The Effect of Roll Angle on the Performance of Halbach Arrays

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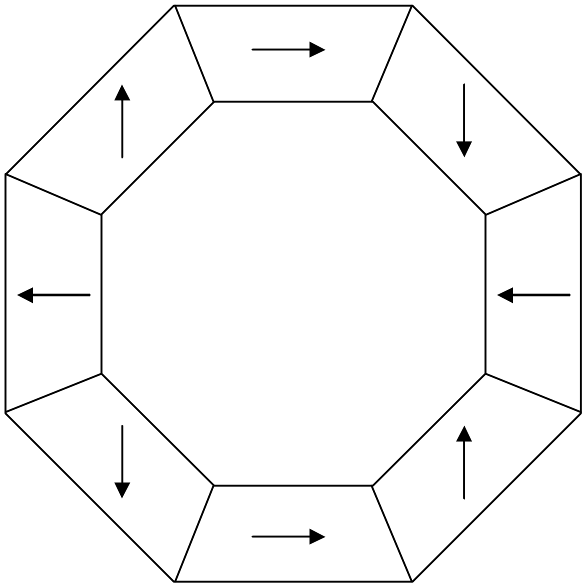
Overview

- Historical
- Theoretical Modeling
- Experimental Testing
- Conclusion

History of Halbach Arrays

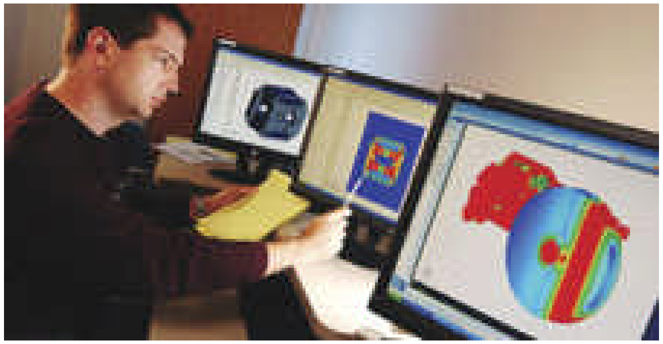
- Concept first described as a “curiosity” by Mallinson in 1973
- First applied to permanent magnets systems by Halbach in 1983



Halbach’s Helical Undulator

Applications of Halbach Arrays

- One-sided flux is useful in a lot of applications
  - Data security
  - Transportation
  - Motor design
- Halbach Arrays are inherently weight-efficient
- Arrays provide higher fluxes than monolothic magnets of the same size



Media Degaussing

QuickTime™ and a decompressor are needed to see this picture.

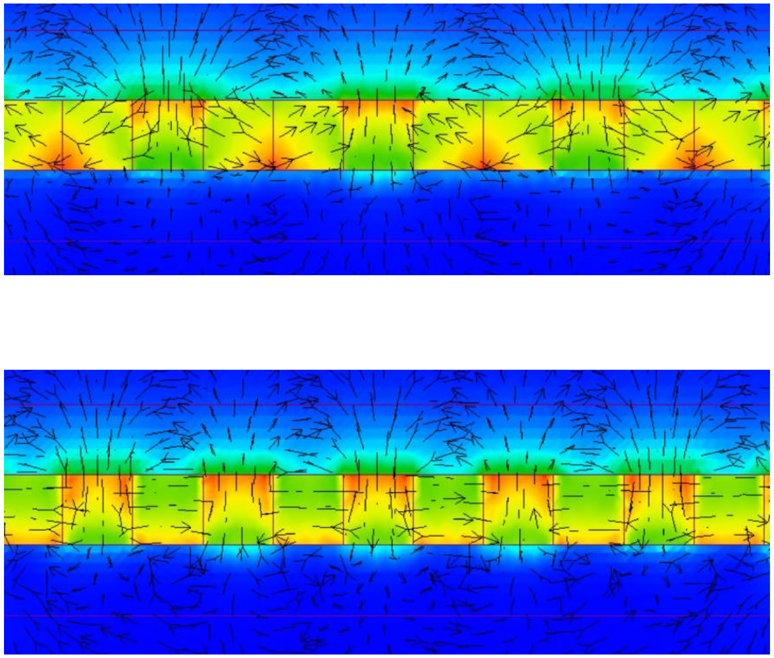
Eddy Current Braking

Optimizing Arrays

- While almost all applications require strong fields, the optimal field morphology is dependent on the intended purpose of the array
  - Degaussers prefer “knife” fields - maximum |B| at any cost
  - Braking systems should maximize dB/dx
  - Flyable systems prefer minimal stray field
  - Wigglers require high spatial frequency

