Bulk High Temperature Superconducting Undulator

Pole optimization and Shimming

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Agenda

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1 Introduction

2 Modelling framework

3 Ferromagnetic pole optimization

4 Ferromagnetic pole shimming

5 Conclusion

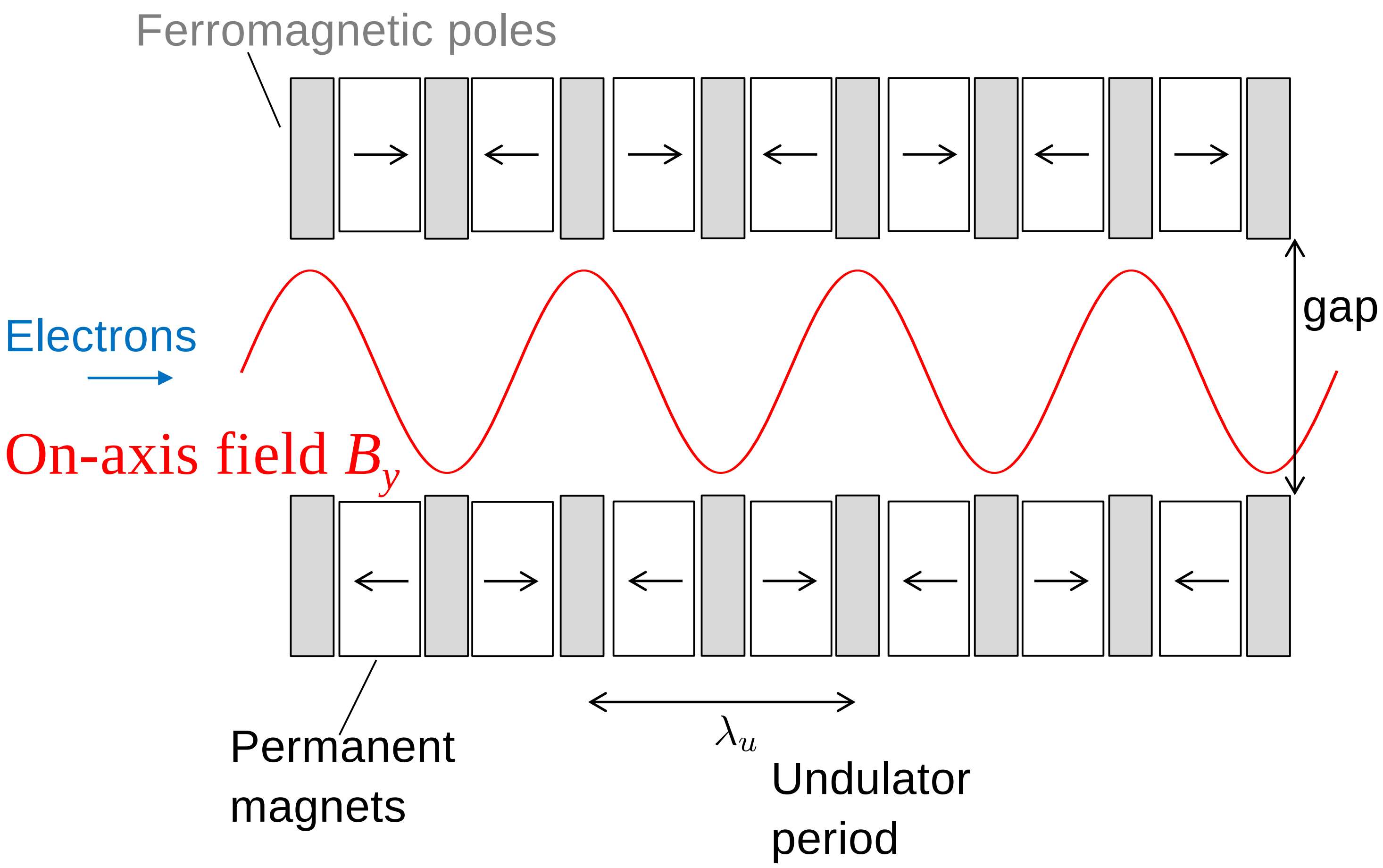
Introduction

Synchrotron radiation is the light emitted when relativistic charged particles are accelerated (where $a \perp v$)

Undulators have been introduced to increase the brightness of the X-ray source by making use of interference effects .

Hybrid undulators make use of ferromagnetic poles to

- Increase the peak on-axis field
- Serve as a tool to locally adjust the field



Traditional hybrid permanent magnet undulator

Introduction

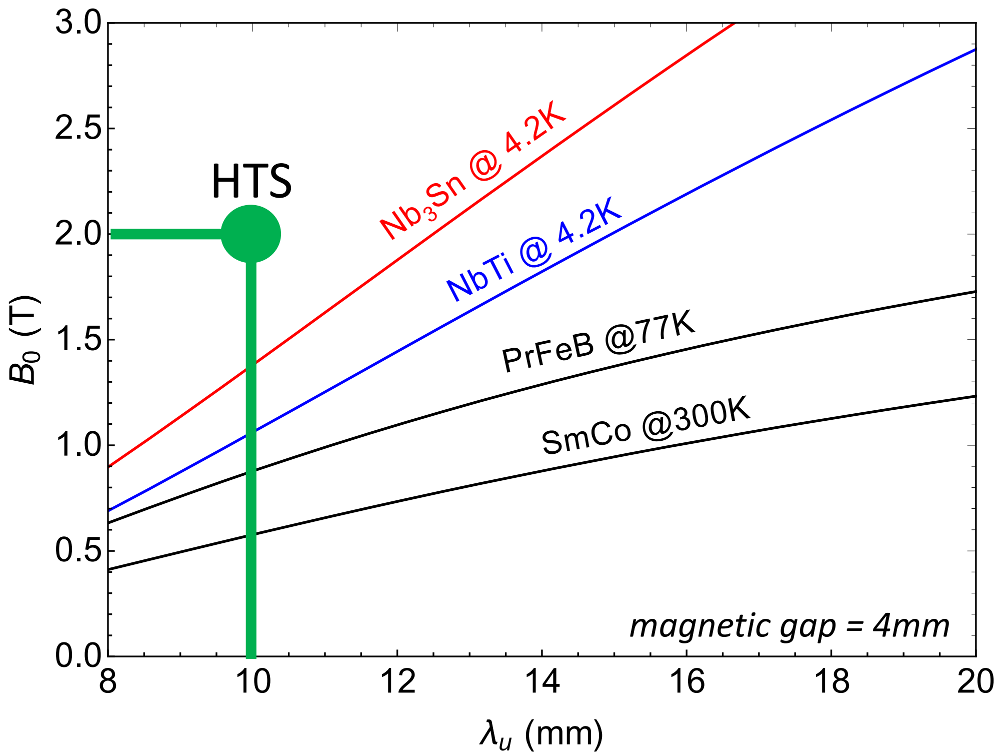
- To increase the flux and energy of synchrotron radiation, higher magnetic fields and lower undulator period
- A record on-axis field of 2.1 T for a 10 mm period undulator has been demonstrated [K. Zhang, 2023]

