NSTX-U

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Numerical optimization of perturbative coils for tokamaks

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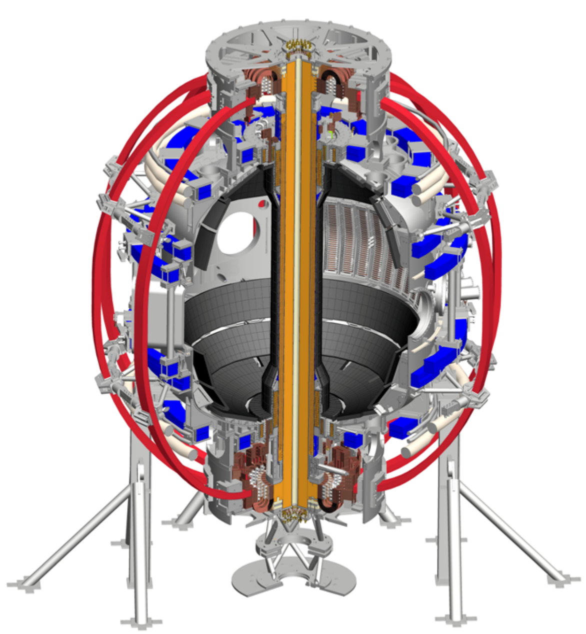

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The application of 3D fields in Tokamaks is commonplace

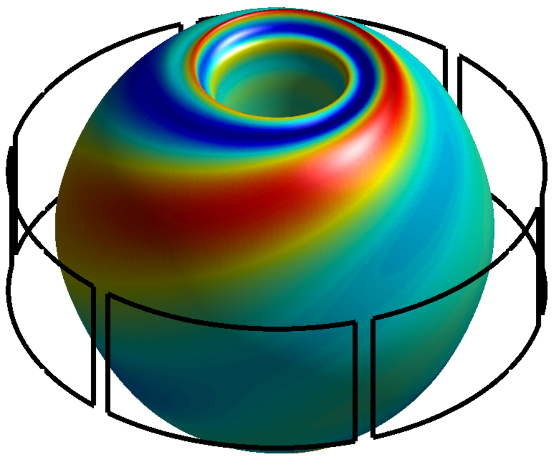
- Tokamaks can greatly benefit from the application of 3D fields
  - Edge Localized Mode (ELM) Control
  - Resistive Wall Mode (RWM) Control
  - Neoclassical Tearing Mode (NTM) Control
  - Error Field Compensation
  - Neoclassical Toroidal Viscosity (NTV) Torque Control

Focus for this talk will be on NTV torque control with applied 3D fields.

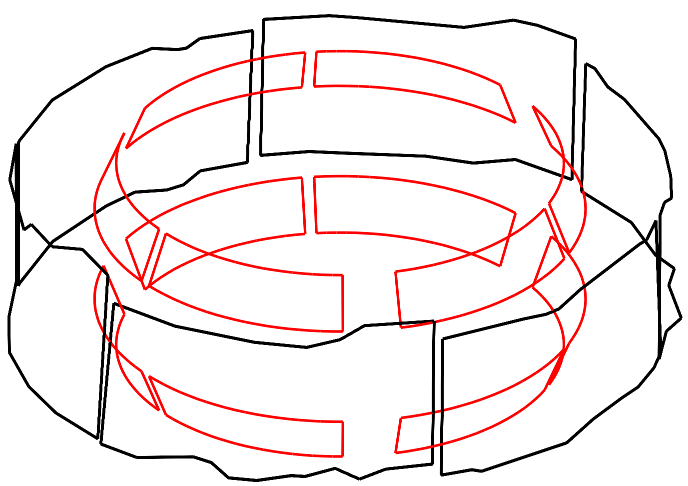
How do we design these coils?

- The design of 3D perturbative coils is dominated by engineering constraints
  - Usually built after the machine
  - Often placed outside the vessel for simplicity
  - Physics focus is on toroidal spectrum control
  - Shapes are simple

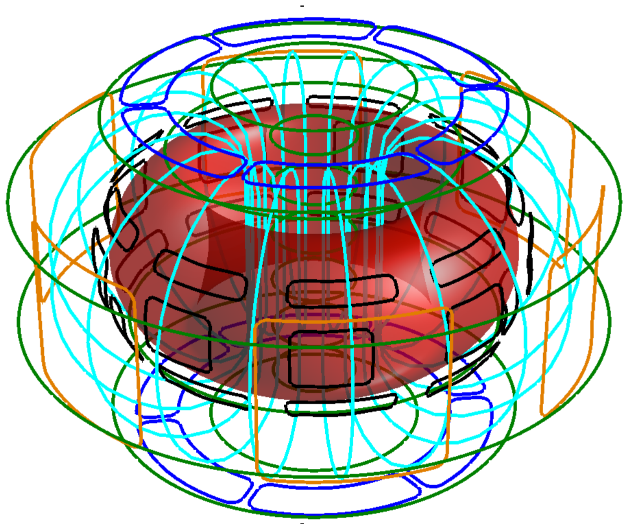
There is a better way!



