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Modeling and Analysis of Aberrations in Electron Beam Melting(EBM) Systems

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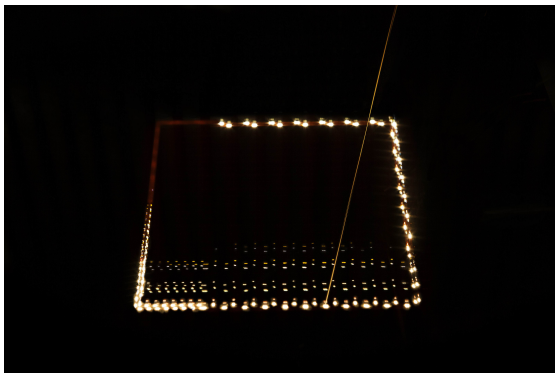
- Arcam AB makes devices for melting metal powder layer by layer
- Electron beam melting
- Used for cost efficient manufacture of orthopedic implants and light aerospace components

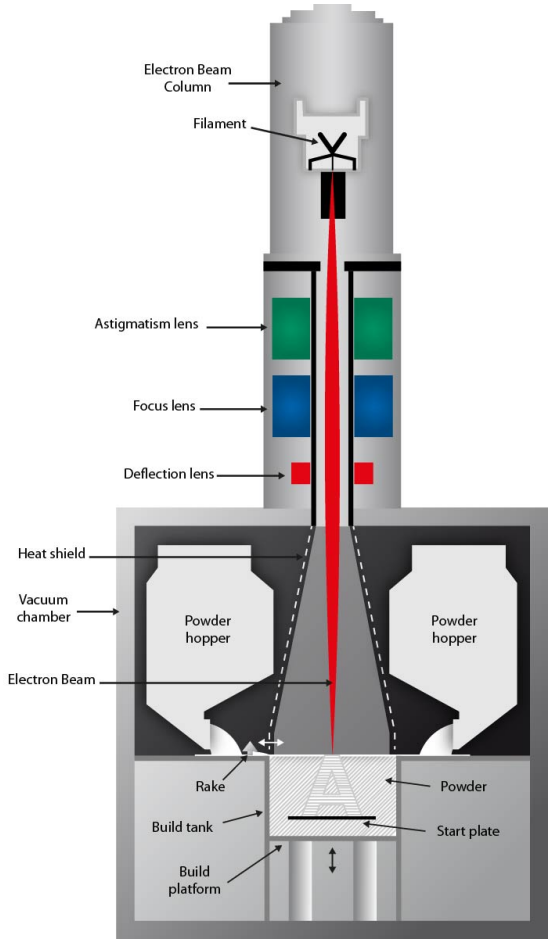


Outline

- Electron Beam Melting
- Electron Optics
- Modeling Framework
- Data Analysis
- Conclusions

EBM Characteristics

- LaB_6 Cathode
- 60 kV acceleration voltage $\sim$ half the speed of light
- $\sim$ 10-100 mA currents: space charge matters
- Divergent beam
- Very large deflection angles