$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{1}{2}K^2\right)$$

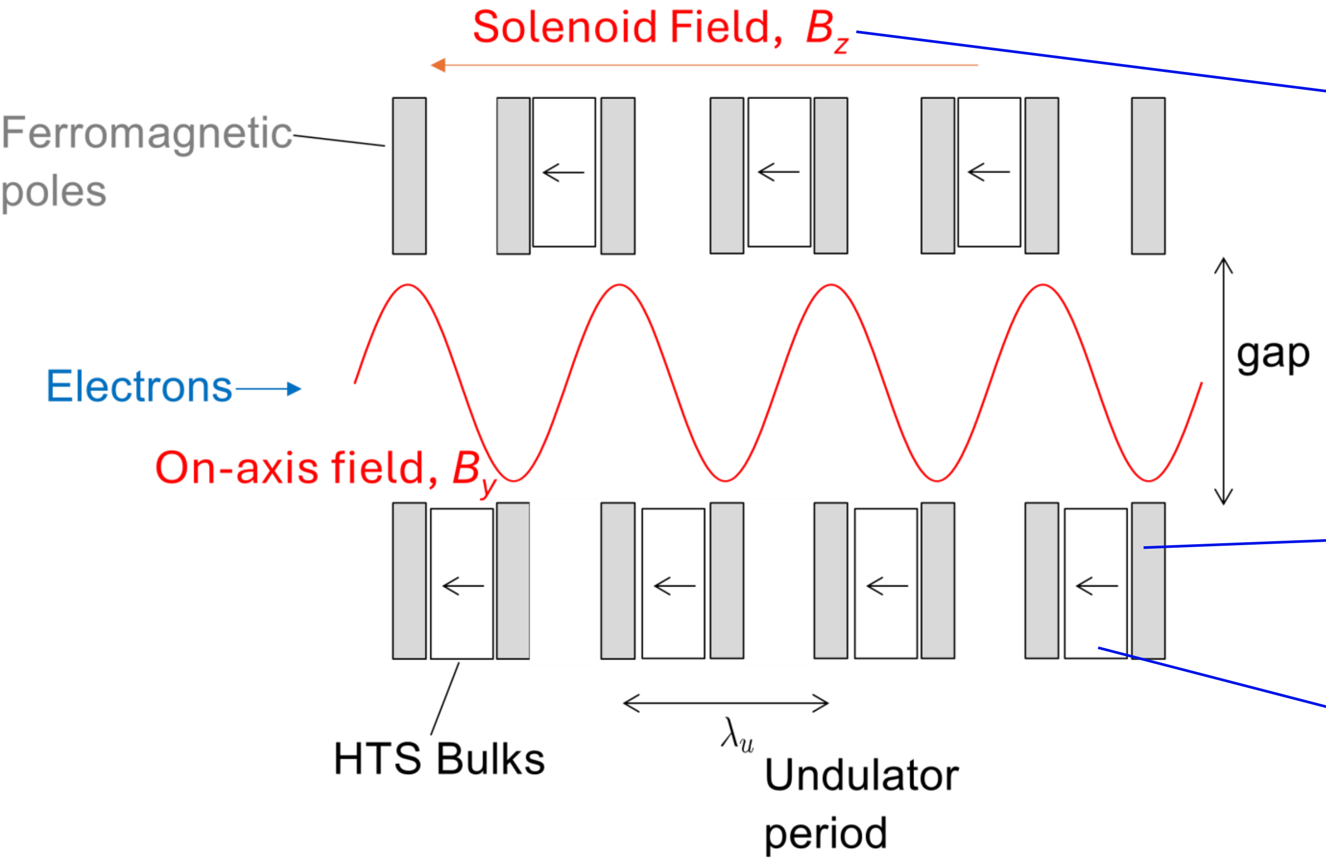
Harmonic Number (n) — Beam Energy (γ) — Deflection Parameter (K)

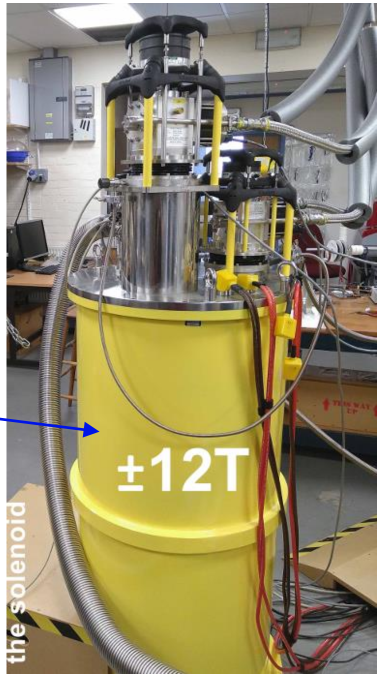
$$K = \frac{B_0 e}{mc}\frac{\lambda_u}{2\pi}$$

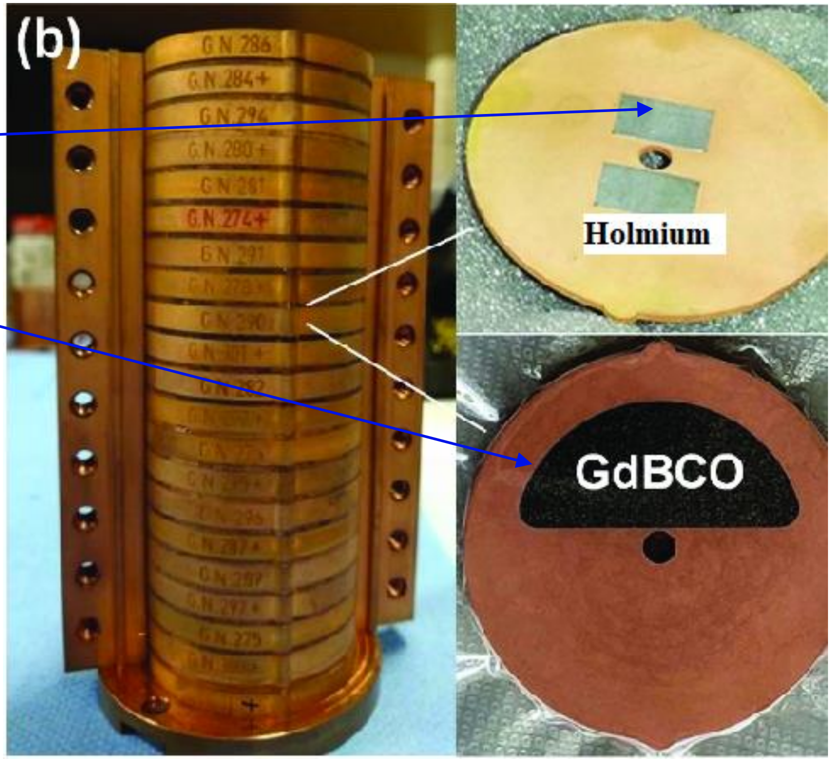
Peak on-axis field (B_0) — Sinusoidal Field