NSTX



DIII-D



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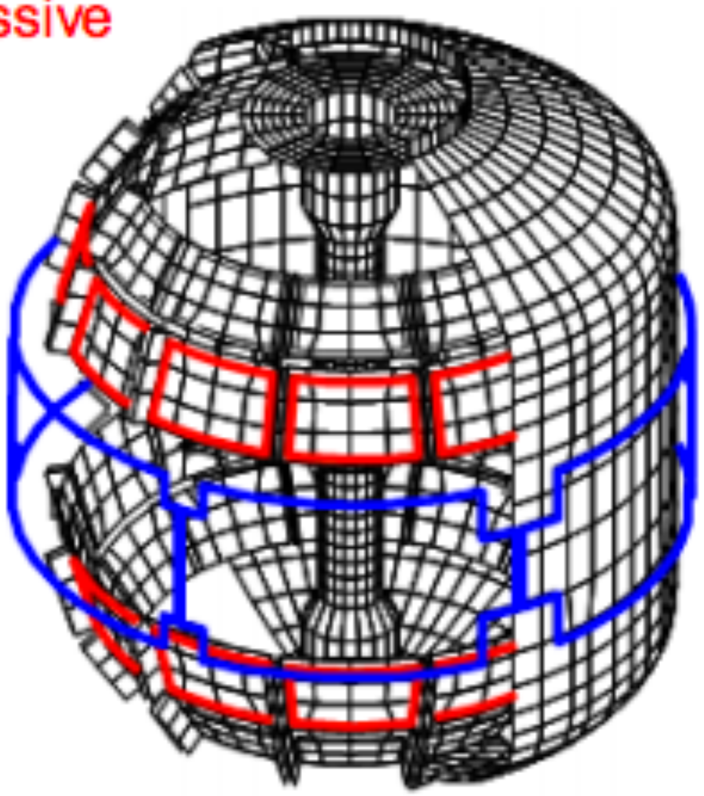
The NSTX Upgrade has motivated looking at new coils

- Part of the NSTX upgrade includes a set of in-vessel 3D perturbative coils (NCC coils)



  - The planned coils clearly have a great deal of utility.
  - If we could redesign them where would we like to put them to control NTV torque?
  - What do numerically optimized coils look like?
  - How close can the NCC coils get us to the numerically optimized physics parameters?

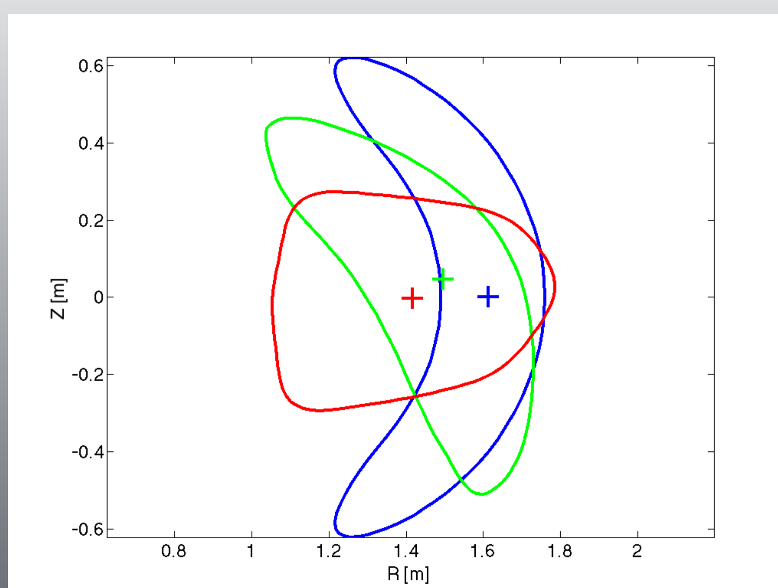
Stellarator optimization can answer these questions!

Stellarator Optimization Fits Model Inputs to Target Physics Parameters

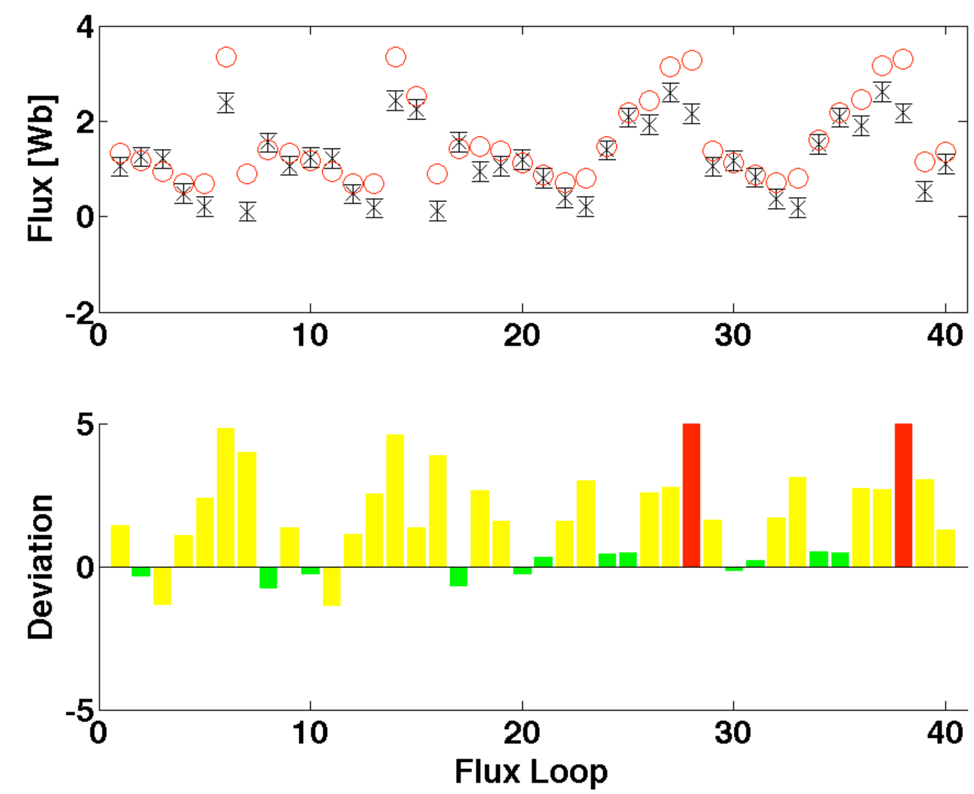
Input Parameters
- Boundary Coefficients
- Vacuum Fields
- Pressure, etc.