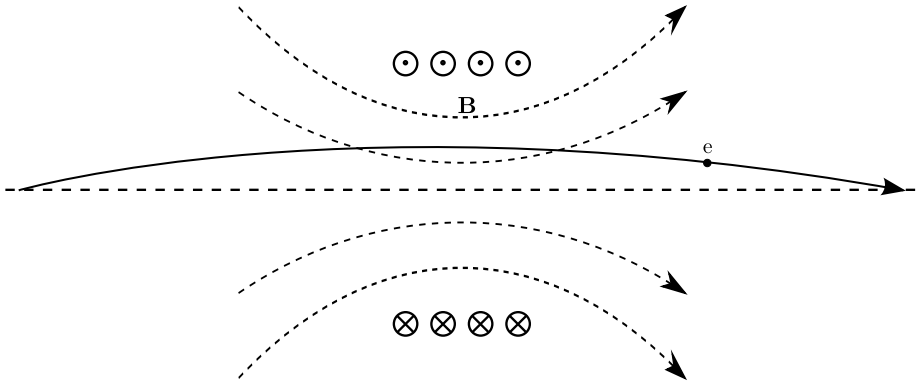


Lorentz Force

$$\mathbf{F} = q(\mathbf{v} \times \mathbf{B} + \mathbf{E})$$

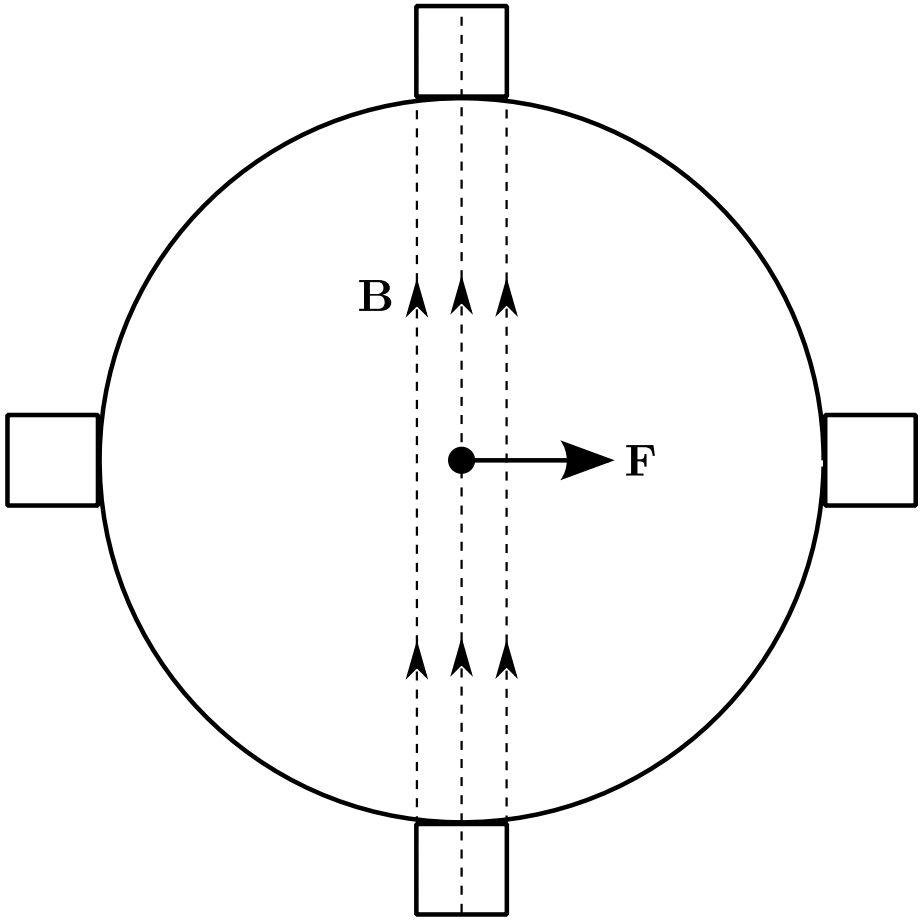
Magnetic Dipole Focusing Lens

- Will work just like a glass lens if thin and weak
- Except for adding rotation
- No negative lensing possible