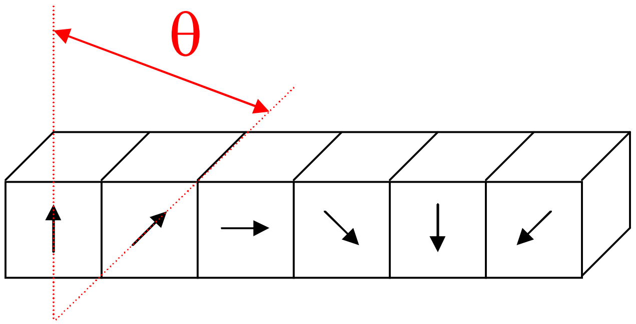
Array Variables

- Halbach Array design involves the intersection of many variables
  - Magnet size/shape
  - Magnet material
  - Array radius
  - Number of members in the array
  - Roll angle

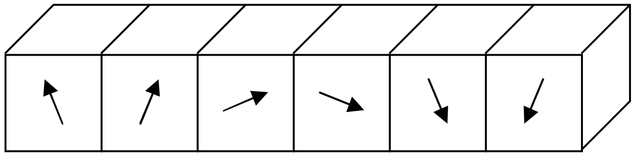


Roll Angle

- Roll Angle describes the difference in orientation between consecutive north poles of an array.
- A 0º roll angle corresponds to a single block of material
- Different arrays with a common roll angle can still be “offset” from each other to produce different properties.



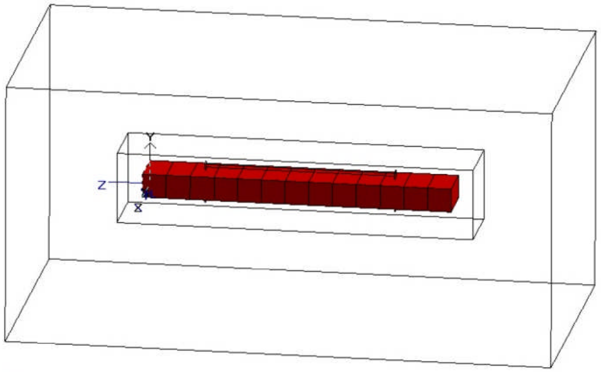
Common Array with
45 degree roll angle
“Orthogonal”



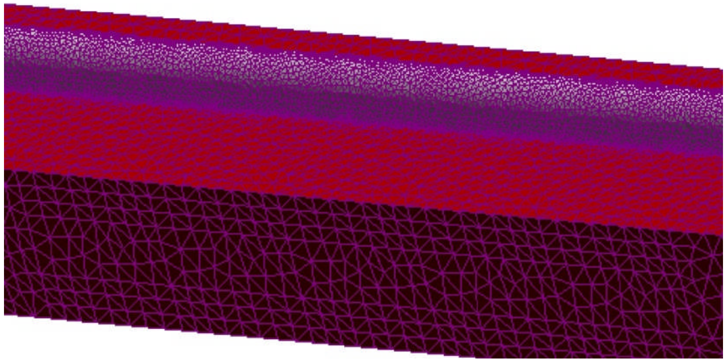
Offset Array with
45 degree roll angle
“Inline”

Finite Element Modeling

- 13-member Halbach array - each unit 0.5´´x 0.5´´x 1´´
- Materials: N4467 and S3069
- Mesh refinement regions
  - Maximum element size within magnet is 0.070´´
  - Secondary refinement region centered at 0.100´´ from surface - max element size is 0.025´´
  - Four mesh layers spaced 0.050´´ from surface of magnets
- Roll Angle:
  - 0, 10, 15, 30, 45, 60, 90 ,120
  - Orthogonal and Inline