These need to result in a good match to these.

Equilibrium Model

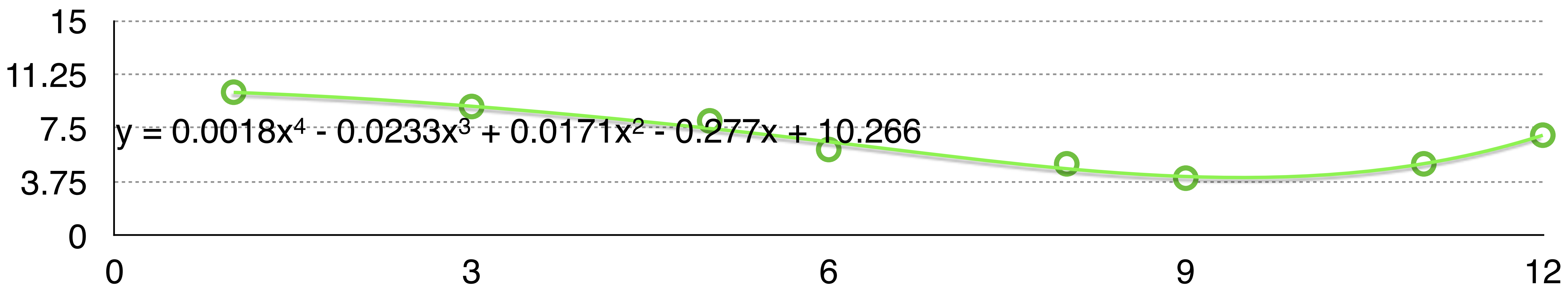


Modeled Values



What methods allow us to optimize our 3D fields?

- In the most general terms we're conducting a non-linear curve fit
  - The input parameters to our equilibrium code serve as our curve coefficients
  - The output from our equilibrium code (or secondary codes) fulfills the roles of our curve
  - Thus many techniques are available to us:
    - Gradient descent, Newton's method, Levenberg-Marquardt, Genetic Algorithms, Differential Evolution, Particle Swarm, Simulated Annealing…



What tools allow us to optimize for NTV torque control?

- The stellarator community has developed STELLOPT[1] for this exact task
  - STELLOPT relies on VMEC
  - Lacks experimental validation at this level
- The IPECOPT code utilizes experimentally validated models
  - The IPEC[2] code computes the perturbed ideal MHD equilibrium model
  - The PENT[3] code then calculates the NTV torque based on this perturbed equilibrium
  - The IPECOPT code reuses the optimization machinery of STELLOPT
  - Highly modular so new targets may be easily added

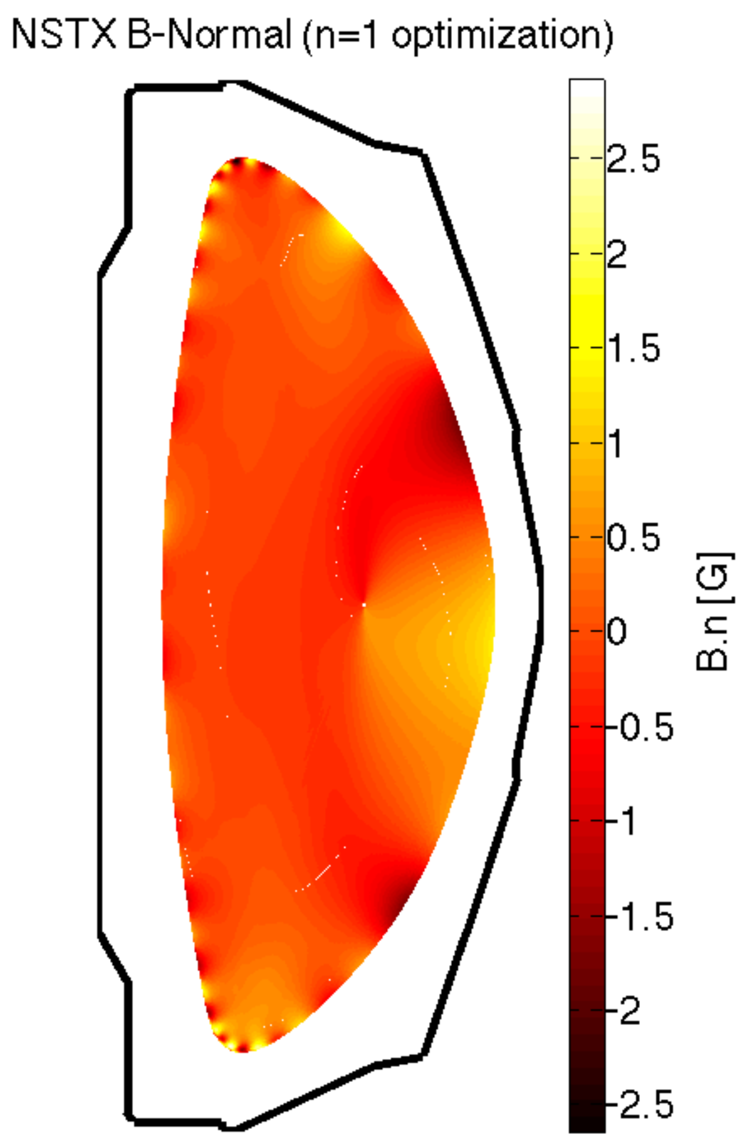
[1] D.A. Spong et al. 2001 Nucl. Fusion 41 711
[2] J-k Park et al. 2007 Physics of Plas. 14 052110
[3] N.C. Logan et al. 2013 Physics of Plas. 20 122507

Ideal Perturbed Equilibrium Code (IPEC)