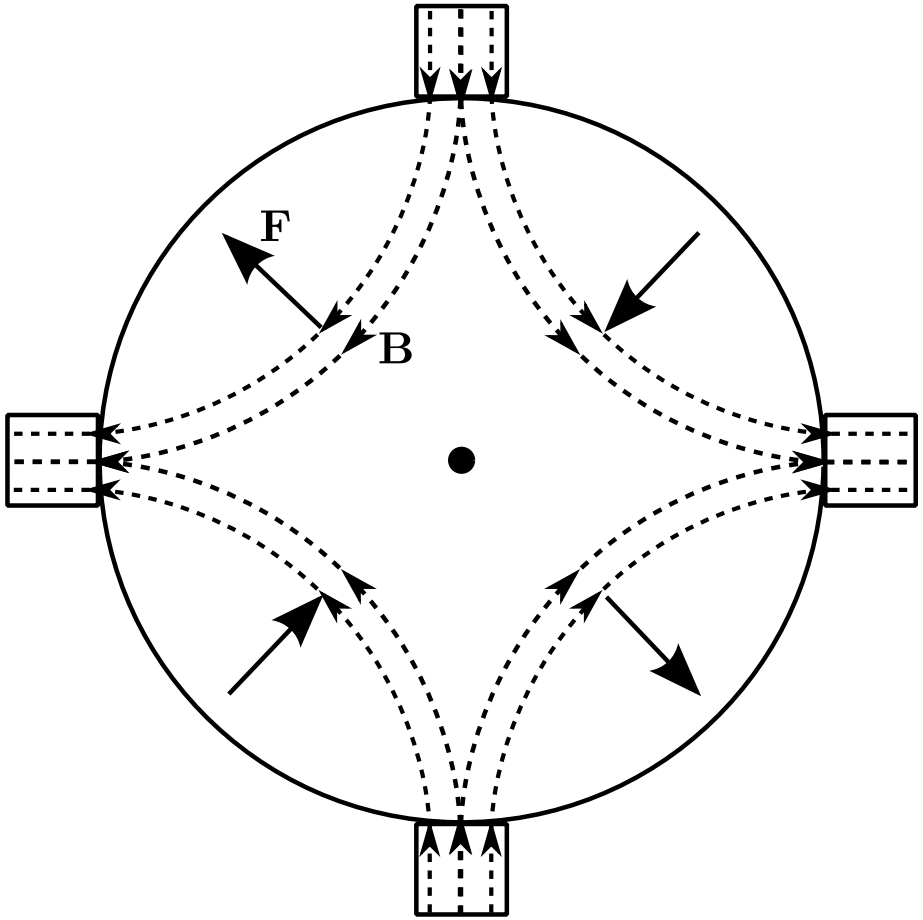
Magnetic Dipole Deflection Lens

- Just a rotated focusing field
- Weaker than focal lens



Magnetic Quadrupole Stigmator Lens

- Focuses along one axis and defocuses along the other
- May remove twofold astigmatism
- Does not affect rays on the optical axis
- Can be generalized to *n*-pole stigmator



- The nature of electron optics makes electron lenses poor
- Scherzer[1] showed in 1936 that perfect magnetic lenses are impossible
- More complex aberration mitigation is needed

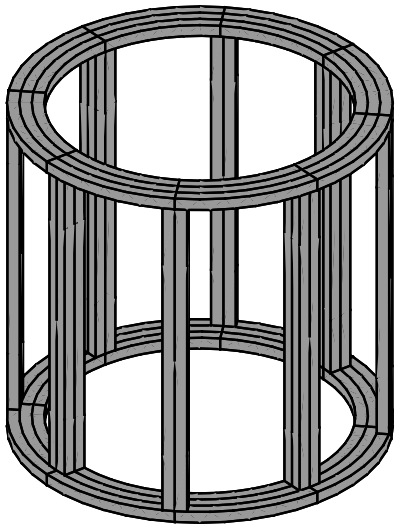
[1] O. Scherzer. “Über einige Fehler von Elektronenlinsen”. In: *Zeitschrift für Physik* 101.9 (1936), pages 593–603. DOI: 10.1007/BF01349606

Coil Model Requirements

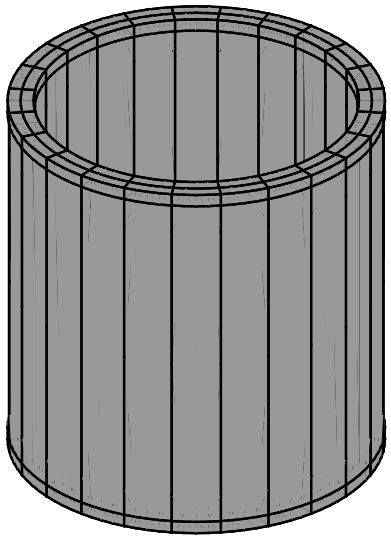
- Need to be able to model any magnetic multipole in 3d
- Parameterizable geometry
- Micron level accuracy
- Must run on limited hardware (RAM $<$ 32GB, 4 cores)