Introduction

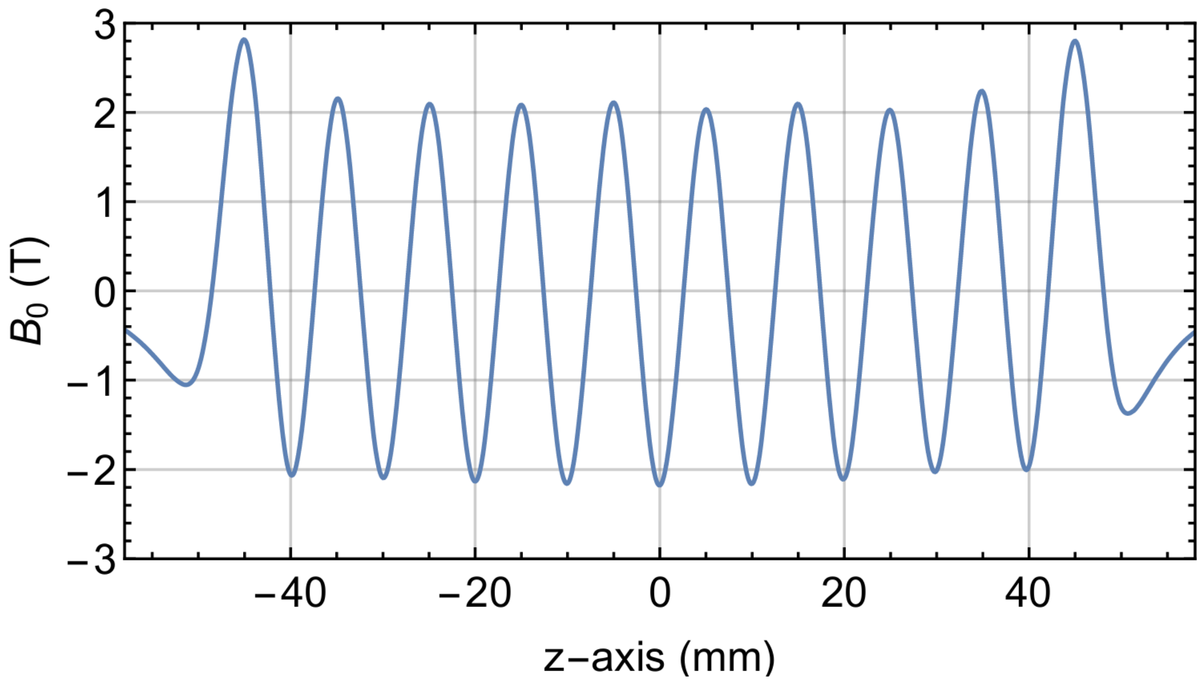




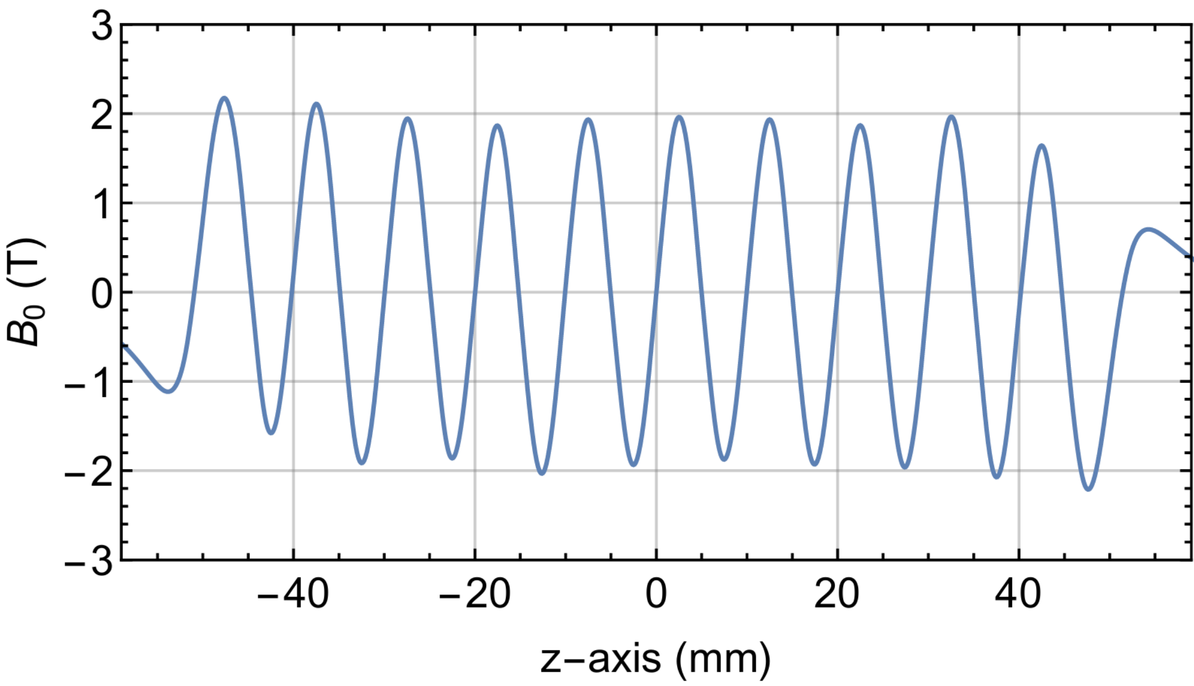


Introduction

- Due to the growth process, the magnetic properties of HTS bulks can vary, leading to deviations from a periodic on-axis field
- A periodic field is required to use the high harmonics of the emitted light
- Need to find strategies to improve the field quality



High quality Nippon steel bulks; Expensive, less errors



SDMG bulks; Cheaper, require more correction for periodic field

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Modelling framework

- The H-ϕ formulation was used to simulate the HTSU for efficient computations [A. Arsenault, 2021]
- Involves solving the well-known H-formulation, combining Faraday and Ampere's law:

$$\nabla \times (\rho(J)\nabla \times H) = -\frac{\partial B}{\partial t}$$

Weak Form

$$\int_\Omega \rho\nabla \times H \cdot \nabla \times \tilde{H} \mathrm{d}\Omega + \frac{\partial}{\partial t}\mu \int_\Omega H \cdot \tilde{H} \mathrm{d}\Omega - \int_\Gamma \hat{n} \times E \cdot \tilde{H} \mathrm{d}\Gamma = 0$$

Using the scalar potential ϕ in non-conducting domains, to decrease computation times by a factor of 3

$$H = -\nabla\phi$$

$$\frac{\partial}{\partial t}\mu \int_{\Omega_{\mathrm{nc}}} \nabla\phi \cdot \nabla\tilde{\phi} \mathrm{d}\Omega - \int_\Gamma \hat{n} \times E \cdot \nabla\tilde{\phi} \mathrm{d}\Gamma = 0$$

Test Function

The equivalent boundary terms leads to a more natural coupling between the two physics

Modelling framework

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- The bulk's properties are modelled with $B = \mu_0 H$ and the superconducting power law resistivity:

$$\rho = \frac{E_c}{J_c}\left(\frac{|\mathbf{J}|}{J_c}\right)^{n-1}$$

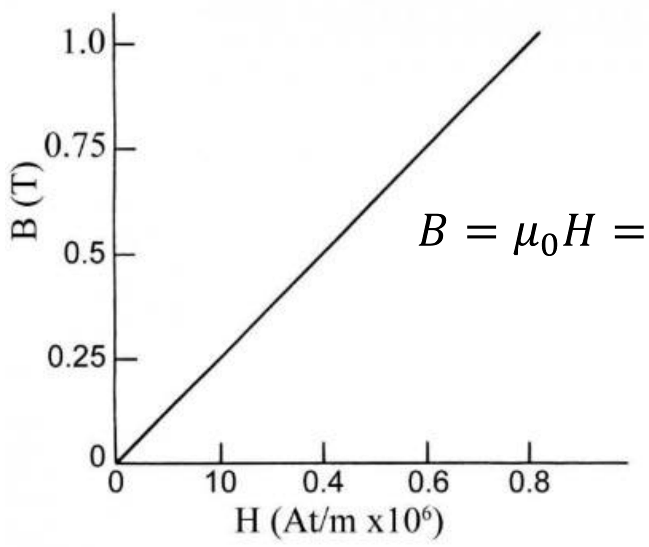
- The air domains are also modelled using $B = \mu_0 H$
- The conductivity of the holmium poles is smaller than that of copper and may be ignored such that the poles are simulated using the ϕ physics as well

Modelling framework

$$\nabla \times (\rho(J)\nabla \times H) = -\frac{\partial B}{\partial t}$$

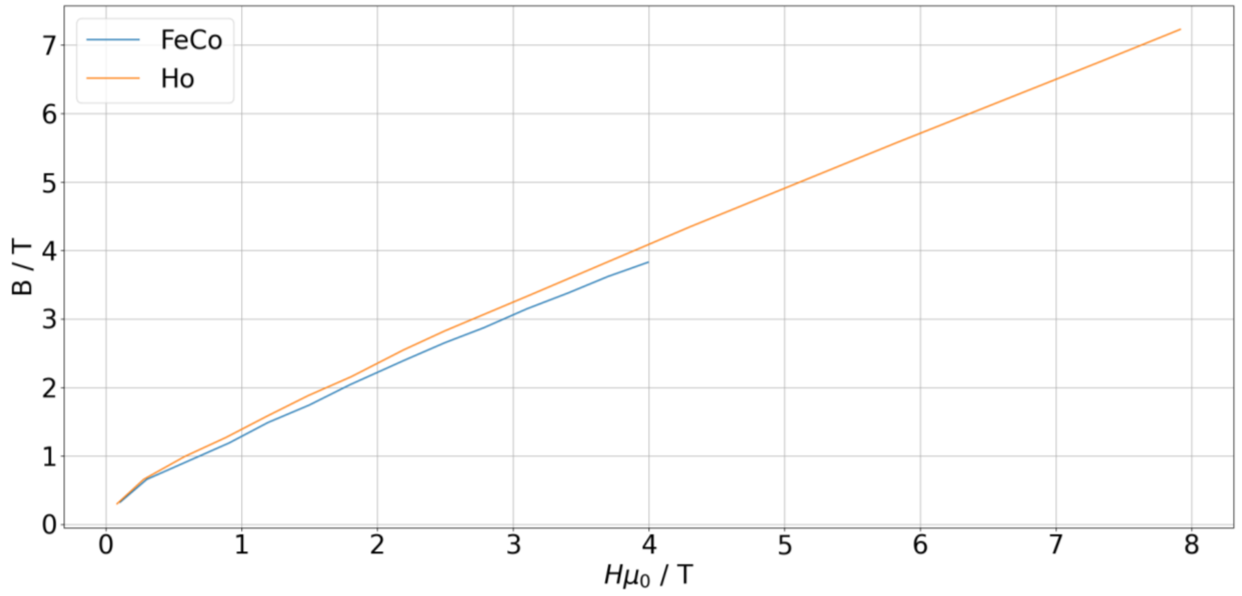
Relationship between B and H

Air and HTS



$$B = \mu_0 H = -\mu_0 \nabla \phi$$

Ferromagnet [M. Norsworthy, 2010]