- IPEC solves the linear ideal perturbed equilibrium equation

$$\nabla \delta p = \delta \vec{j} \times \vec{B}_0 + \vec{j}_0 \times \delta \vec{B}$$

- Utilizes the output from DCON
- Inverse representation (single toroidal mode number)
- Utilizes virtual casing technique
  - Input: B-Normal on boundary
  - Output: Plasma response



Perturbed Equilibrium Nonambipolar Transport (PENT)

- PENT solves for neoclassical toroidal torque
  - Utilizes the IPEC equilibrium
  - Solves the following integral equations

$$T_\phi = -\frac{n^2}{\sqrt{\pi}}\frac{R_0}{B_0}\int d\Psi NT \int d\Lambda \bar{\omega}_b \left|\delta \vec{J}_l\right|^2 \int dx \Re_{Tl}$$

$$\Re_{Tl} = \frac{\left[\omega_\phi + \omega_{*T}\left(x - \frac{5}{2}\right)\right] x^{5/2} e^{-x}}{i\left[\left(l - \sigma nq\right)\omega_b + n\left(\omega_E + \omega_D\right)\right] - \nu_i}$$

An IPEC based optimization code (IPECOPT)

- Calculates a least squares fit of IPEC input parameters to target physics parameters
  - Based on STELLOPT
  - Multiple optimization techniques
  - Targeting NTV torque as calculated by PENT
  - Fixed and free boundary optimizations

