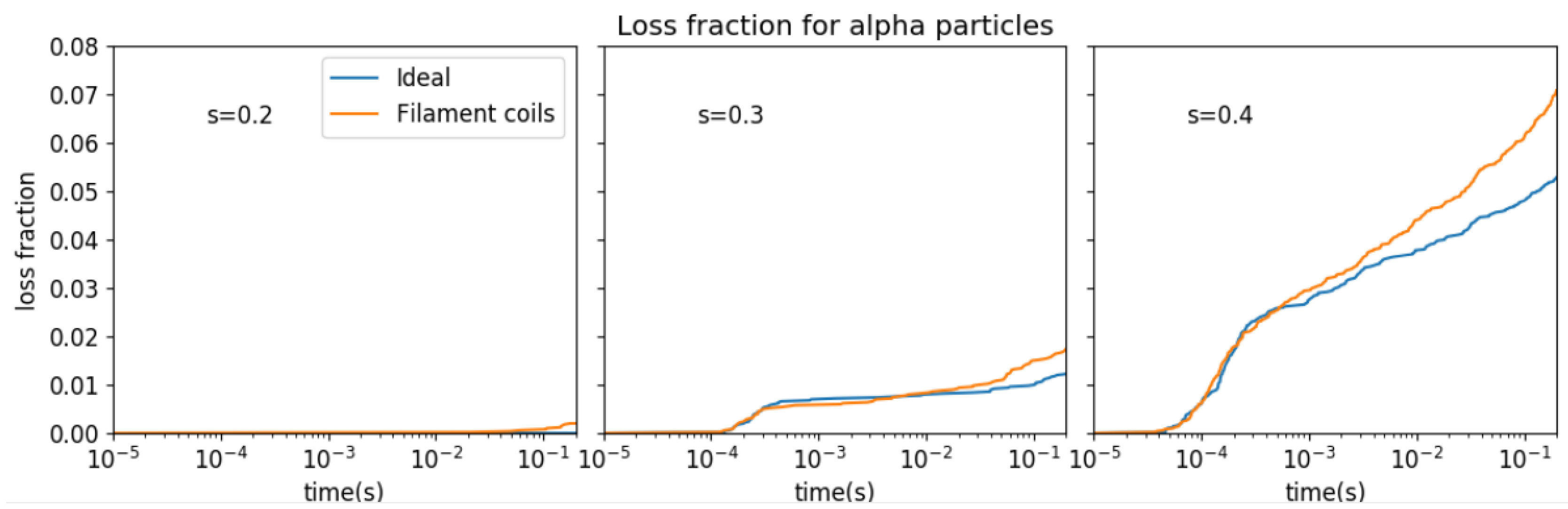
Application of Ferromagnetic Inserts to Reduce Modular Coil Ripple in Stellarators

T. Kruger, C. Martin, D.T. Anderson, A. Bader *University of Wisconsin-Madison*

Motivation for Using Ferritic Inserts in a Stellarator

- Modular coils impose a short wavelength nonsymmetric mode in magnetic spectra which is referred to as modular coil ripple
- Coil ripple is detrimental to energetic particle confinement and can lead to unacceptable losses of fusion born alpha particles



- To model ferromagnetic materials we use the finite element solver ANSYS [1]
- ANSYS requires finite build coils to carry out its analysis

Design of Finite Build Coils

- We start coil design with winding surface calculations using REGCOIL [2]