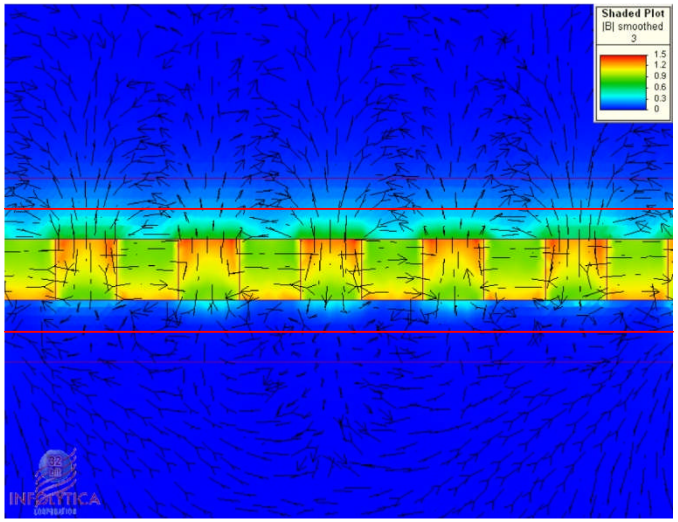
Overall Model Geometry



Mesh refinement

Model Data Analysis

- Finite element code returns three dimension vector matrix of data
- Data must be reduced to understandable parameters
- Field is “probed” at 0.100´´ from active and passive surfaces
- Field data digested into three parameters



Centerline slice of 90º Orthogonal array, showing vector B field and data sampling lines

Data Parameters

- Average Field: “Output”

$$P = \overline{\left|\vec{B}\right|}$$

- Power Ratio: “Efficiency”

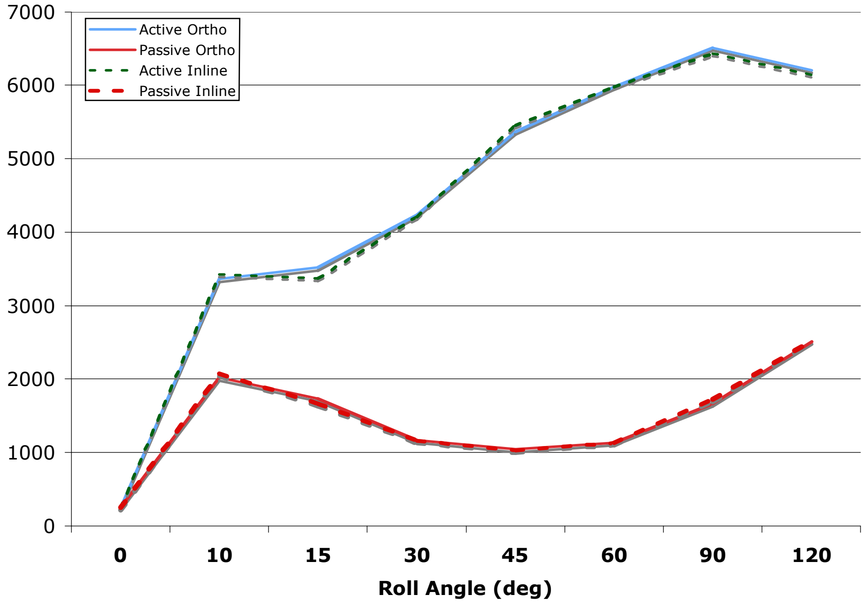
$$P_r = \frac{P_{active}}{P_{passive}}$$

- Evenness Parameter: “Regularity”