$$B = -f(|\nabla\phi|)\frac{\nabla\phi}{|-\nabla\phi|}$$

BH-Curve

Get Sign of Magnetic Field

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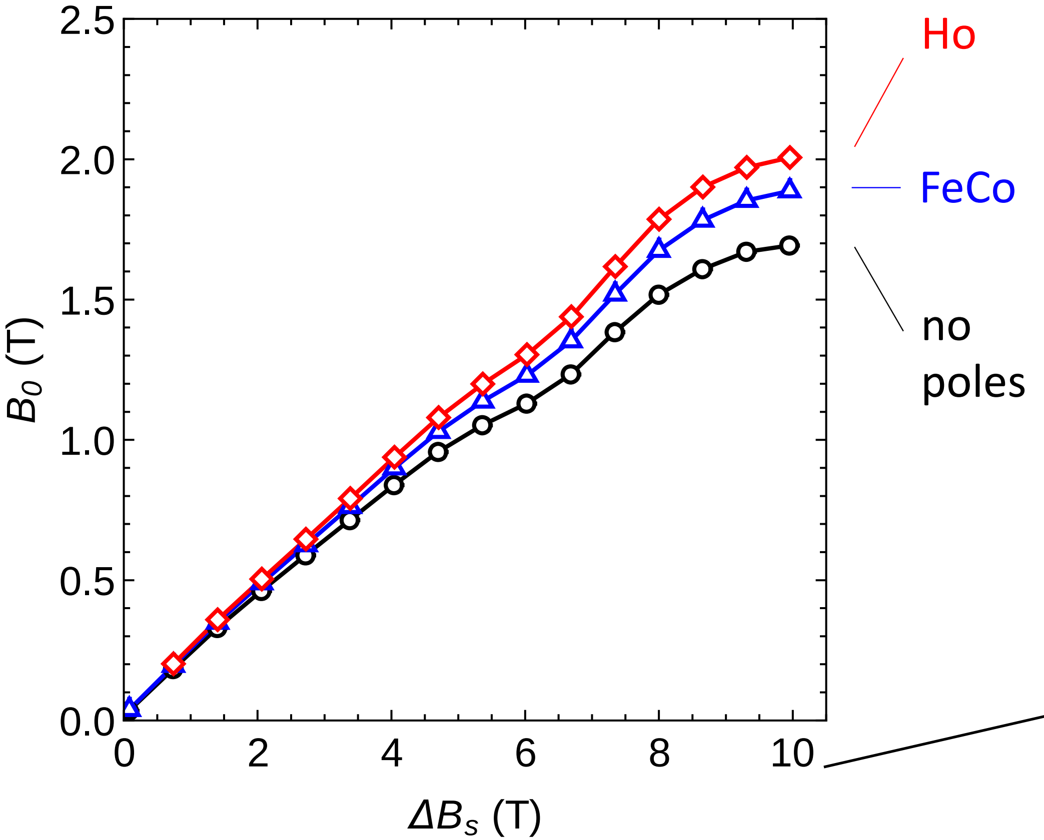
Ferromagnetic pole optimization

- Traditional undulators use iron cobalt for the poles
- However, at the HTSU operating temperature (<10K) stronger materials become available
- We tested a 20-bulk sample with both materials
- Holmium was found to give a 0.1T peak on-axis field increase compared to iron cobalt [M. Calvi, unpublished]