$$\chi^2 = \chi_b^2 + \lambda \chi_k^2$$

$$\chi_b^2 = \int d^2a\, B_{normal}^2$$

$$\chi_k^2 = \int d^2a\, K(\theta,\varphi)^2$$

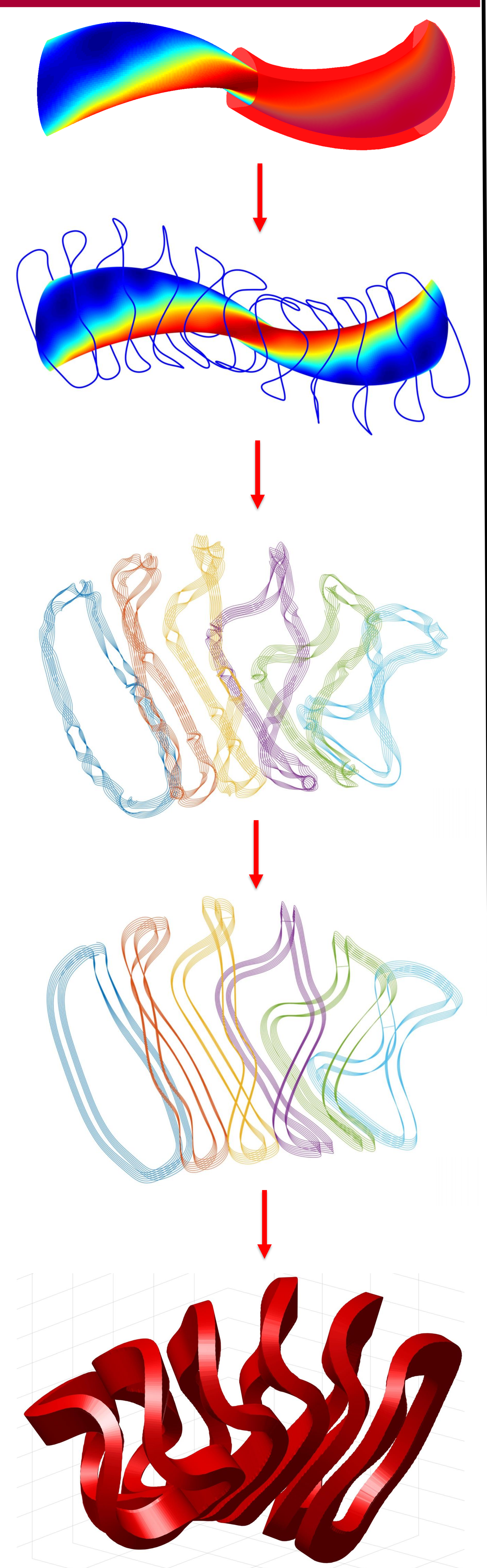
- χ_b^2 is the main objective function used throughout this work
- Current potential contours are cut to produce single filament coils that are input to FOCUS [3]
- FOCUS performs non-linear optimizations where the coils are no longer constrained to lie on a winding surface

$$\boldsymbol{r}(\theta) = \left[\sum_{n=0}^{N} X_{c,n}cos(n\theta) + X_{s,n}sin(n\theta)\right]\hat{\boldsymbol{x}} + \cdots$$

$$\left[\sum_{n=0}^{N} Y_{c,n}cos(n\theta) + Y_{s,n}sin(n\theta)\right]\hat{\boldsymbol{y}} + \cdots$$

$$\left[\sum_{n=0}^{N} Z_{c,n}cos(n\theta) + Z_{s,n}sin(n\theta)\right]\hat{\boldsymbol{z}}$$

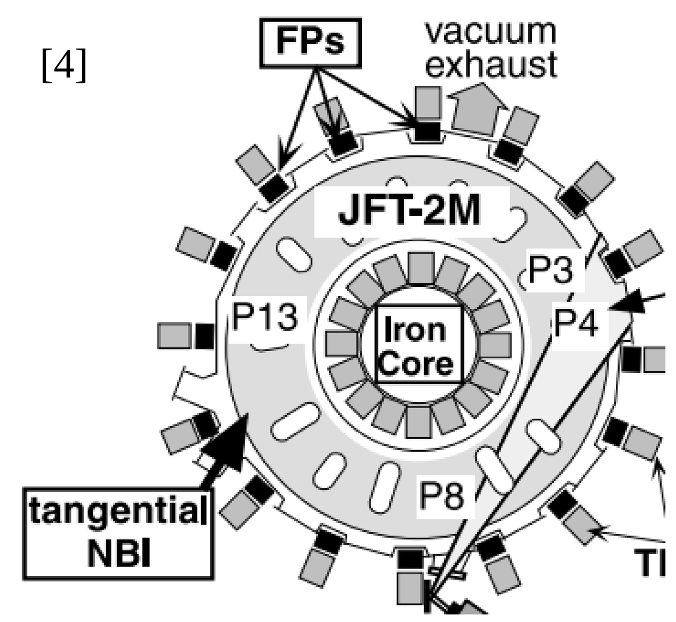
- We use local coordinate frames located at the single filament coils to parameterize multi-filament coils
- See poster by Luquant Singh for multi-filament coil parameterization and optimization
- Multi-filament parameterization allows for optimization of important quantities
  - Tilt of coil finite build
  - Coil aspect ratio
  - Coil centroids
- Multi-filament coils approximate finite build coils
- Build directions for multi-filament coils are the same build directions that are used for finite coils
- Once the finite coils are produced the model is reproduced in ANSYS