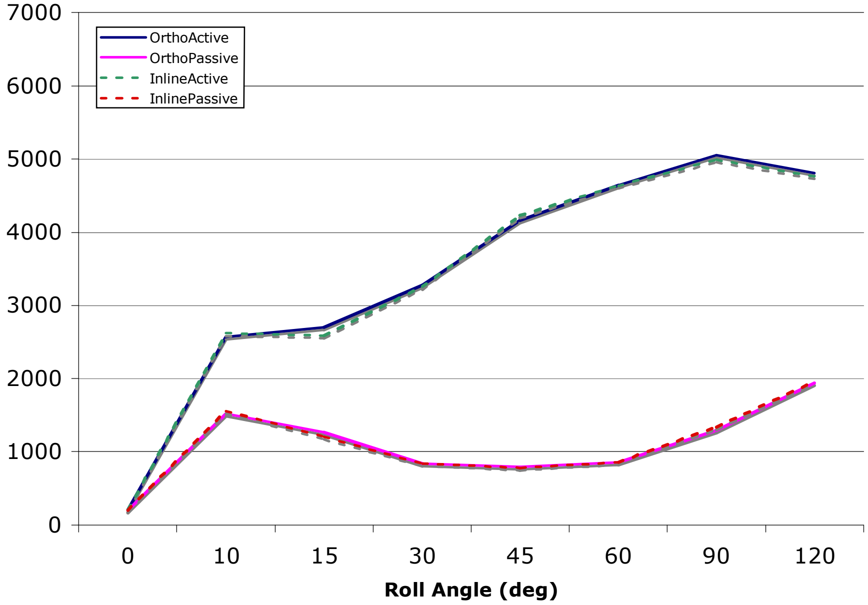
$$E = \frac{1}{\sigma\left(\left|\vec{B}(x)\right|\right)}$$

Average Field Plots

- Same Overall performance between materials
- Better isolation in SmCo, Higher field in NdFeB



