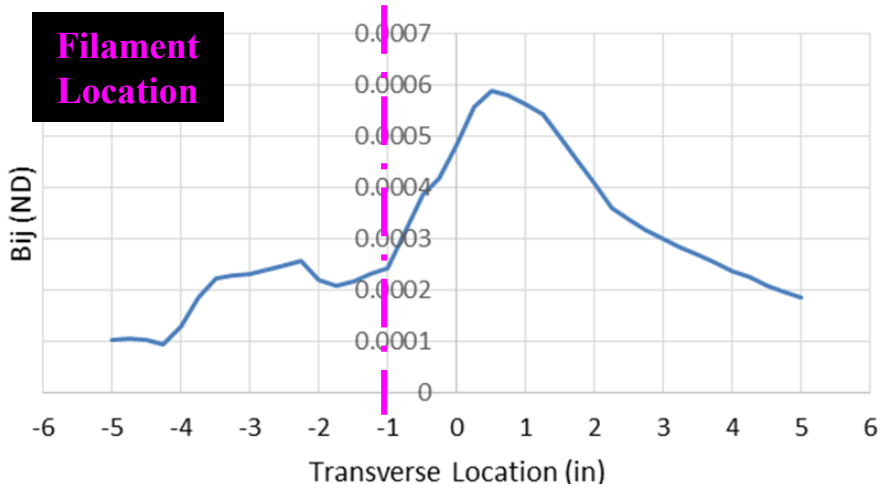
# Analytical Studies Completed To Date

- Mesh & # rays study to evaluate model sufficiency
- One or six filaments, base, no reflector
- One filament at 3 locations, base, flat back of reflector
- One filament at 3 locations, base, full reflector
- One filament, base, reflector component combinations (flat back & [longitudinal sides/fillets/ends])
- Six filaments, base, flat back of reflector and full reflector

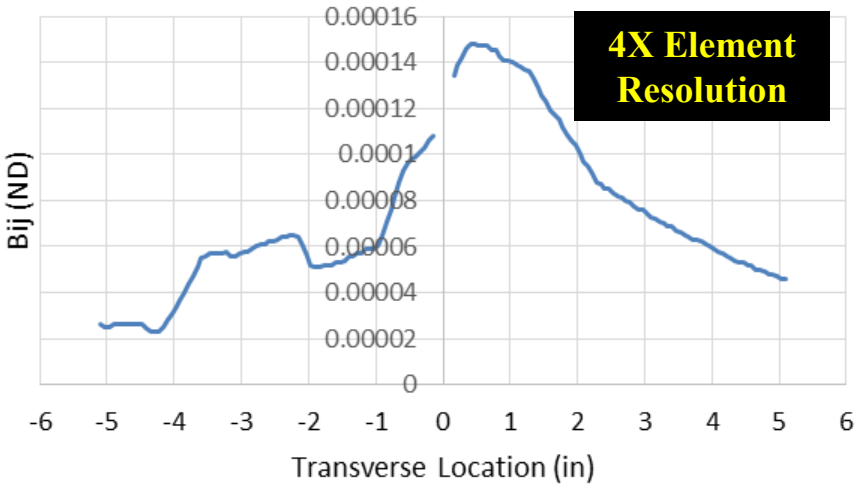
# Verification of Mesh & Rays/Node

**Mesh changed from initial ¼ inch width to 1/16th inch width, Rays/Node increased from 5M to 30M, negligible difference in transverse heat flux distribution**