$$\chi^2 = \sum_{i=1}^{m} \frac{\left(Y_i - y_i\right)^2}{\sigma_i^2}$$

m: number of targets

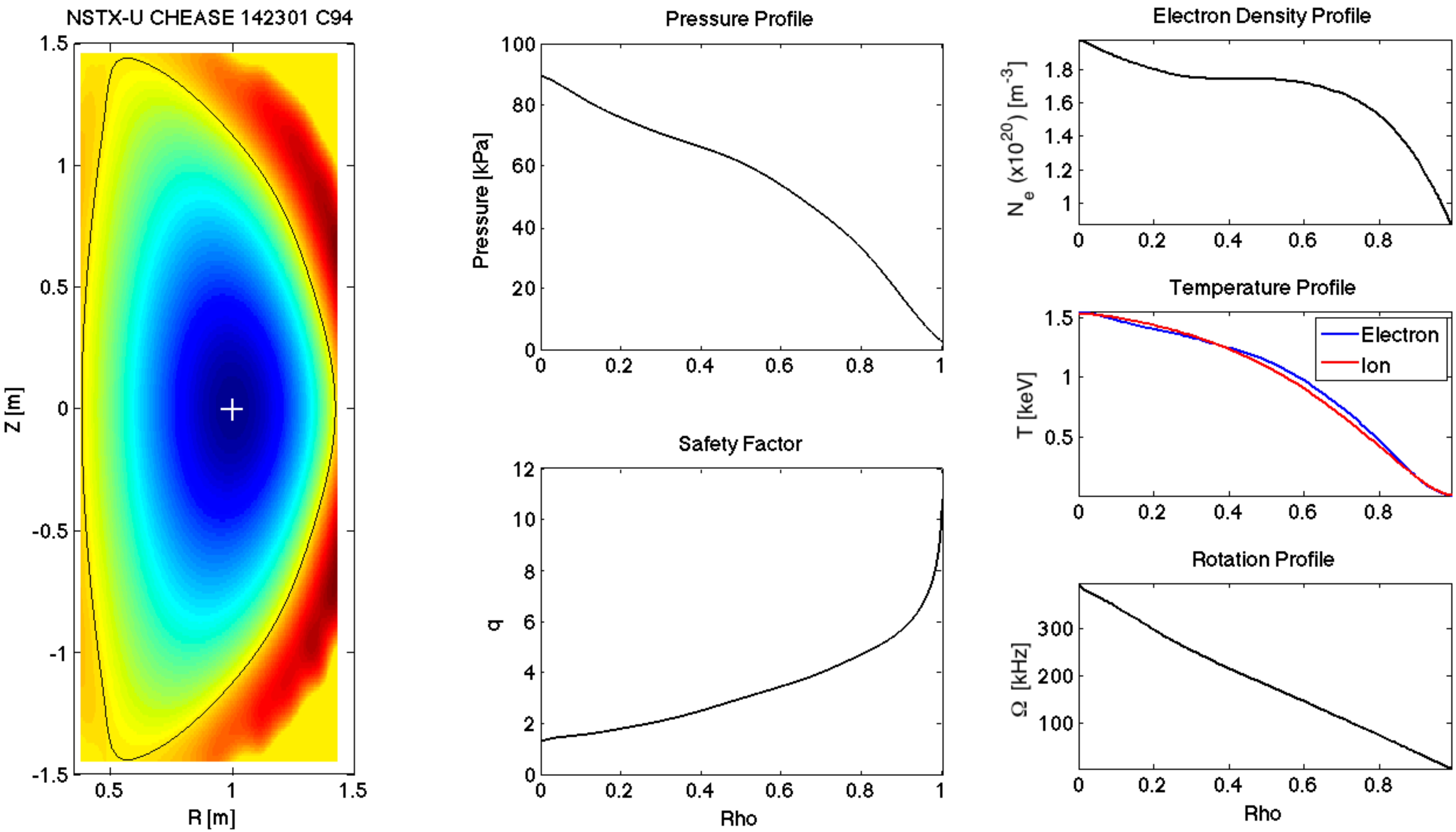
Y: target values

y: simulated values

sigma: weights

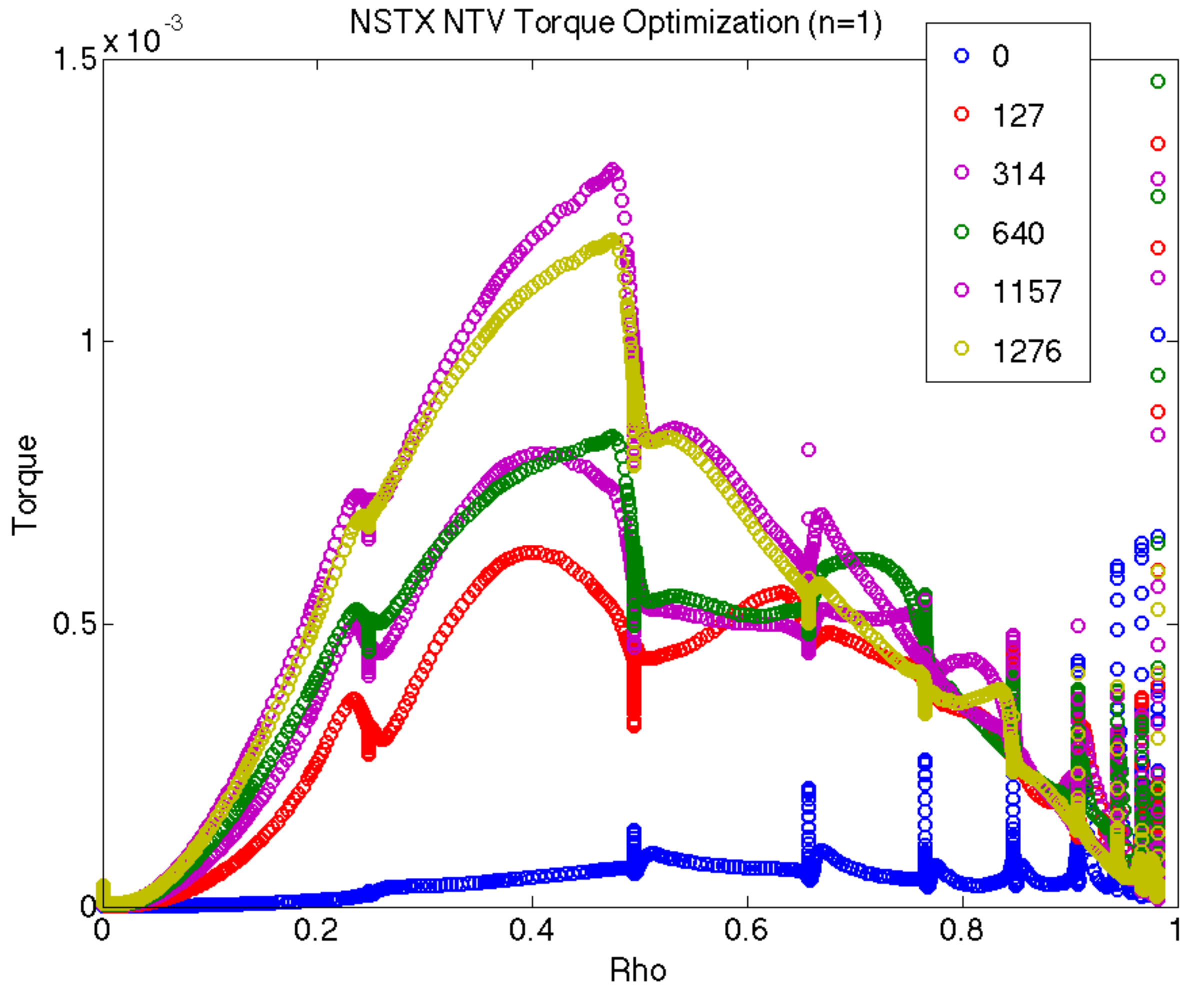
An NSTX-U equilibrium provides a basis for optimization

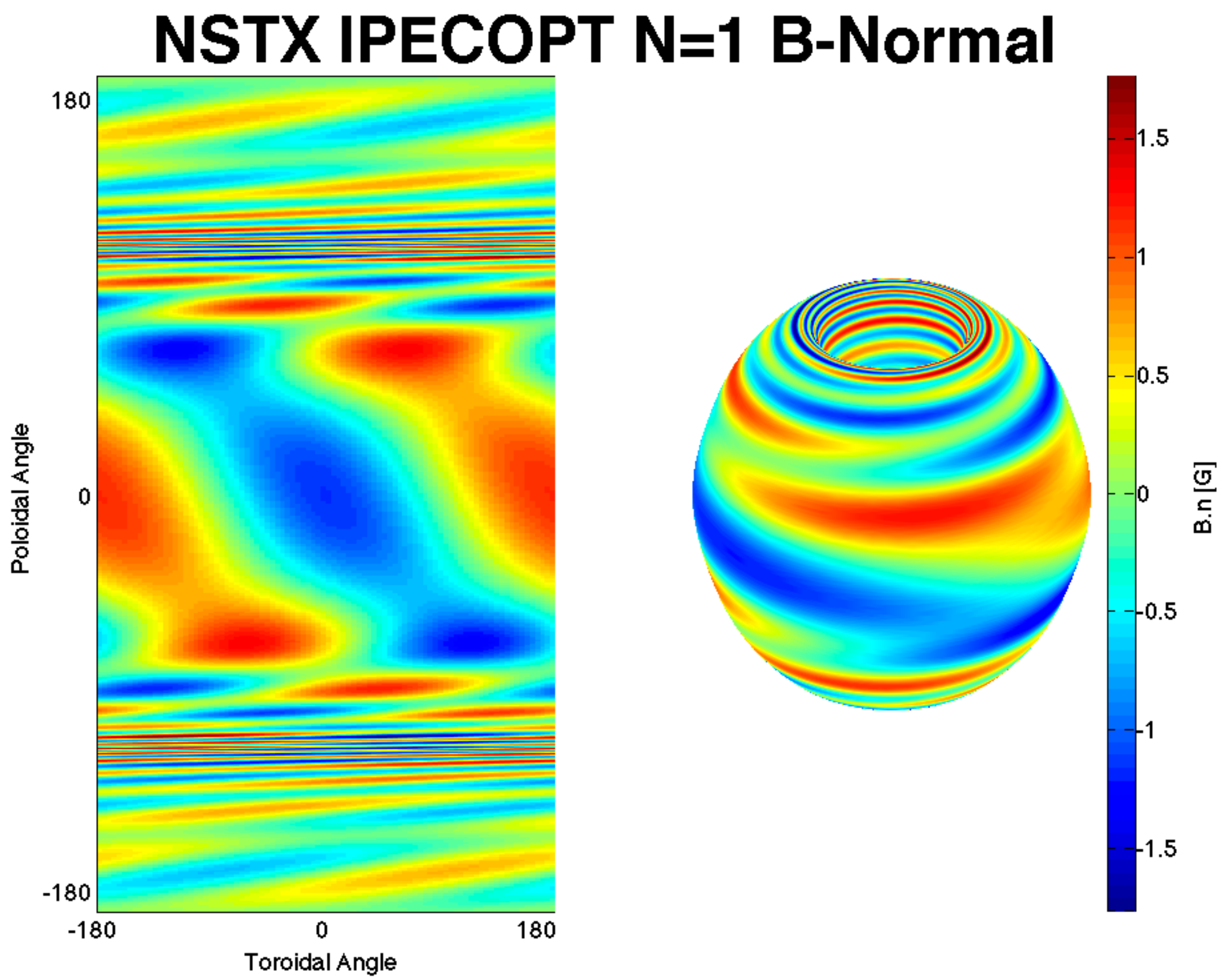
- The simulated NSTX-U equilibrium had the following properties