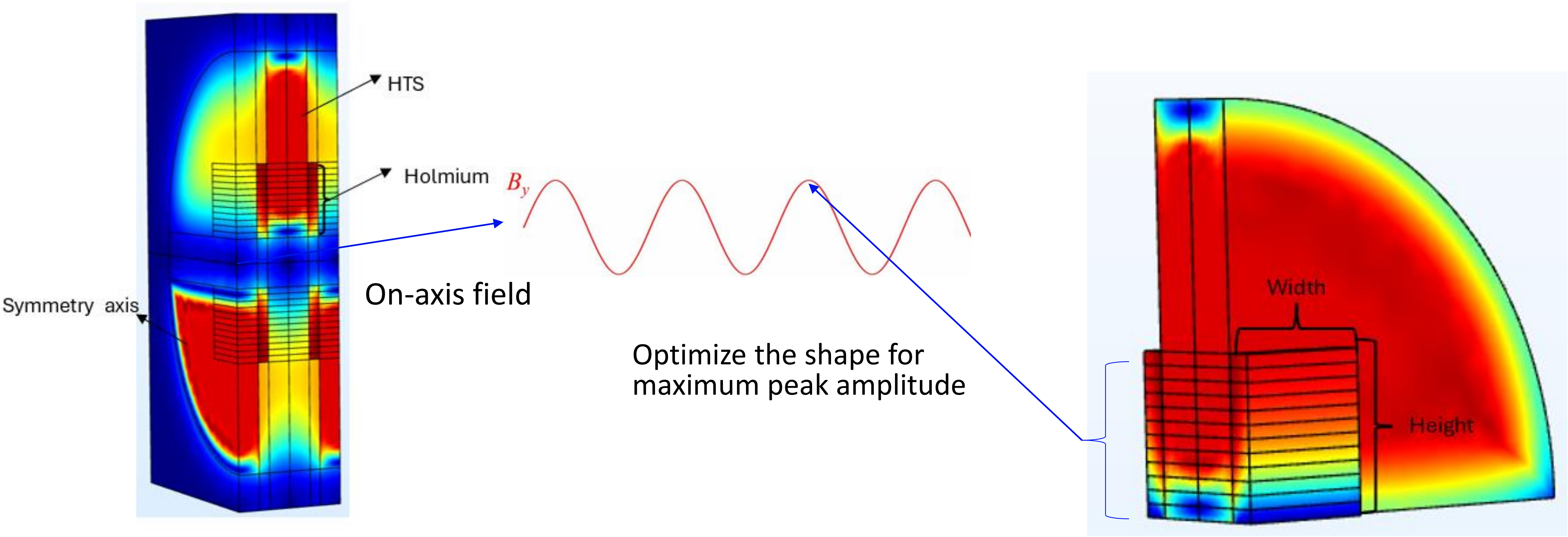
Avg. Peak On-axis magnetic



Change in external solenoid field

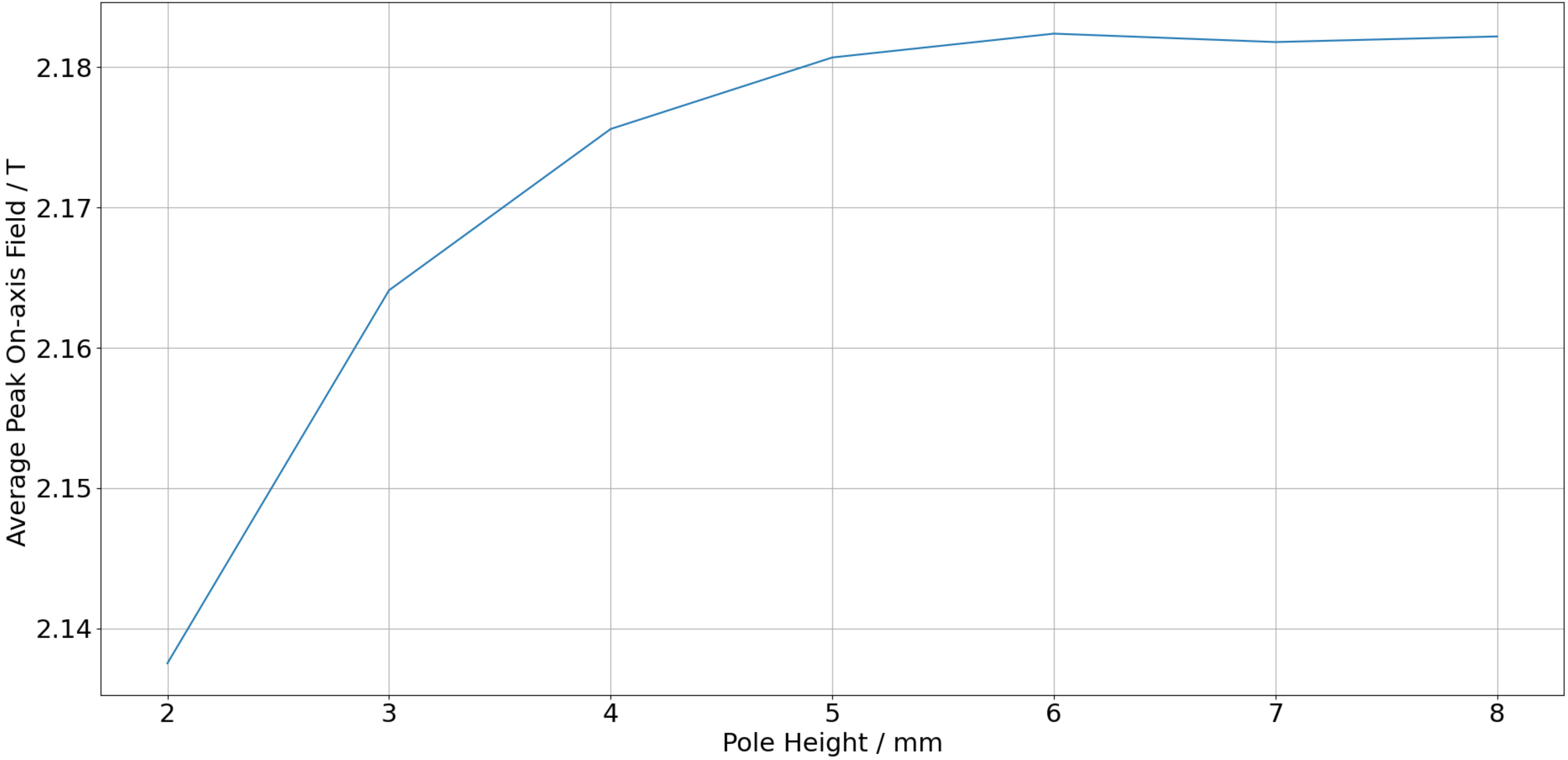
Ferromagnetic pole optimization

- We implemented a periodic model to optimize the ferromagnetic pole shape in order to get the maximum peak field amplitude