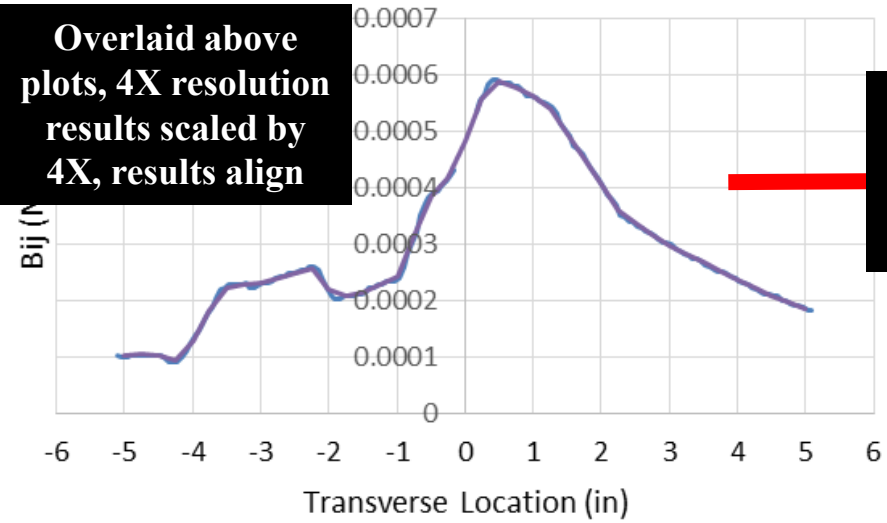
**Filament Location**



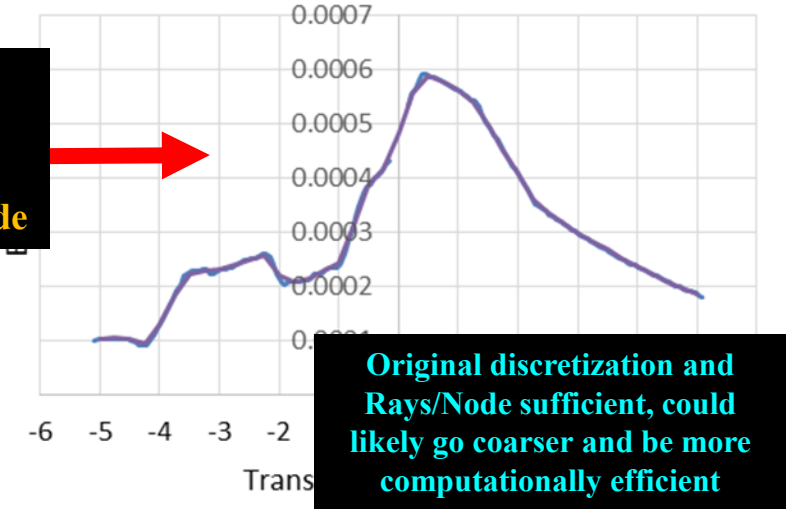

**4X Element Resolution**



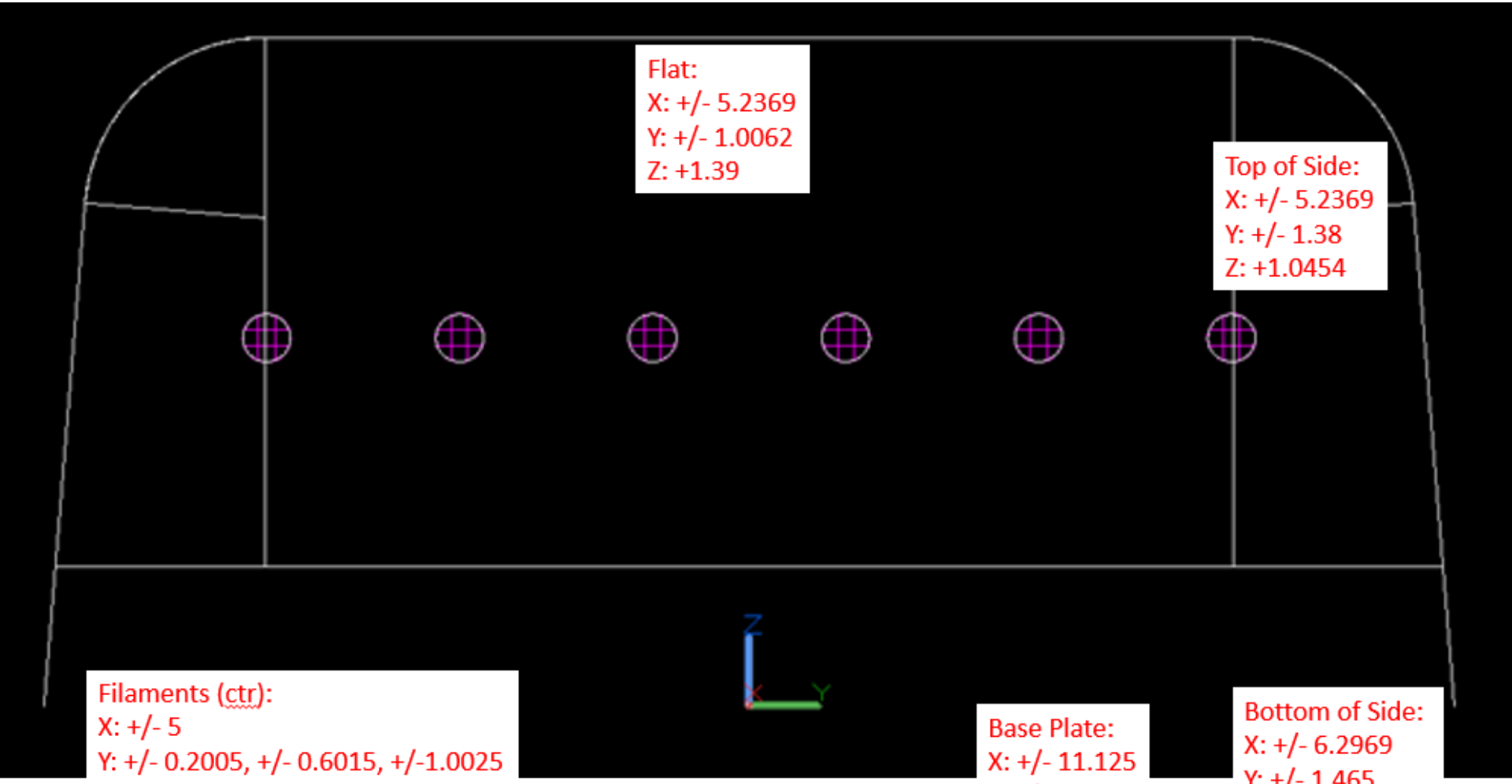

**Overlaid above plots, 4X resolution results scaled by 4X, results align**



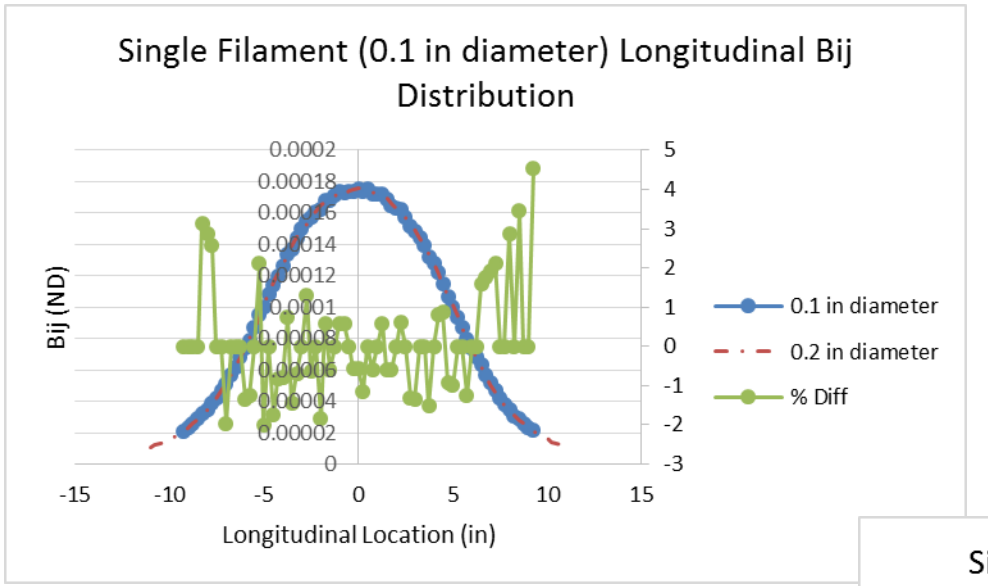

**Added 25M rays/node, appended to existing 5M/node**




**Original discretization and Rays/Node sufficient, could likely go coarser and be more computationally efficient**


Flat:
X: +/- 5.2369
Y: +/- 1.0062
Z: +1.39
Top of Side:
X: +/- 5.2369
Y: +/- 1.38
Z: +1.0454
Z
Y
Filaments (ctr):
X: +/- 5
Y: +/- 0.2005, +/- 0.6015, +/-1.0025
Z: +0.765
0.1 inch diameter
Base Plate:
X: +/- 11.125
Y: +/- 5.125
Z: -4
Bottom of Side:
X: +/- 6.2969
Y: +/- 1.465
Z: 0.0