Hand-wound deflection coil prototype from the 90s

Geometry



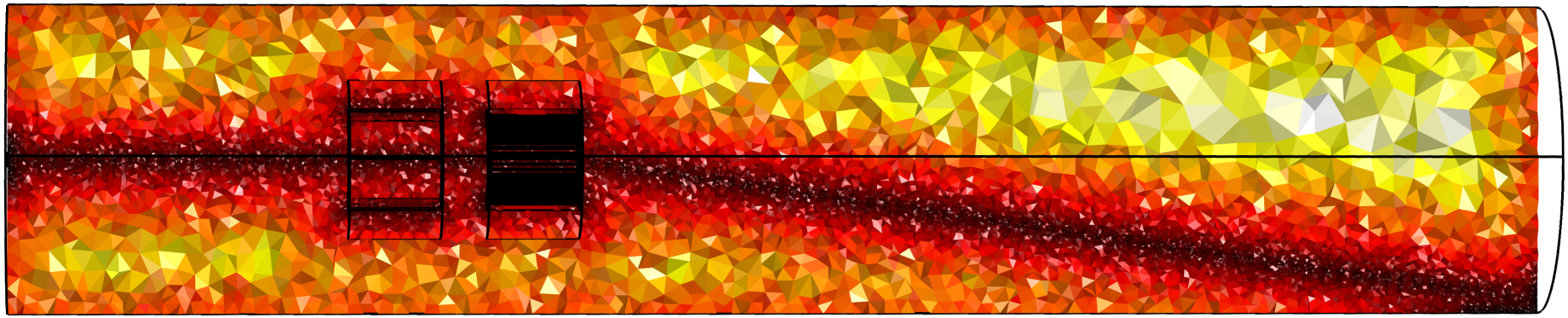
Early model



Current model

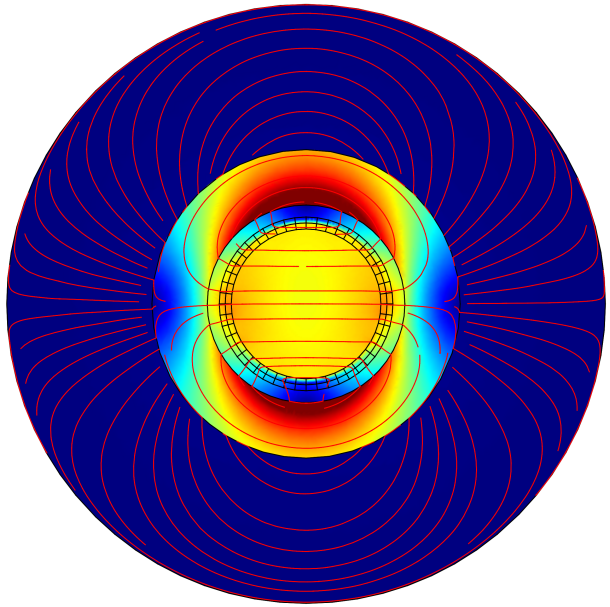
Discretization

- Automatic tetrahedal meshing in COMSOL
- Mesh is manually refined where it matters
- We know where the beam is