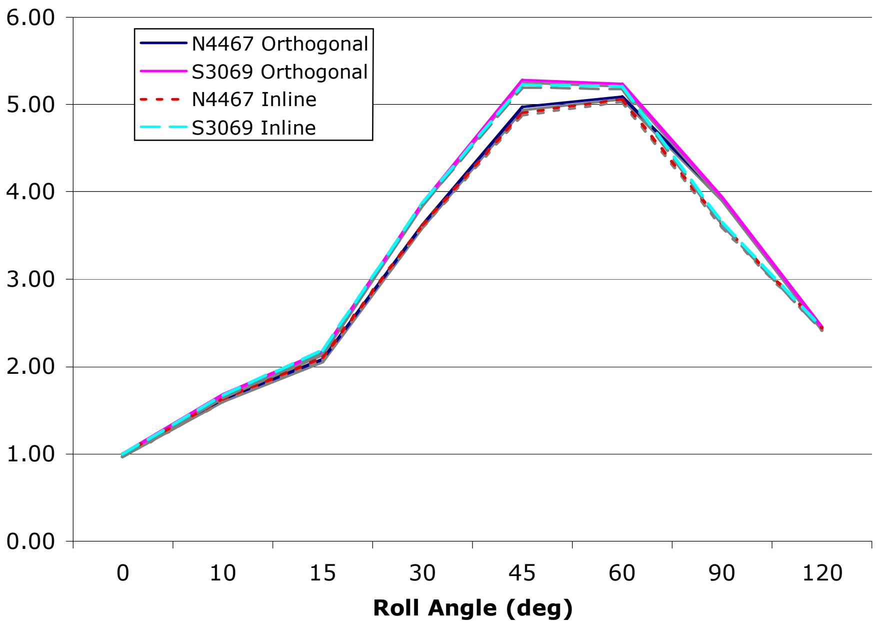
N4467 arrays



S3069 arrays

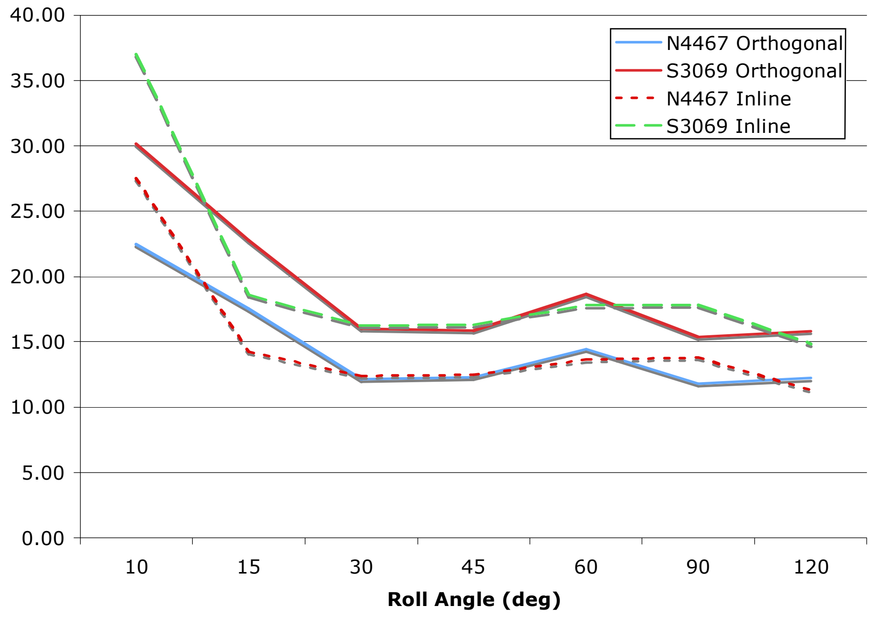
Power Ratio Plot

- Better Power Ratio in S3069 due to higher coercivity.
- Little difference between orthogonal and inline arrays
- Best power ratios at 60º roll angles in N4467. Comparable values in 45º for S3069.



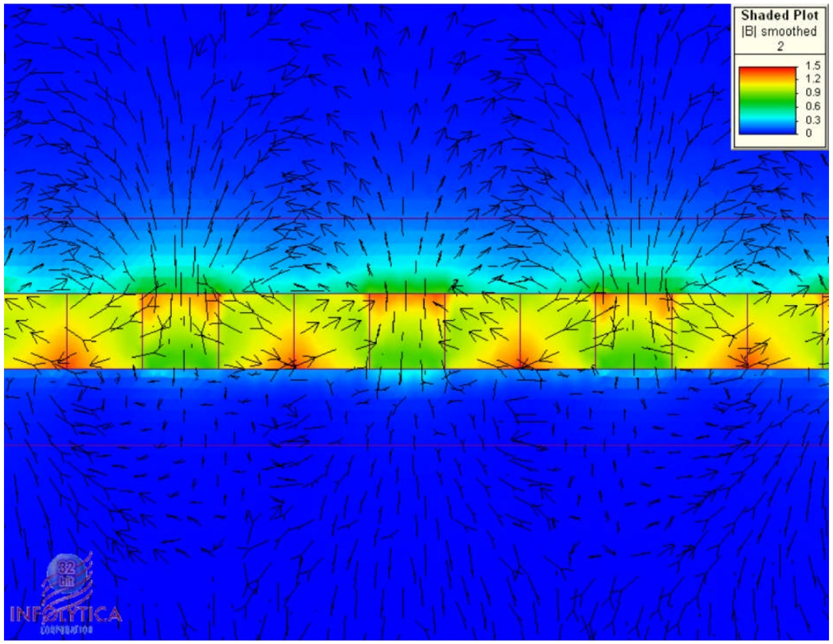
Evenness Parameter Plot

- S3069 has higher evenness than N4467
- The inline configuration has a local maximum at higher roll angles

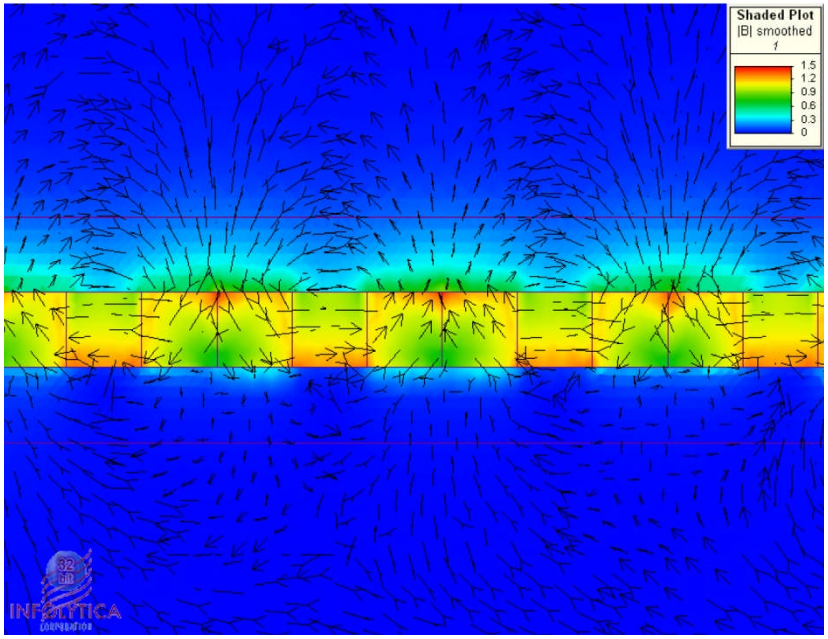


Orthogonal vs. Inline

- 2D Vector plots help account for difference
- Orthogonal array has narrower, taller poles