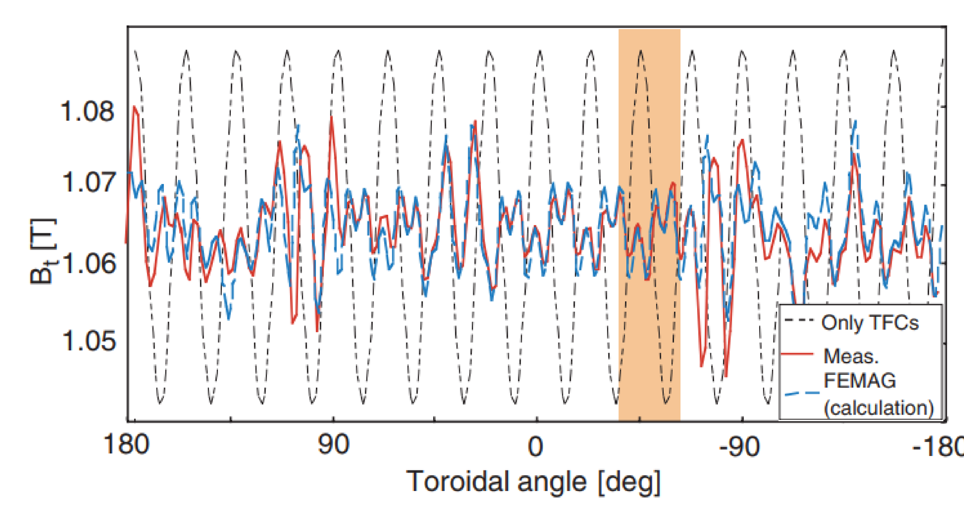
Ferritic Inserts are Used in Tokamaks and Designed for ITER

- Ferritic inserts used in the JFT-2M tokamak and have shown to reduce coil ripple, n= 16 mode
- Higher order harmonics arise, specifically secondary and tertiary ripple modes n = 32, 48
- Ferritic inserts are placed inside the coils and only on the outboard, low field side

[4]

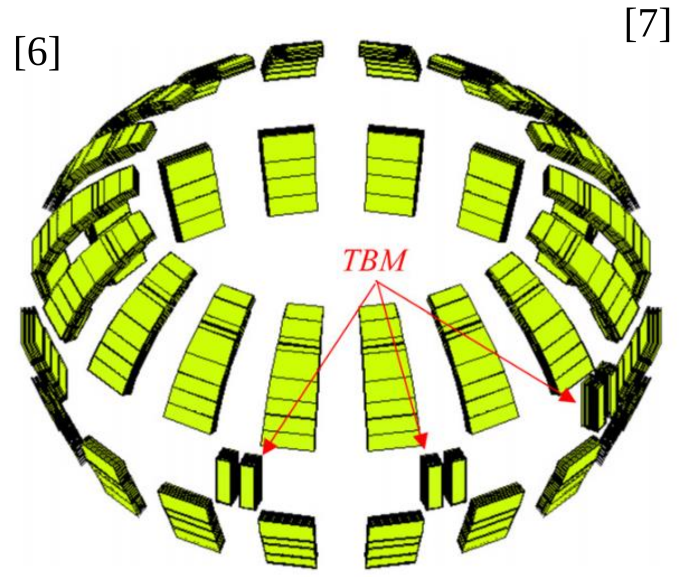


[5]