Can we optimize for core torque with n=1 fields?

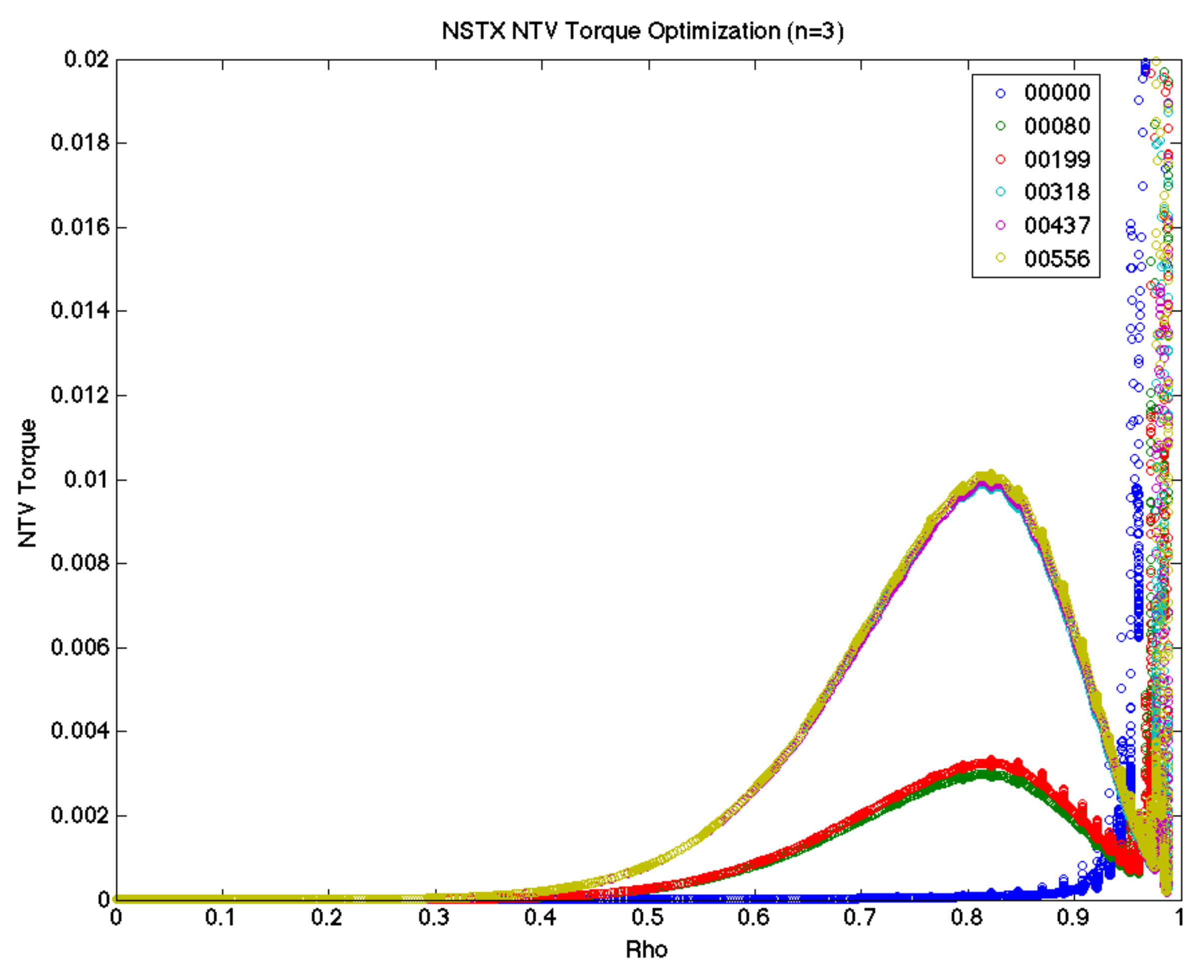
- Pitch non-resonant fields seem to drive core torque
  - Torque inside rho 0.5 maximized (outside minimized)
  - Total plasma field was optimized for n=1