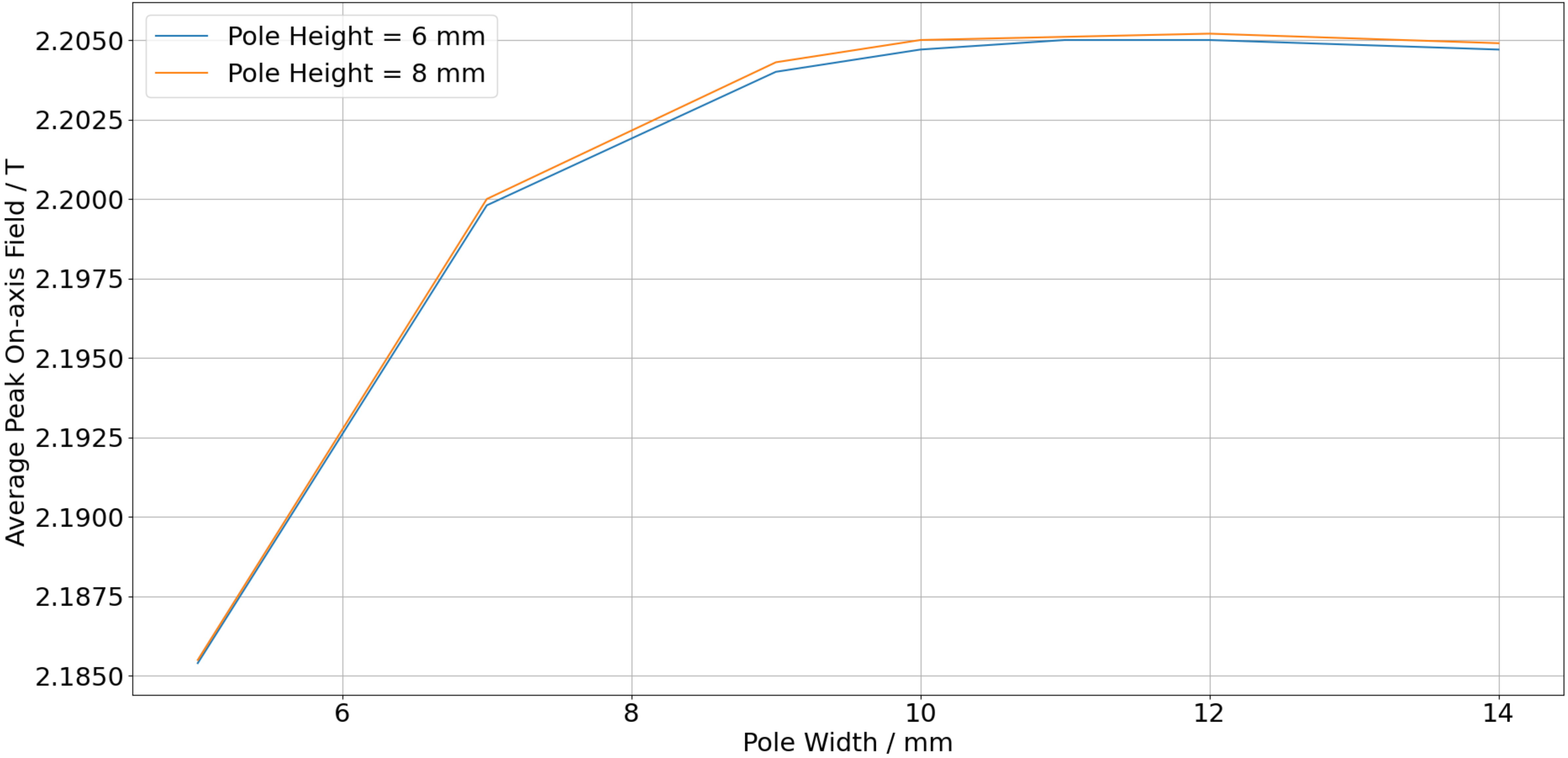
Ferromagnetic pole optimization

- 2D height sweep: Optimum height of 6 mm



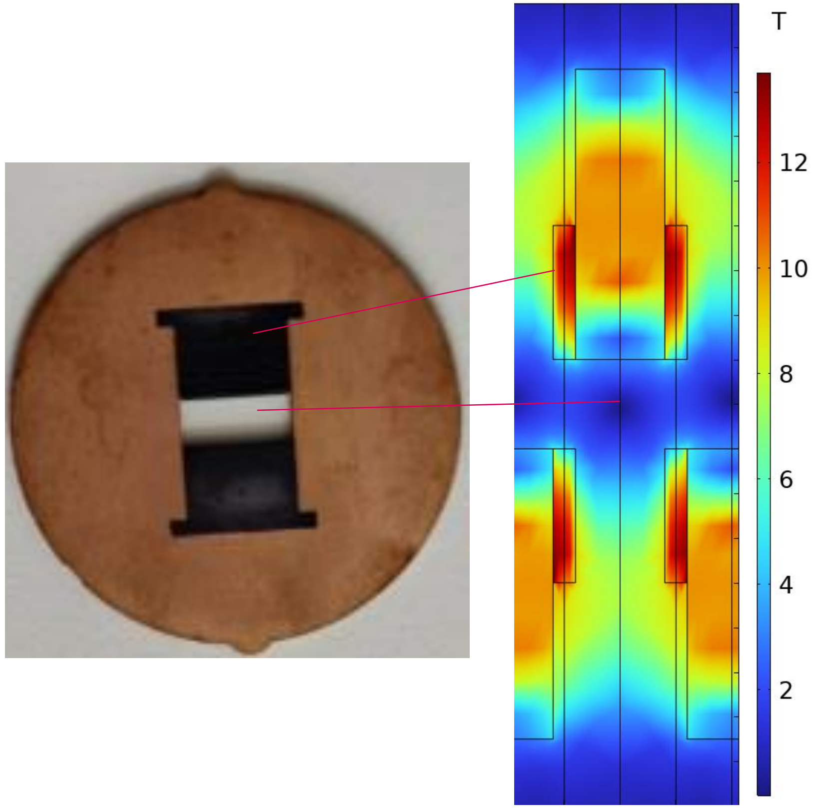
Ferromagnetic pole optimization

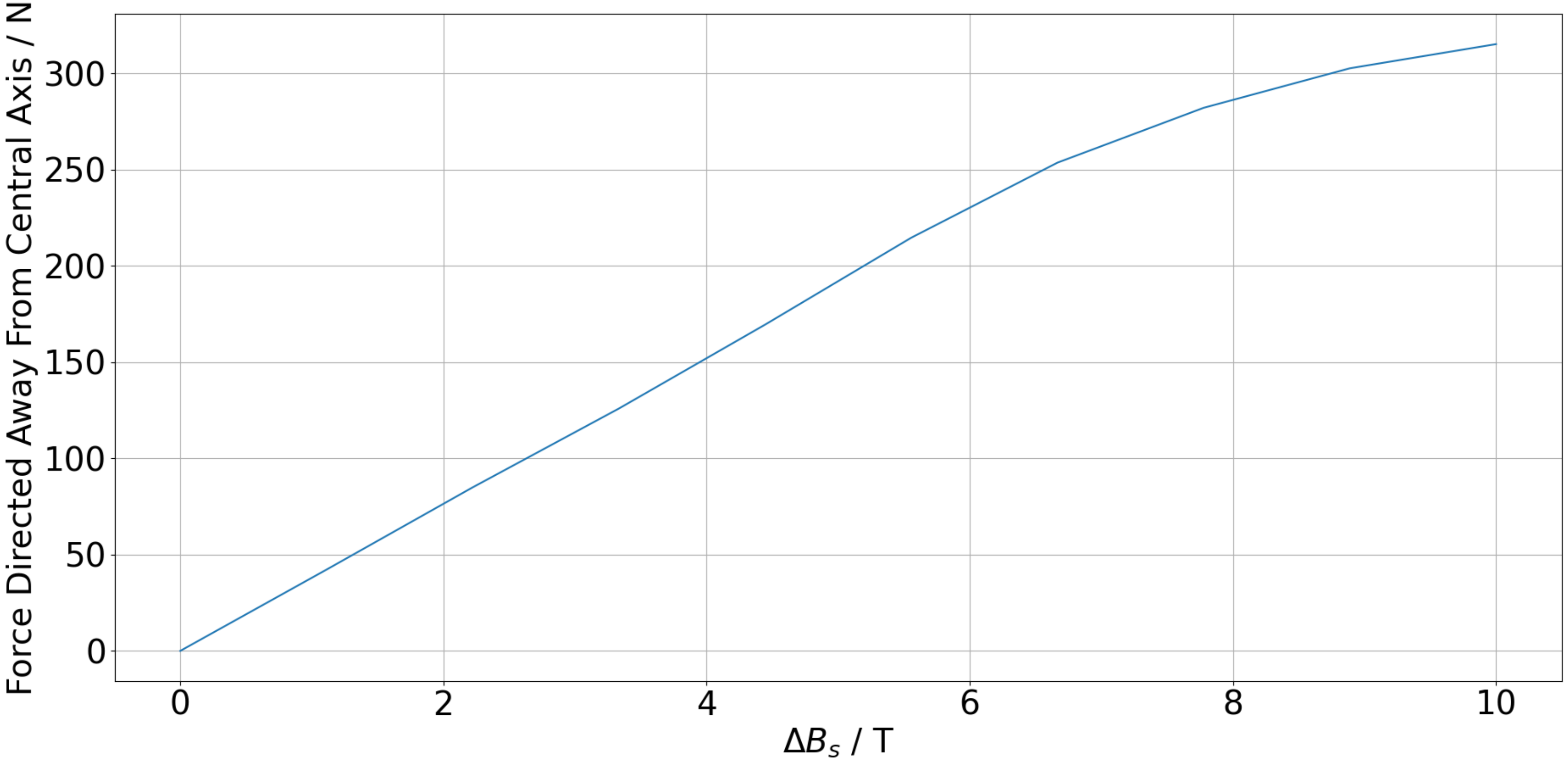
- 3D width sweep: Optimum width of 10 mm



Ferromagnetic pole optimization

- To shim the HTSU the pole will be trimmed at the gap