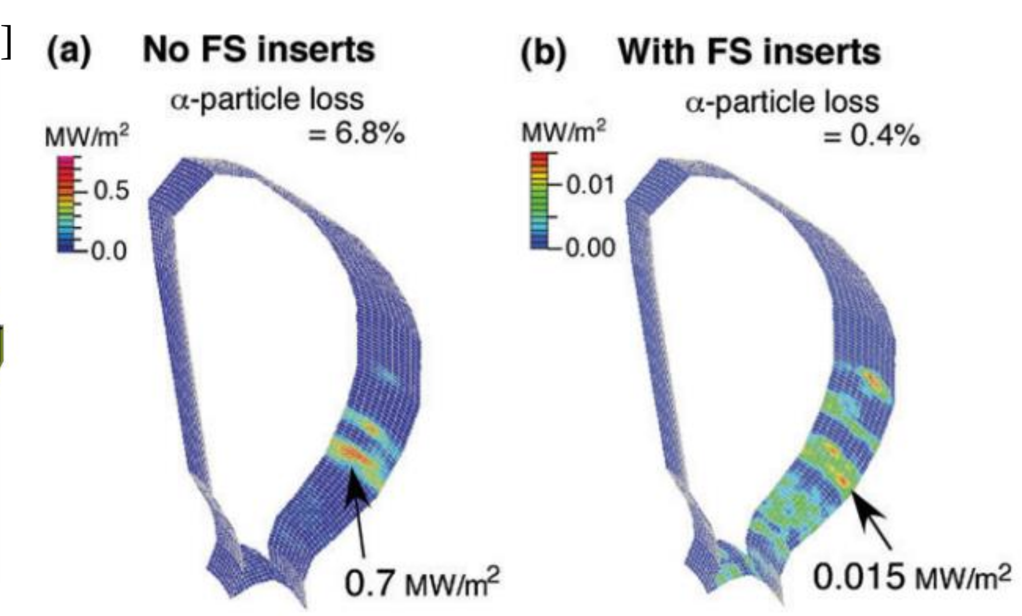


- Ferritic inserts are going to be used in ITER and have important physical implications
  - Reduced coil ripple
  - Decrease alpha particle loss
  - Decrease heat fluxes to first wall

[6]