Dipole Field

- Generated with our multipole script



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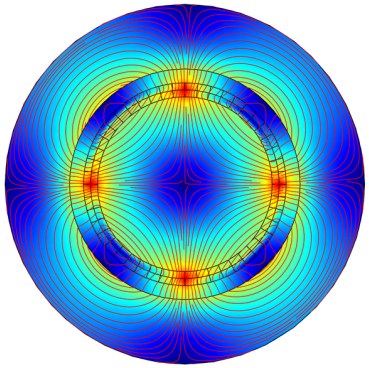
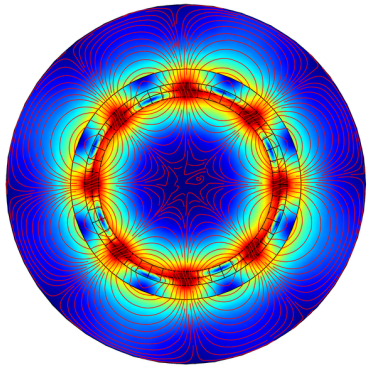
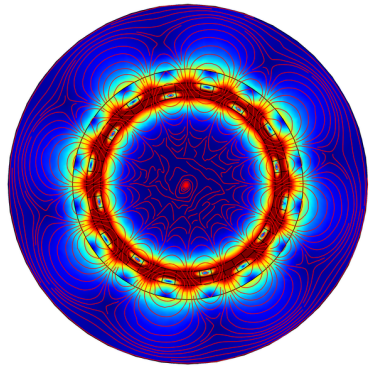
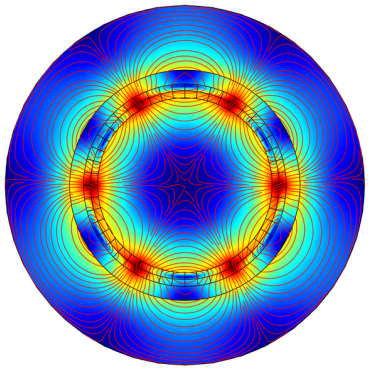
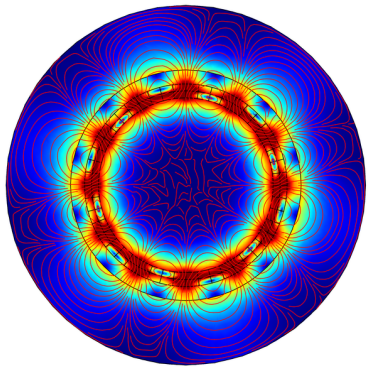
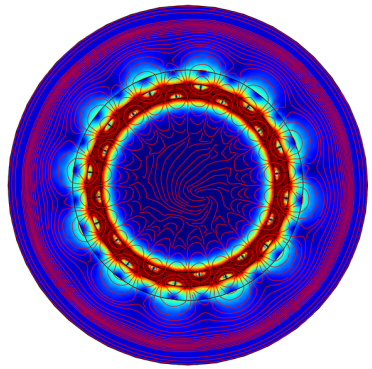
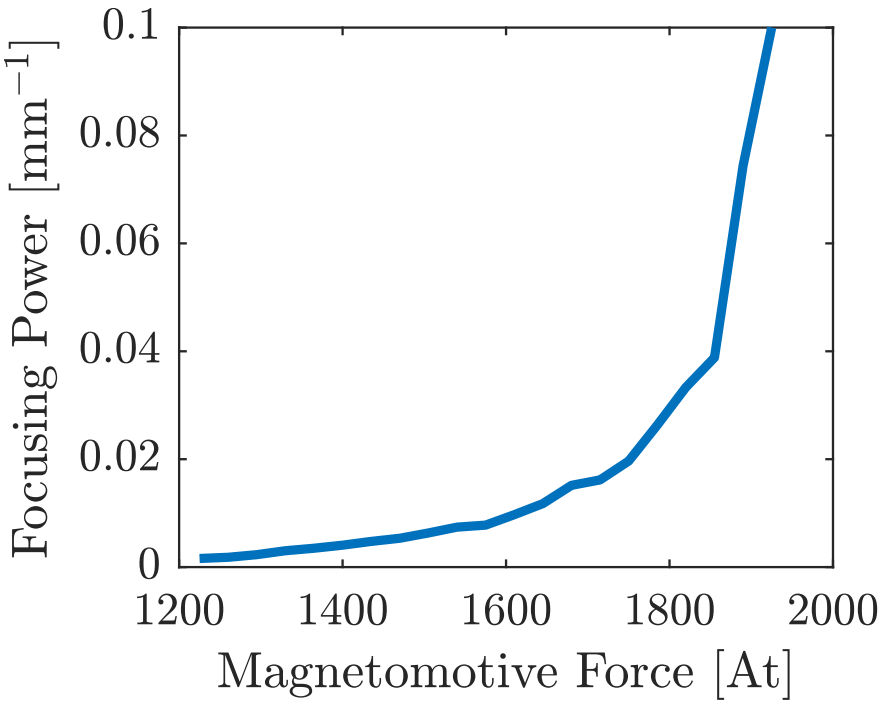
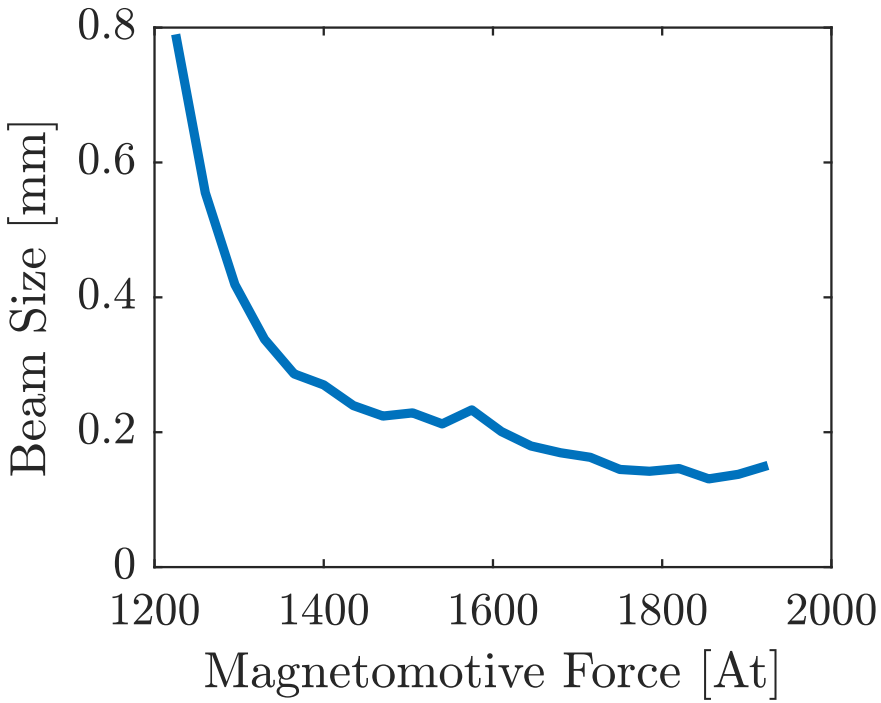
Stigmator Fields