- In traditional permanent magnet undulators the magnetic force pulls the poles towards the gap
- For the HTSU the opposite occurs, as the field is stronger in at the center of an HTS





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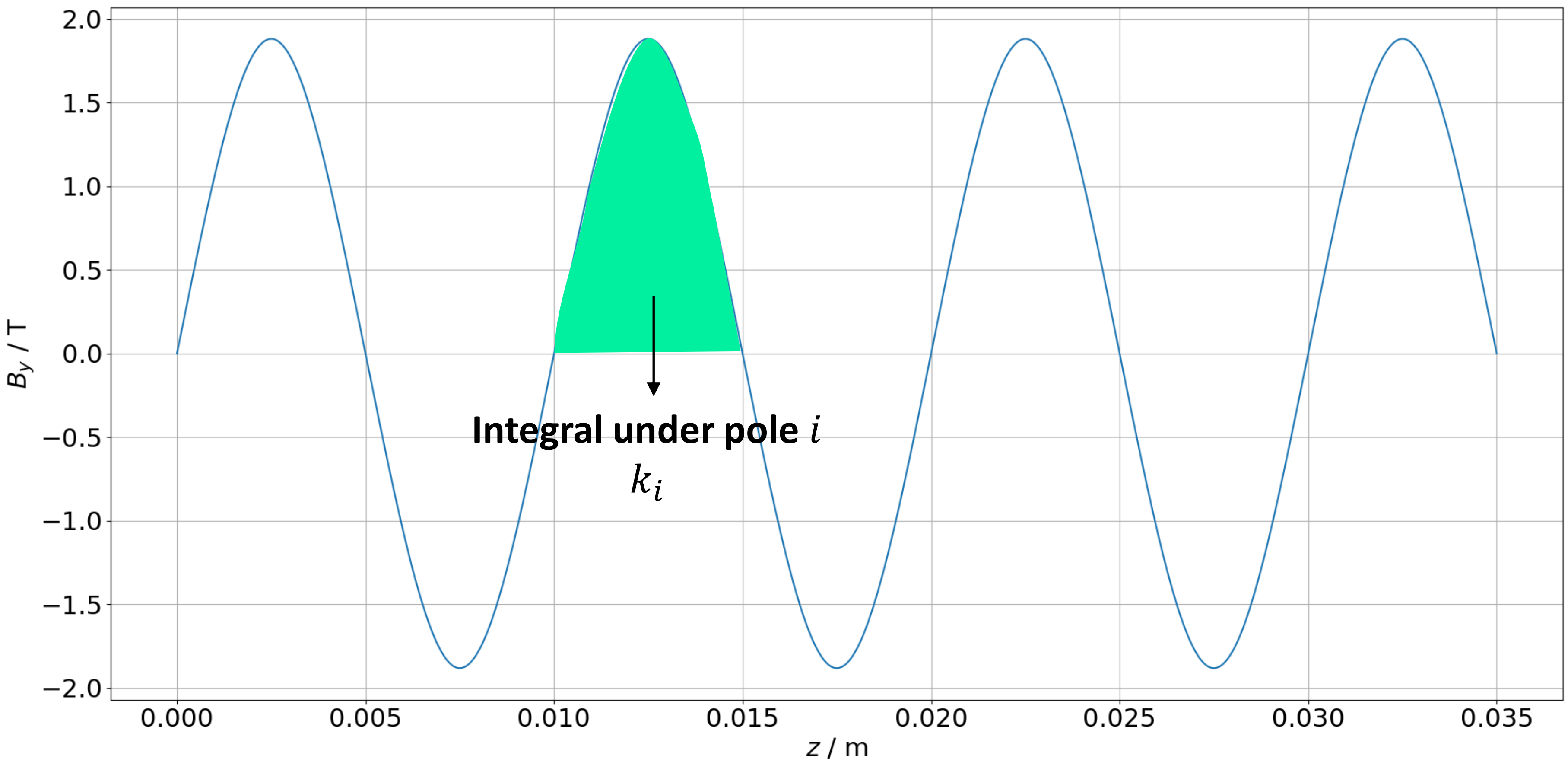
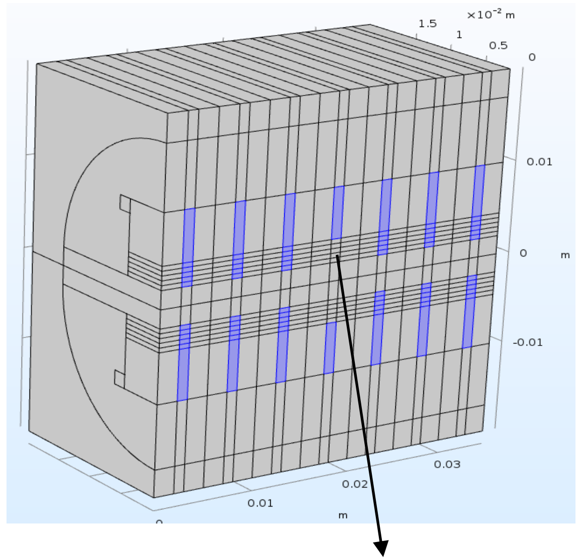
Ferromagnetic pole shimming