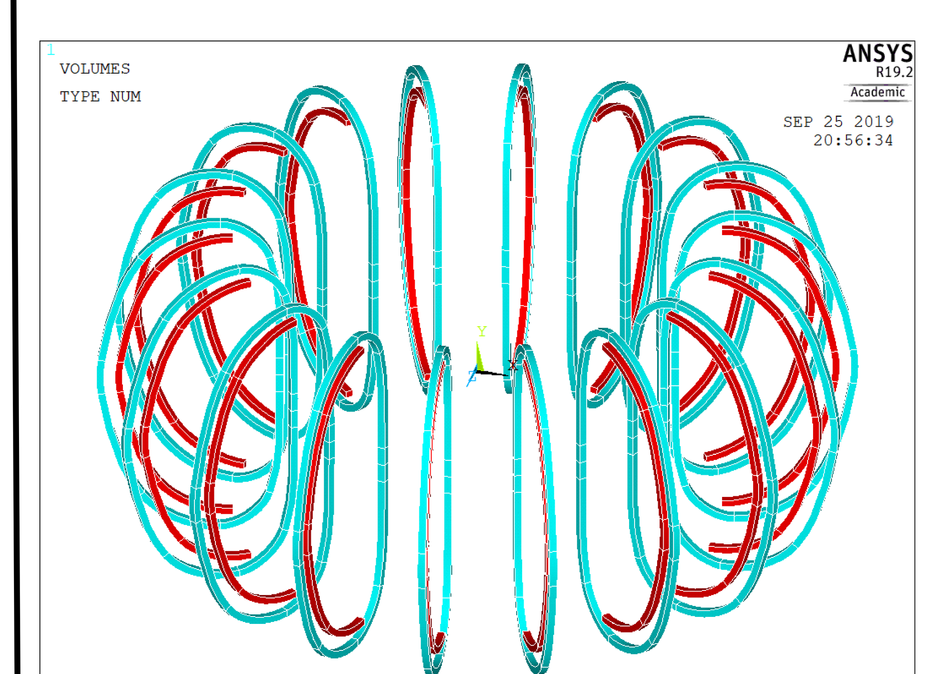


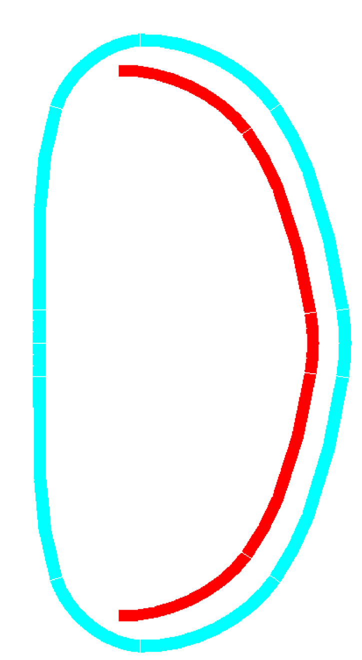
[7]

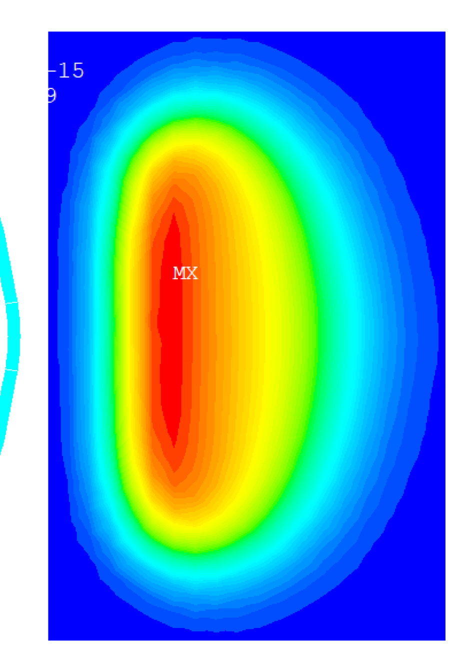


Example of Ferritic Inserts for a Shaped Tokamak

- D shaped tokamak coils modeled with rectangular coil cross sections and uniform current density
- Ferritic material with relative permeability equal to 1000, roughly equal to ferromagnetic steel

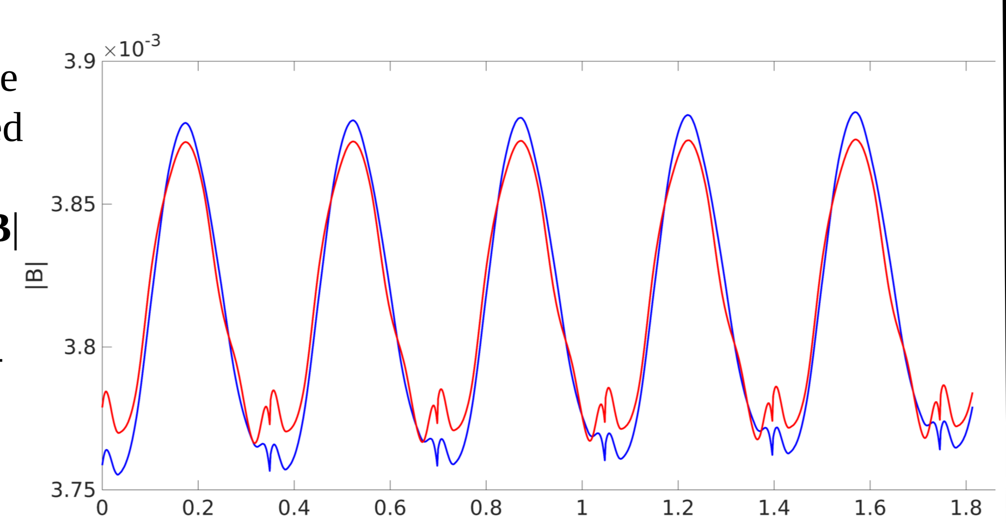






- Ripple of coils plotted in blue and ripple of coils with ferritic inserts plotted in red
- Zero ripple case would have constant |**B**|

$$\delta_{TF}(R,Z) = \frac{B_{\varphi,max}(R,Z) - B_{\varphi,min}(R,Z)}{B_{\varphi,max}(R,Z) + B_{\varphi,min}(R,Z)}$$