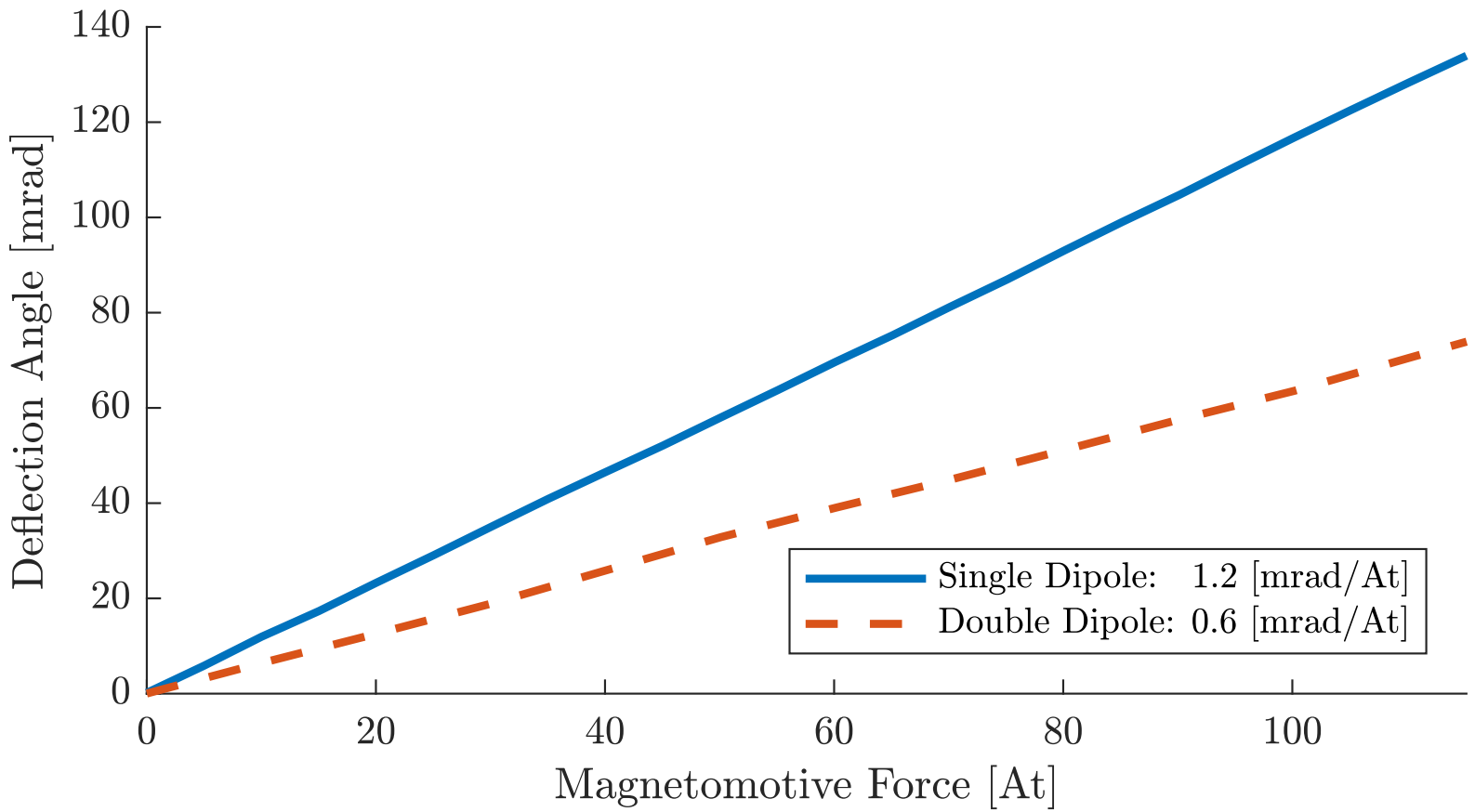







Focusing

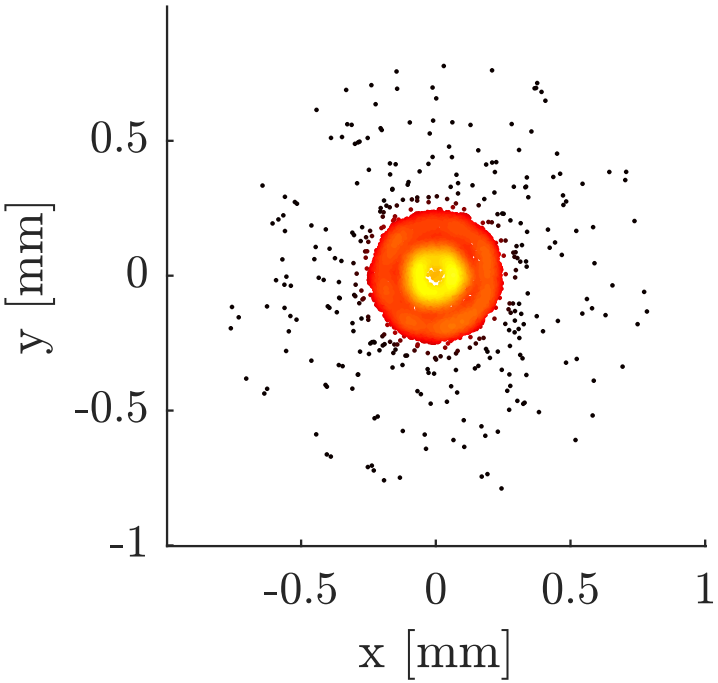

Focusing Power [mm^{-1}]
0.1
0.08
0.06
0.04
0.02
0
1200
1400
1600
1800
2000
Magnetomotive Force [At]

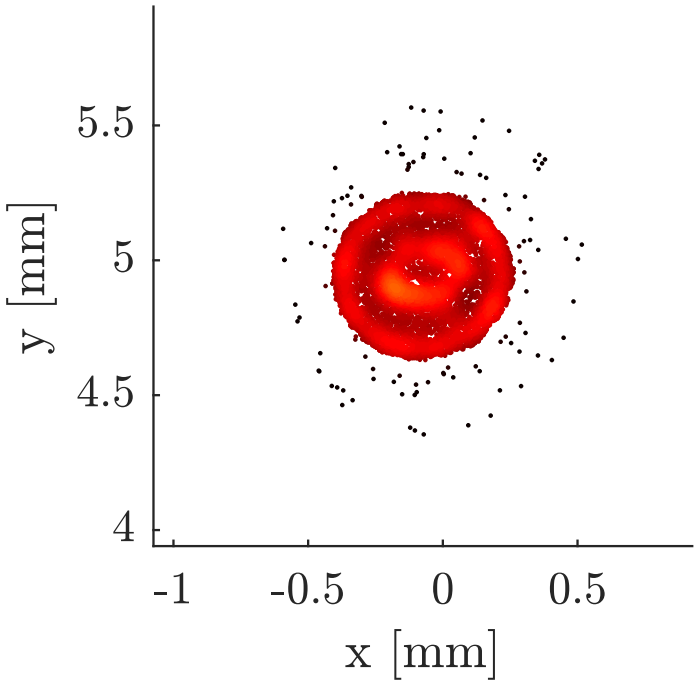

Beam Size [mm]
0.8
0.6
0.4
0.2
0
1200
1400
1600
1800
2000
Magnetomotive Force [At]

Deflection


Deflection Angle [mrad]
140
120
100
80
60
40
20
0
0
20
40
60
80
100
Magnetomotive Force [At]
Single Dipole: 1.2 [mrad/At]
Double Dipole: 0.6 [mrad/At]