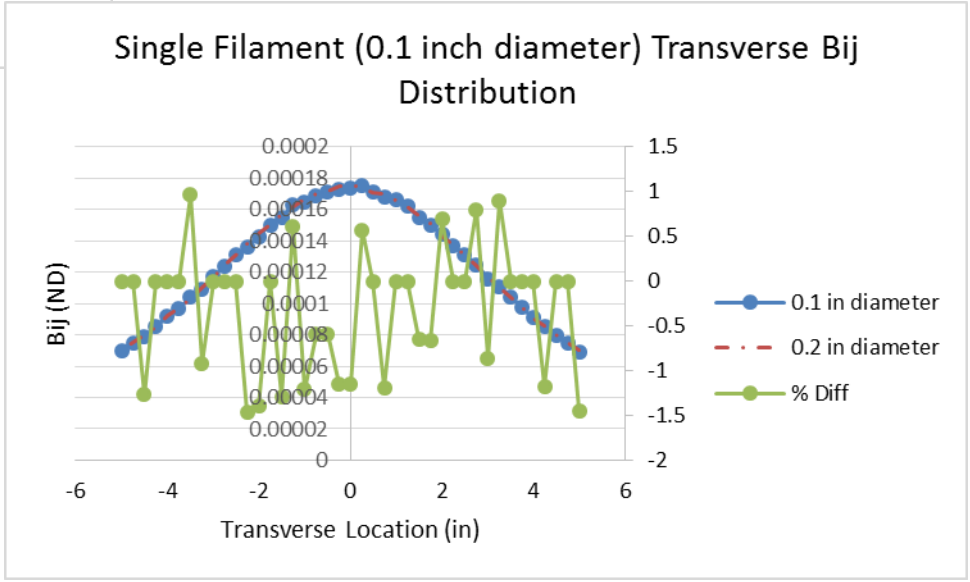
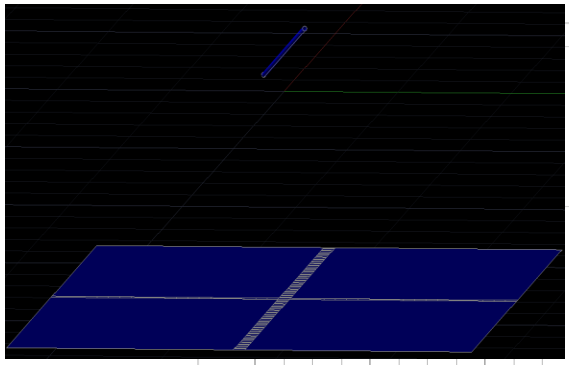
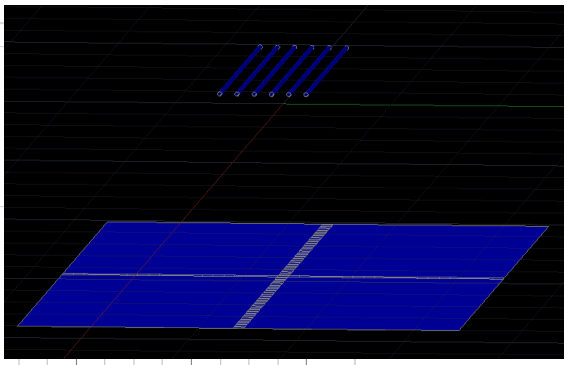
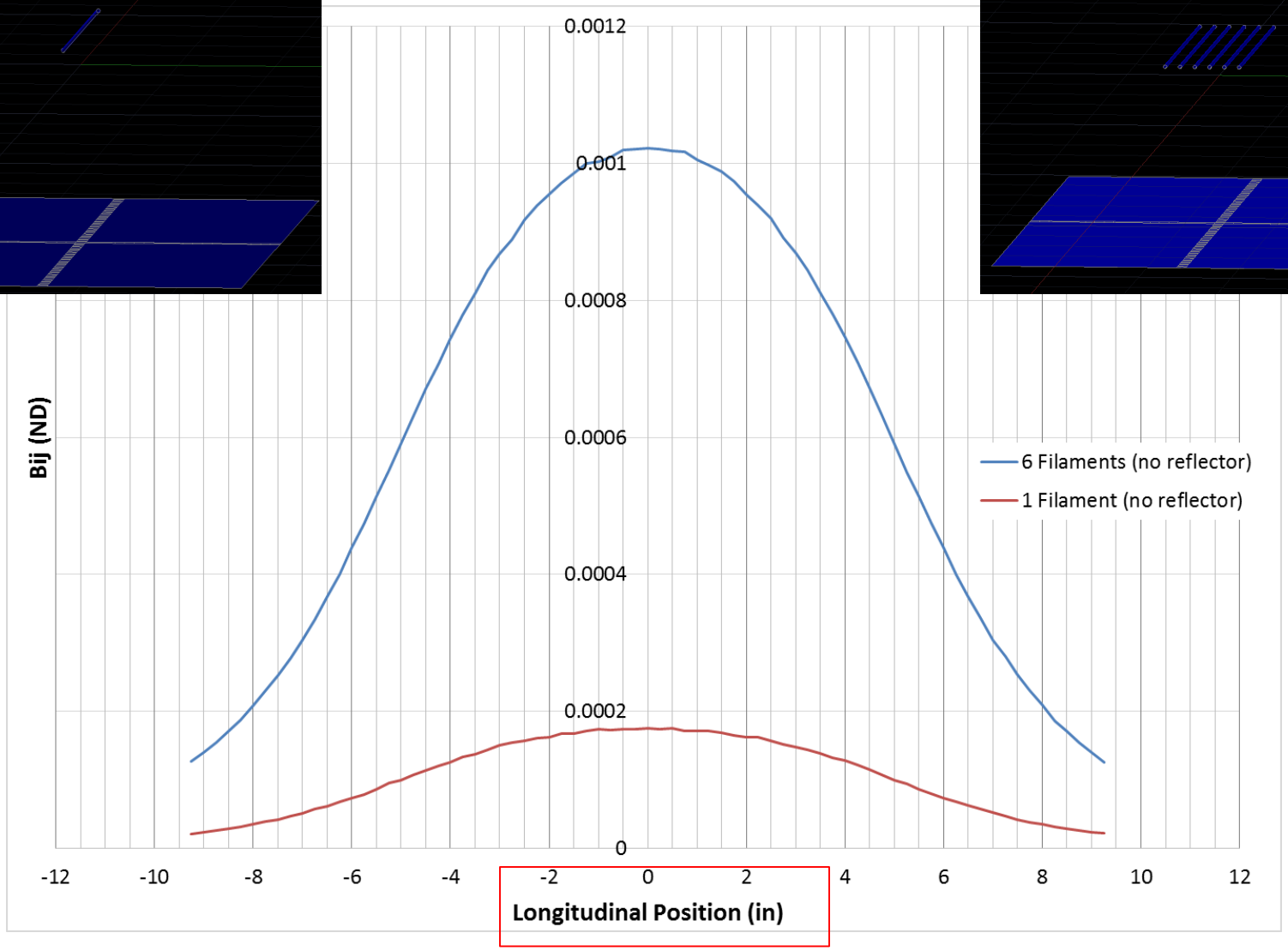
# Evaluation of Filament Diameter Sensitivity




**% error is 2nd axis in each plot**

**Transverse stays within +1/-1.5%**

**Longitudinal is within +5/-2.5%, but exchange factor is much smaller**



# [1/6] Filaments, Base, No Reflector