- Modular coil ripple is reduced from roughly 1.5% to 1.2%

Progress on Ferritic Inserts for the HSX Stellarator

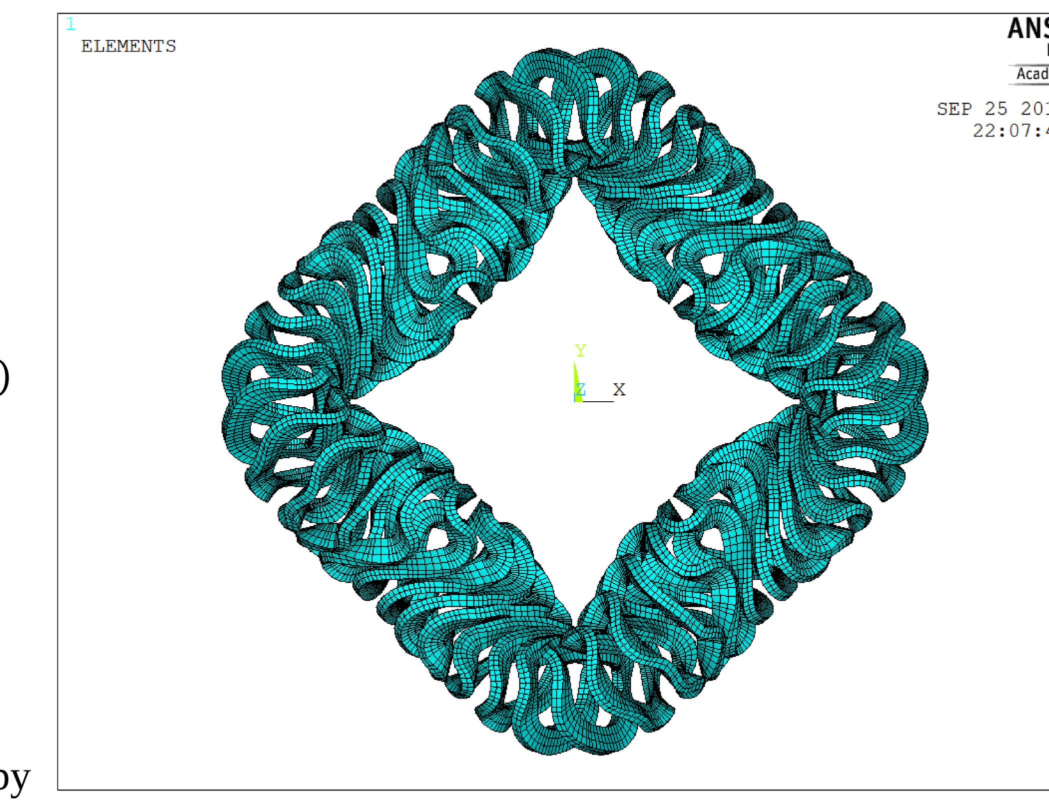
- Model of HSX coils has been created in ANSYS
- Ripple calculation for stellarator is from Boozer spectrum