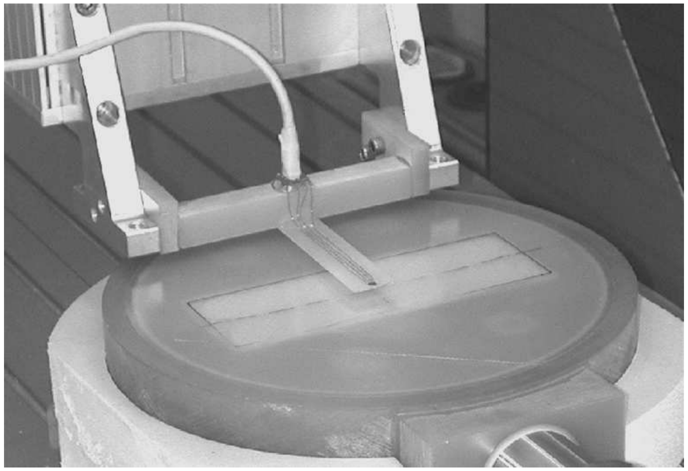
60º Orthogonal



60º Inline

Experimental Validation

- Three models were selected for validation
  - 90 Orthogonal
  - 60 Orthogonal
  - 60 Inline
- Arrays were constructed and probed to compare to modeled field



3-axis Hall probe

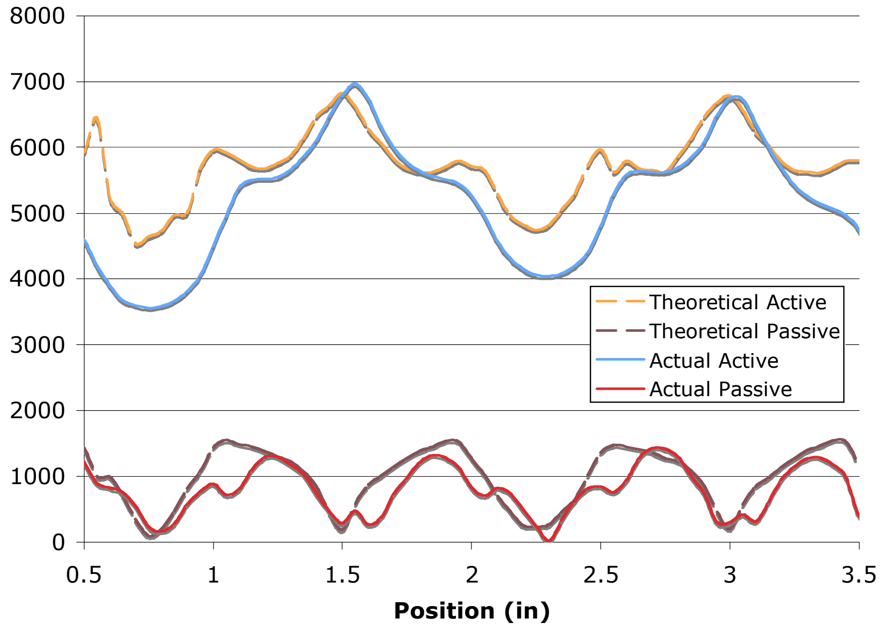
Measurement Setup and Error

- F.W. Bell three-axis Gauss probe and meter
  - The three Hall Effect sensors in the probe are displaced from each other
  - Probe centroid is taken as measurement location.
  - X and Y data points are offset to compensate for position, Z probe is ignored (B_z ~100x smaller than B_x and B_y components)
- Computer-controlled XYZ stage
- Data was sampled every 0.050´´
- Thickness of the probe puts the measurement centroid at 0.122´´ from the magnet surface