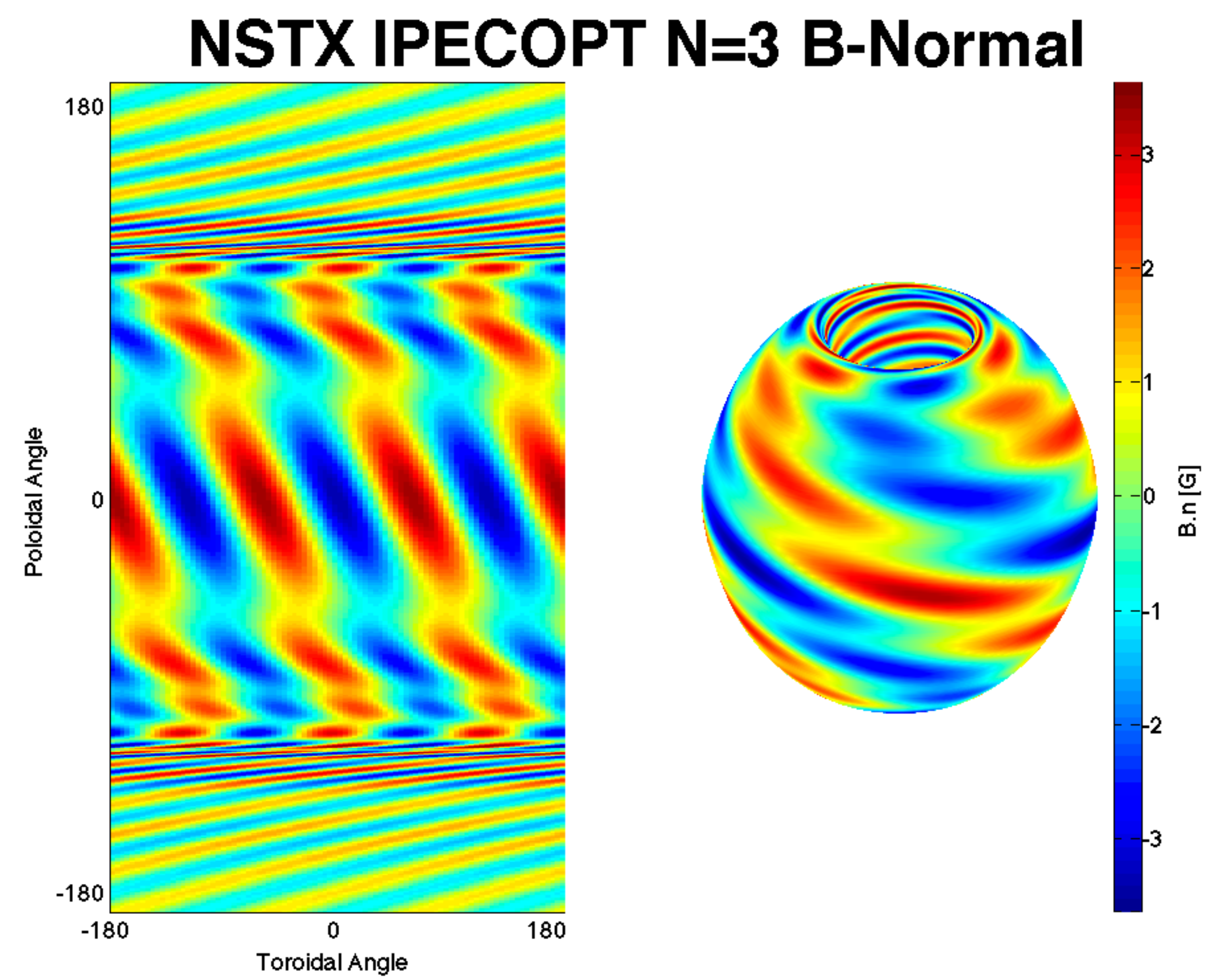




What about edge torque?

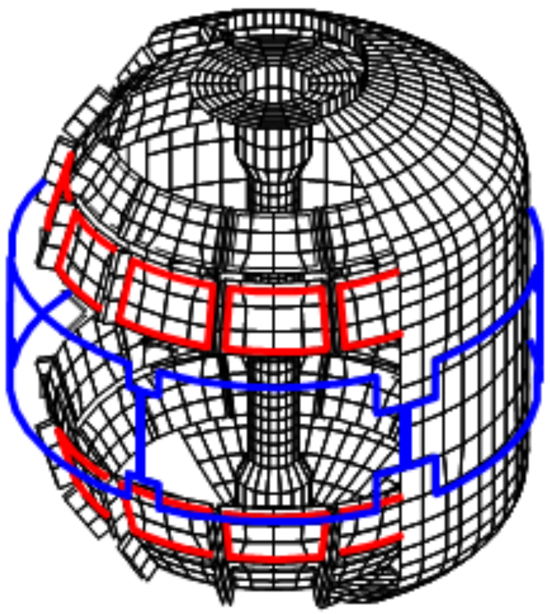
- Driving edge torque produced a more complex mode structure
  - Maximized torque outside of rho = 0.5 (minimized inside)
  - Total plasma field was optimized for n=3