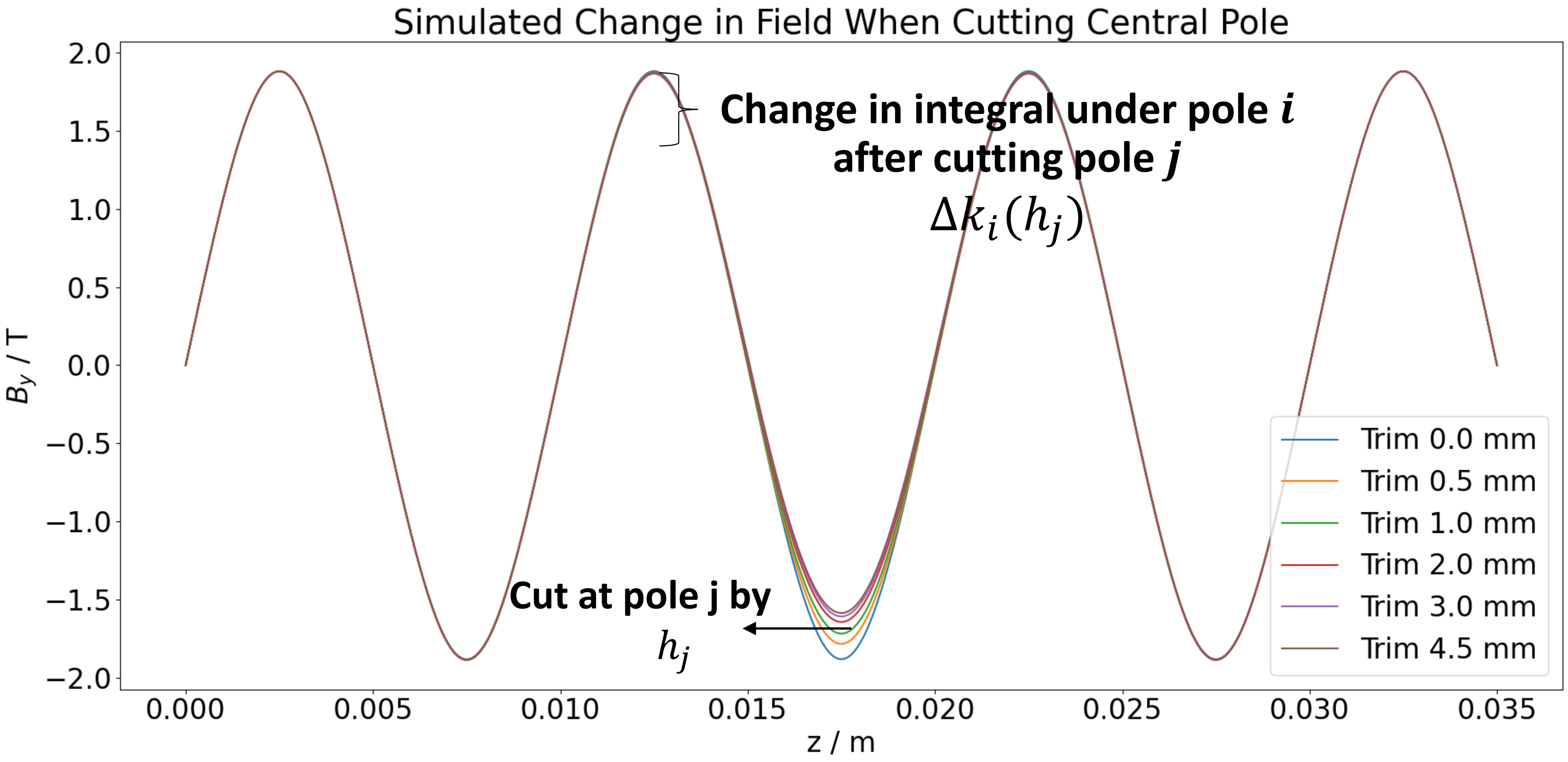


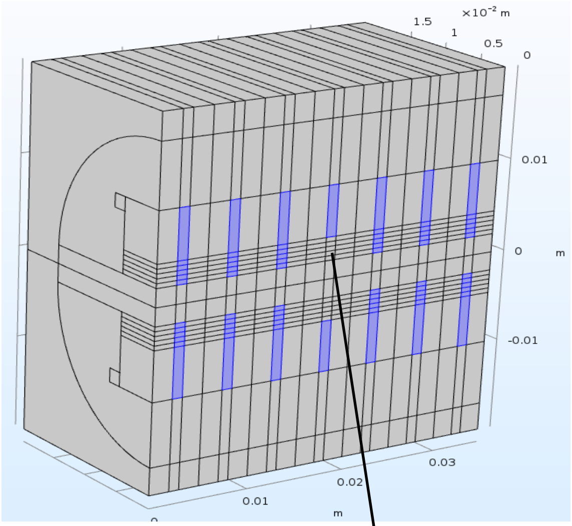
Simulate cut at pole j

h_j

On –axis field of 3.5 Periods, with no cut; $h_j = 0$

Ferromagnetic pole shimming





Simulate cut at pole j

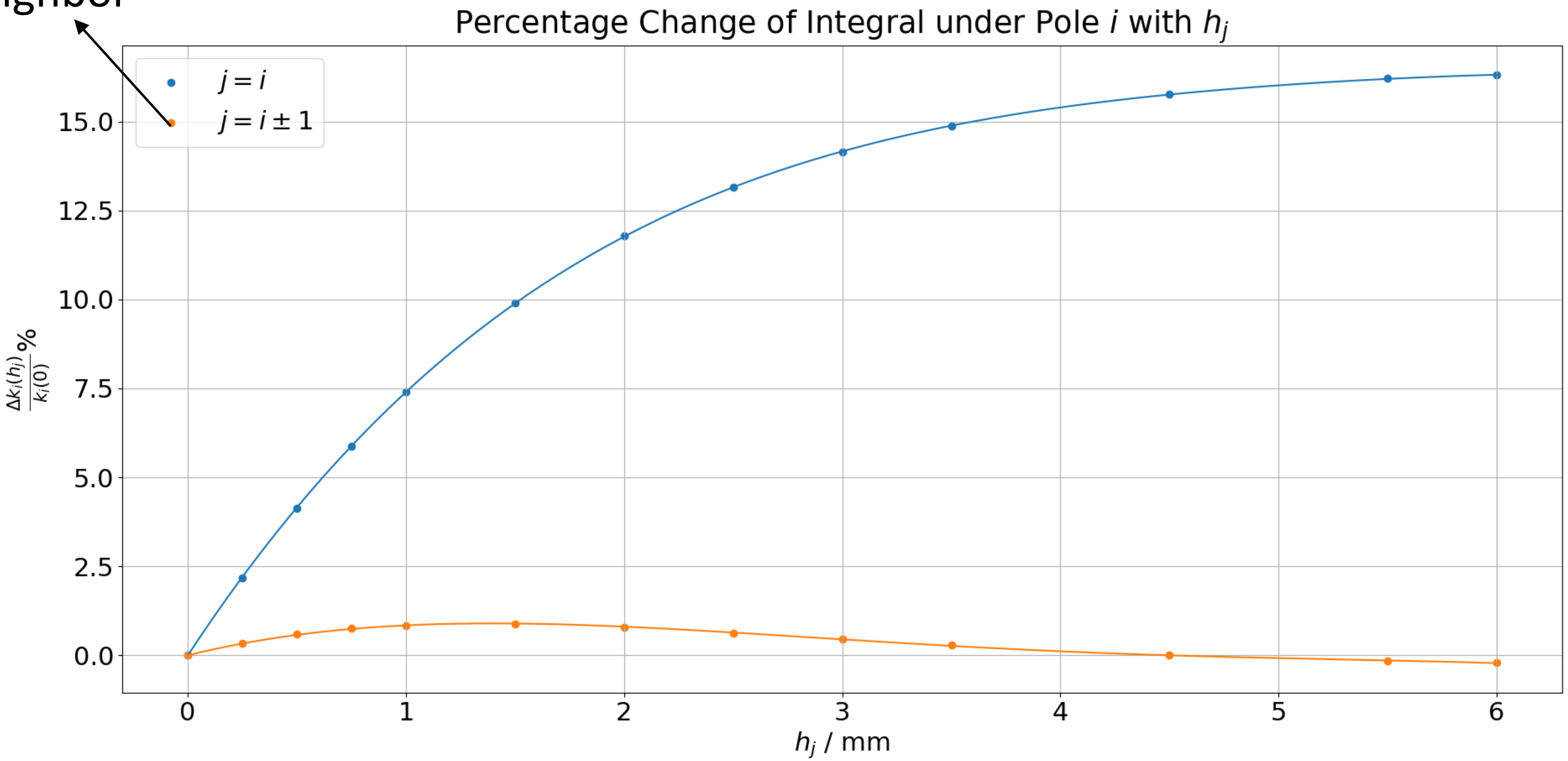
Assuming: $\Delta k_i(\mathbf{h}) = \Delta k_i((0, ..., h_{i-3}, ...0)) + ... + \Delta k_i((0, ..., h_i, ...0)) + ... + \Delta k_i((0, ..., h_{i+3}, ...0))$

Ferromagnetic pole shimming

- For each pole i fit a 4th order polynomial $a_{ij}\, h_j^4 + b_{ij}\, h_j^3 + c_{ij}\, h_j^2 + d_{ij}\, h_j = \Delta \mathrm{k_i}$
- Use coefficients to build circulant matrices $\left(\underline{A}\right)_{ij} = a_{ij}, \ldots$, and let $\left(\underline{h}\right) = h_j$
- The change in the integral between each two zeros $\underline{\Delta k}$ due to a set of cuts $\underline{h}$ is given by

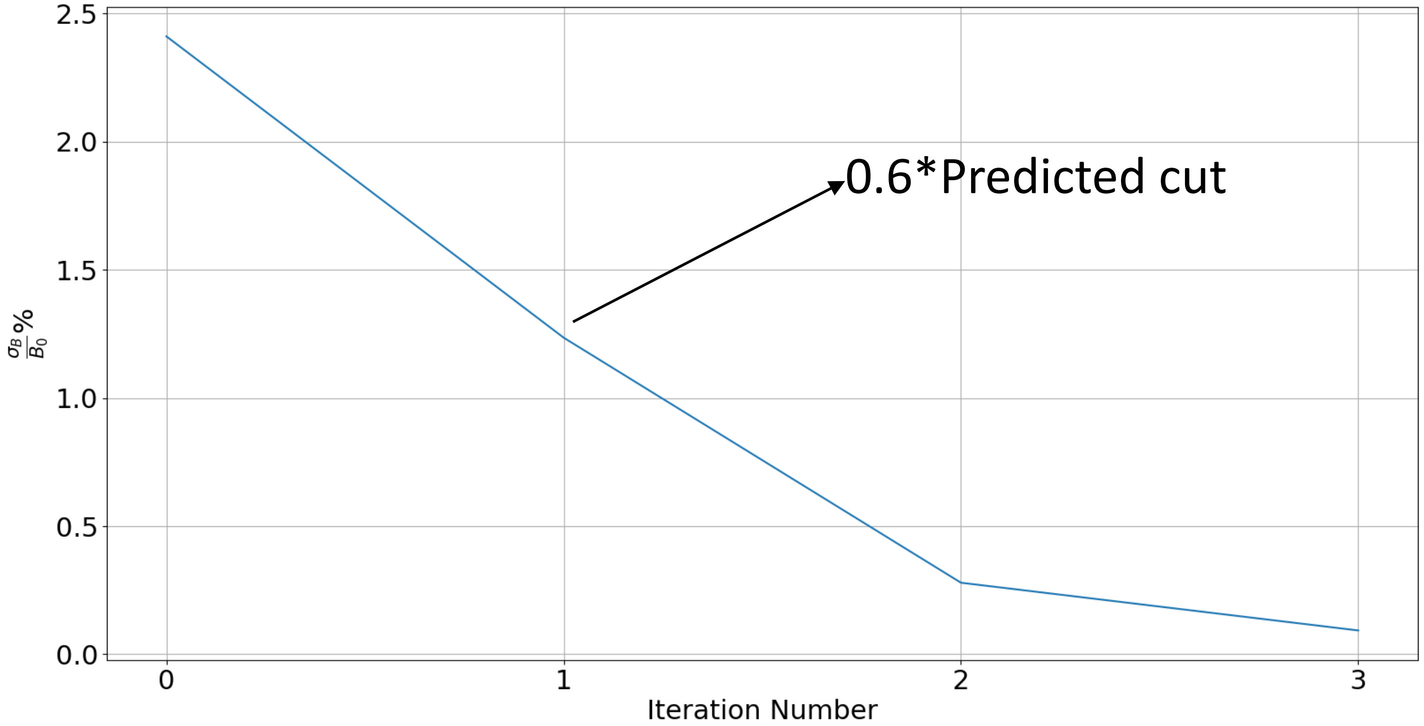
$$\underline{A}\ \underline{h}^4 + \underline{B}\ \underline{h}^3 + \underline{C}\ \underline{h^2} + \underline{D}\ \underline{h} = \underline{\Delta \mathrm{k}}(\underline{h})$$

1st Neighbor



Ferromagnetic pole shimming

- From experimental data we can obtain the first field integral of each peak, K_i
- To get a uniform field we minimize $\mathrm{R} = \underline{K} - \mathrm{avg}(\underline{K}) + \underline{\Delta \mathrm{k}}(\underline{h})$ to obtain how much the poles should be cut
- With 3 iterations, we can reduce the error from 2.4% down to 0.2% by simulation
- Target: 0.1% (If all parameters between model and simulated field are the same than we can go to 0% barring mesh errors)



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Conclusion

- The HTS undulator field is nonuniform due to the different properties of each bulk -> Need to improve the field quality
- We also optimized the shape of the HTSU poles to maximize the field amplitude
- Finally, a pole cutting algorithm was developed to predict how much each pole should be cut to improve the field quality.
- The pole shimming gives a more fine-tuned field optimization, where we show that the error can go from 2.4% to 0.2% in three iterations by simulations