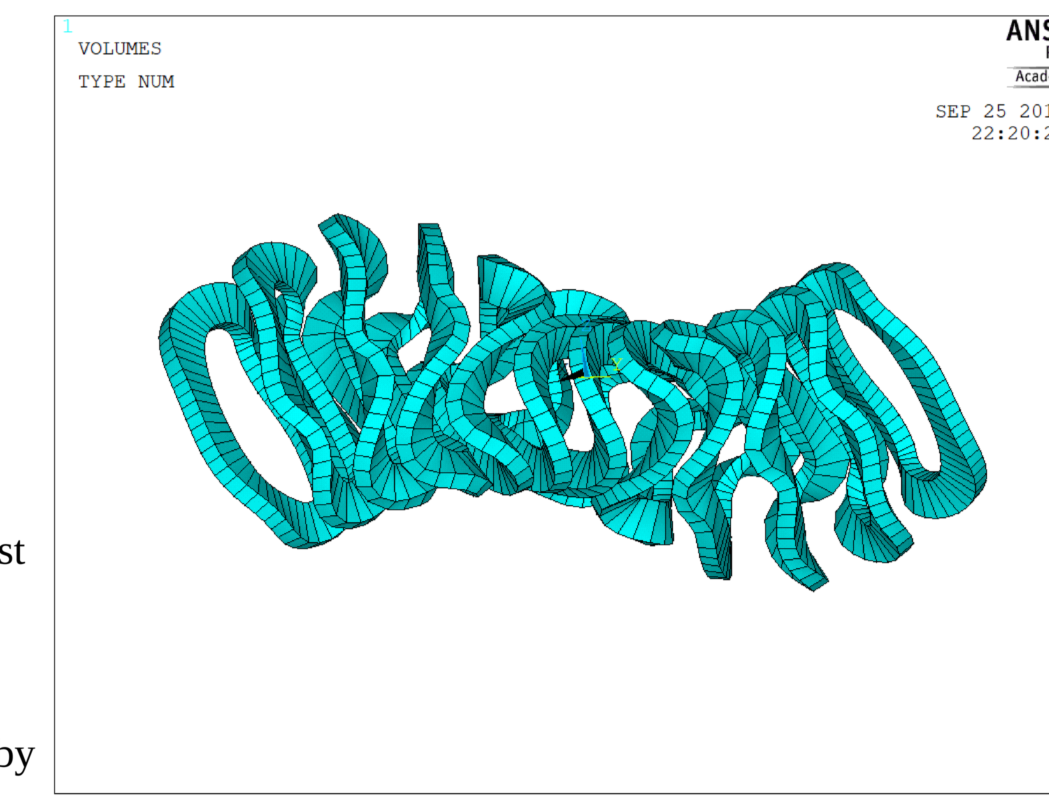
$$B = B_0 \sum_{n,m} b_{nm} \cos(n\varphi - m\theta)$$

- Modular coil ripple for the HSX stellarator is captured in the $b_{48,0}$ mode amplitude
- Initial ferritic inserts can be approximated and optimized by assuming a magnetization direction and using a far field dipole field

$$\boldsymbol{B}(\boldsymbol{r}) = \frac{\mu_0}{4\pi}\left[\frac{3(\boldsymbol{m}\cdot\hat{\boldsymbol{r}})\,\hat{\boldsymbol{r}} - \boldsymbol{m}}{r^3}\right]$$

- Low field side of field is observed to have highest coil ripple
- Ferritic inserts will be placed on low field side due to highest ripple being on low field side
- Optimization of $b_{48,0}$ mode amplitude will be carried out by minimizing $\int d^2a\, B_{normal}^2$





Future Work

- Implement a more accurate interpolation from ANSYS tetrahedral mesh to mgrid
- Compare magnetic field solutions from ANSYS finite coils to multi-filament models
- Construct a realistic tokamak coil set model in ANSYS, possibly ITER
- Optimize ferritic inserts for the realistic tokamak model
- Perform optimization of approximated magnetic dipoles and use solution as input to optimization of ANSYS model
- Constrain optimization to toroidal anulus which will be defined by spacing between coils and vacuum vessel
- Evaluate ripple reduction through boozer spectrum
- Optimize ferritic inserts for existing and future stellarators and calculate difference of fusion born alpha particles losses at ARIES-CS scale

References

- [1] ANSYS Academic Research Mechanical, Release 19.2
- [2] M. Landreman, Nuclear Fusion, 57(4), 046003 (2017)
- [3] C. Zhu et al., Plasma Physics and Controlled Fusion, 60(6), 065008 (2018)
- [4] K. Shinohara et al., Fusion Science and Technology, 49:2, 187-196 (2006)
- [5] K. Shinohara et al., Nuclear Fusion, 43, 586 (2003)
- [6] K. Shinohara et al., Nuclear Fusion, 51, 063028 (2011)
- [7] K. Tobita et al., Plasma Phys. Control. Fusion, 45, 133 (2003)

This work is supported by US DOE grant DE-FG02-93ER54222 and UW Foundation under grant 135AAD3116

22nd ISHW, September 23-September 27, 2019, Madison, Wisconsin