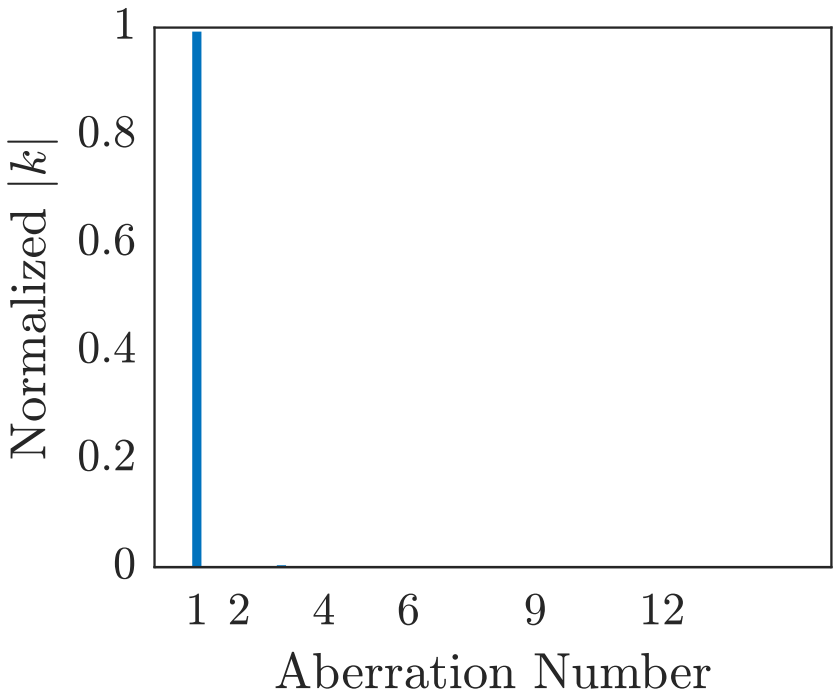
Deflection





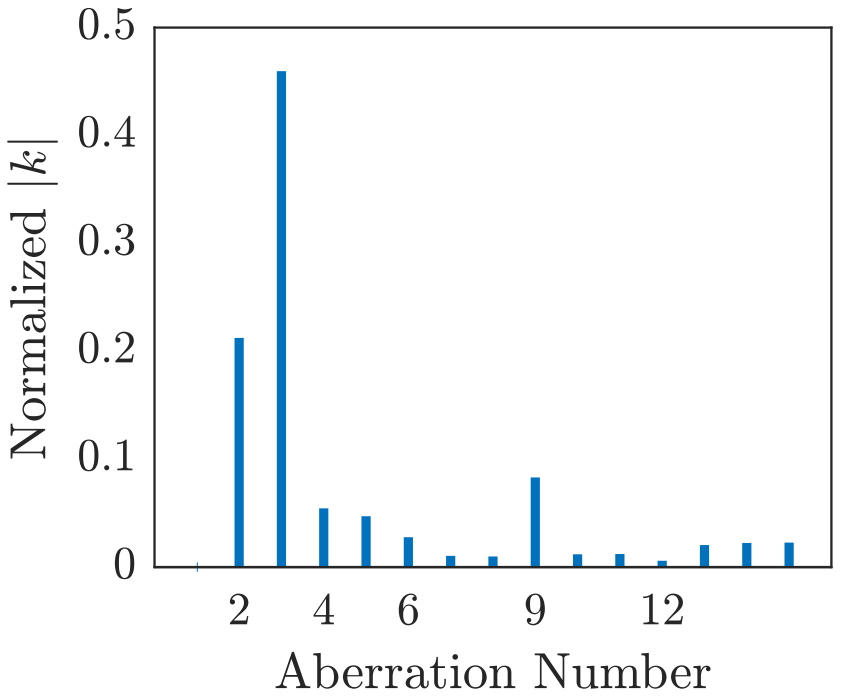
Deflection

- What happens when we deflect the beam?
- Spectrum dominated by shift



Deflection

- What happens when we deflect the beam?
- Spectrum dominated by shift
- Remove and normalize
- We see twofold astigmatism



Conclusions

- Methods from electron microscopy can be used to identify aberrations
- We now have flexible tools to simulate it
- Knowledge is necessary in order to design and control aberration correction for improved performance.

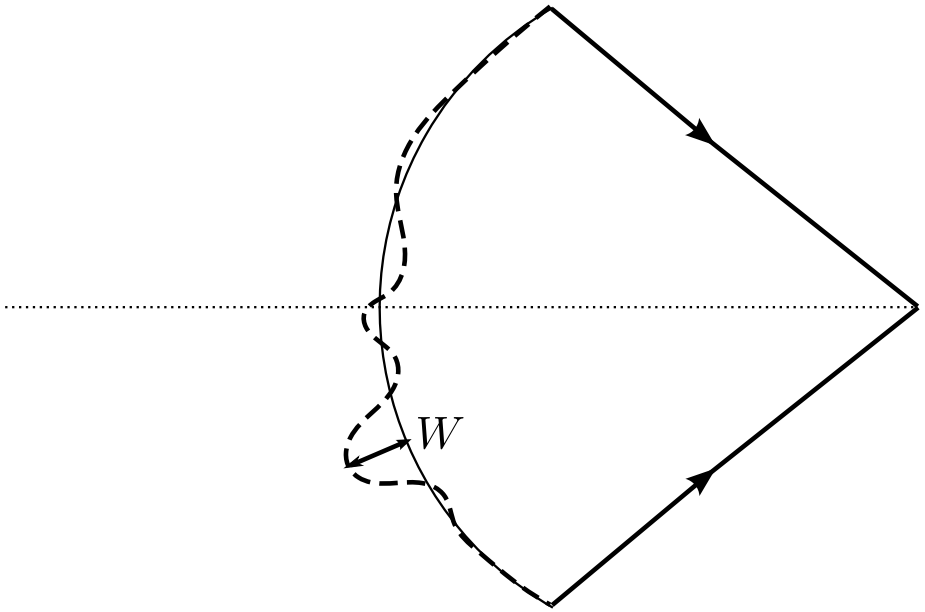
Possible Future Studies

- Simulate and measure electron density
- Simulate and optimize correction
- Simulate polepieces with new materials and geometries

Thank You

Aberration Function

- Deviation from ideal beam
- Quantified in wave front aberration function
- Usually expanded in a power series and a Fourier series
- Gradient sometimes equivalent to image aberration



Contours of Basis Functions