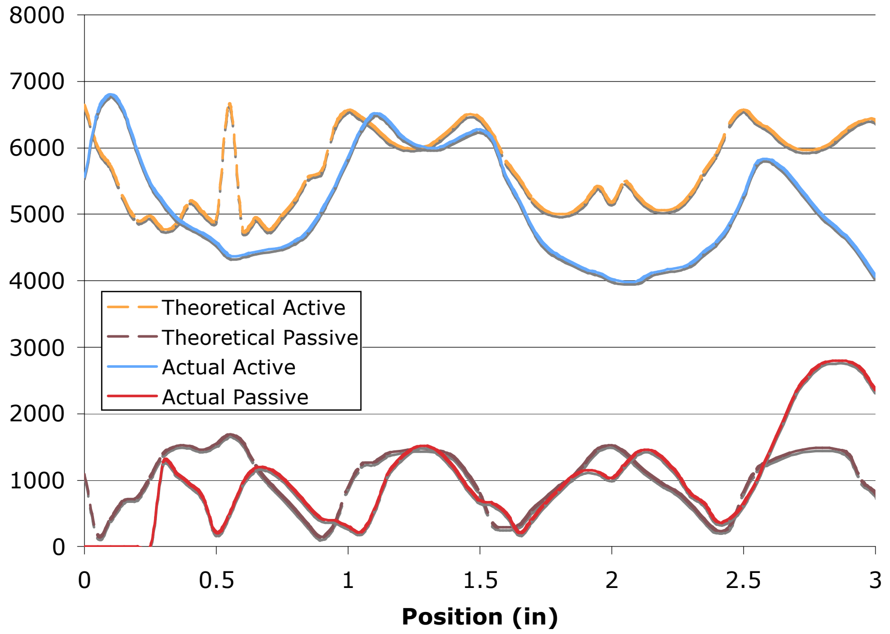
Measurement/Model Comparison

- Strong Agreement in peak magnitude and shape
- Some divergence in the troughs

60º Inline

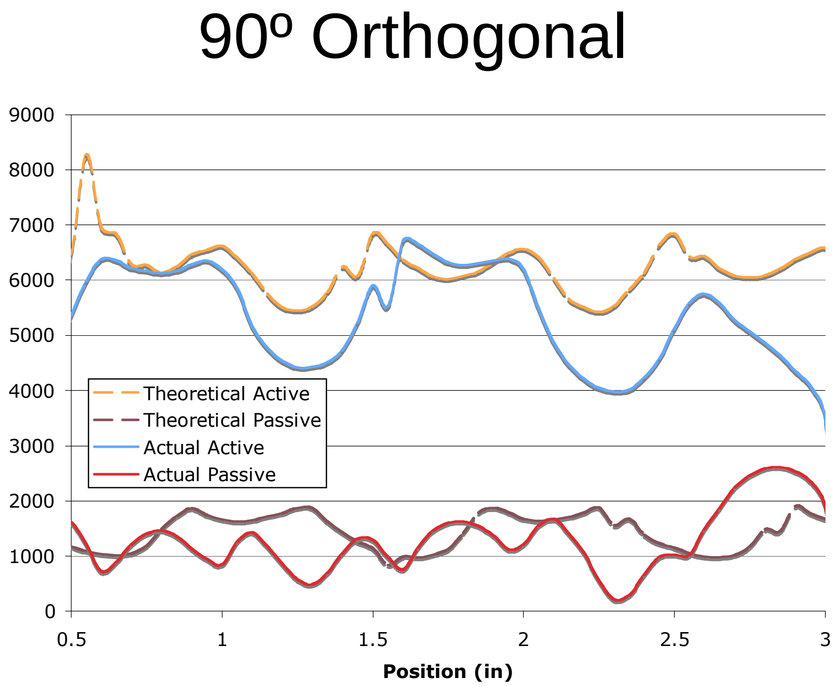


60º Orthogonal



Measurement/Model Comparison

- Good active side agreement
- Passive side shows a different spatial frequency than modeled
- Difference can be attributed to demagnetization effects in the material



90º Orthogonal

Conclusions

- 3D magnetostatic modeling can accurately predict the performance of Halbach arrays
- Introducing small amounts of roll angle will have a large effect
- Halbach arrays outperform monolithic magnets
- Varying roll angle will allow for array property customization
- Adding roll angle offsets will change field morphology without changing flux density
- Real materials will show some divergence away from active side peaks