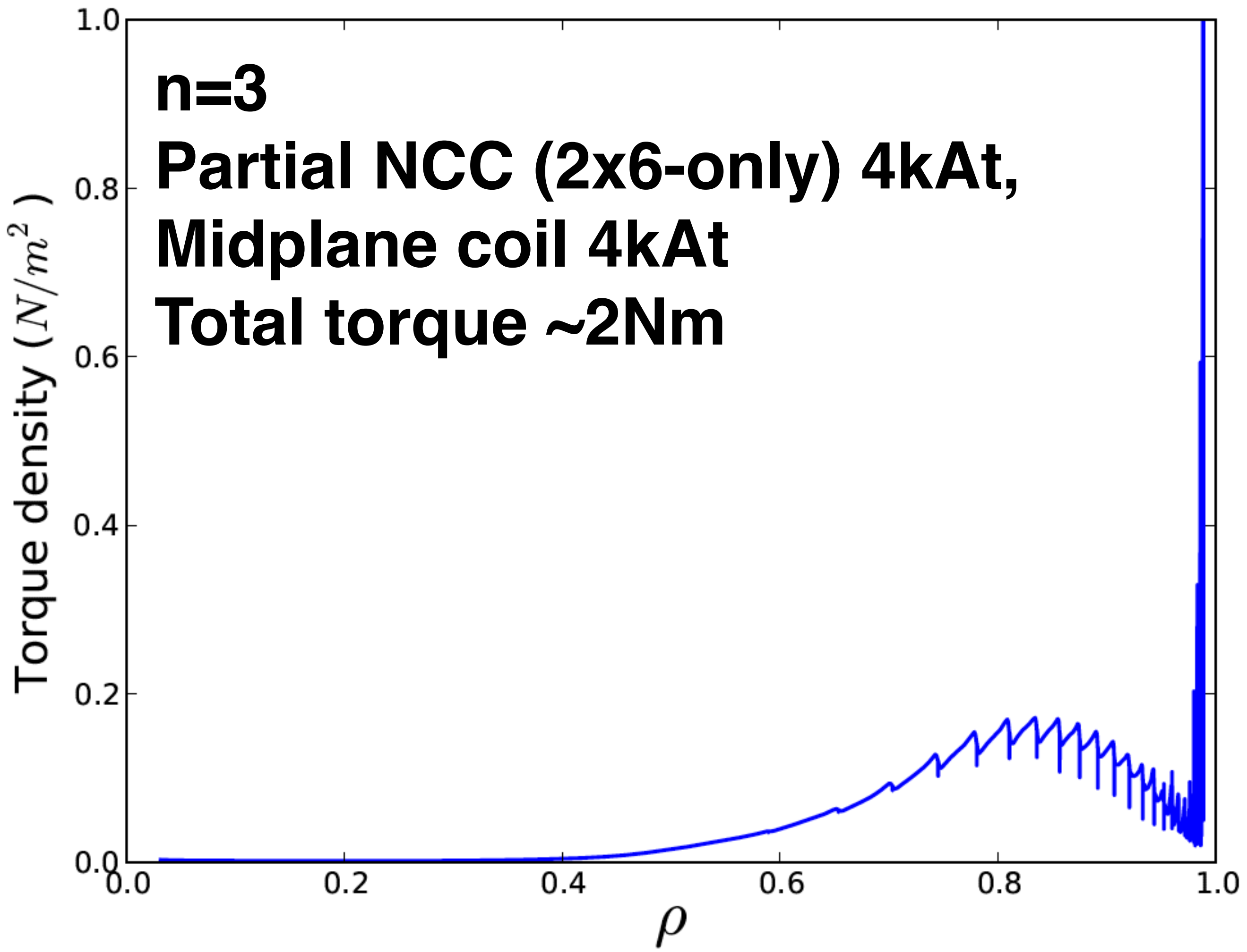


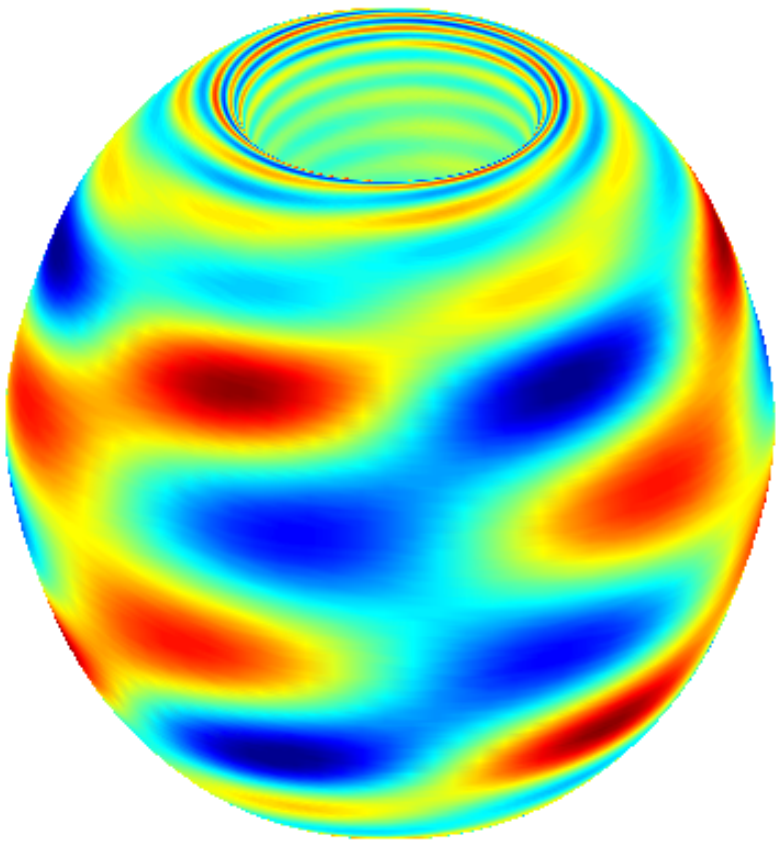


Can we mimic such a spectrum with the NCC?

- About twice the edge torque seemed possible.
  - Partial-NCC and mid-plane coils used
  - No numerical optimization performed







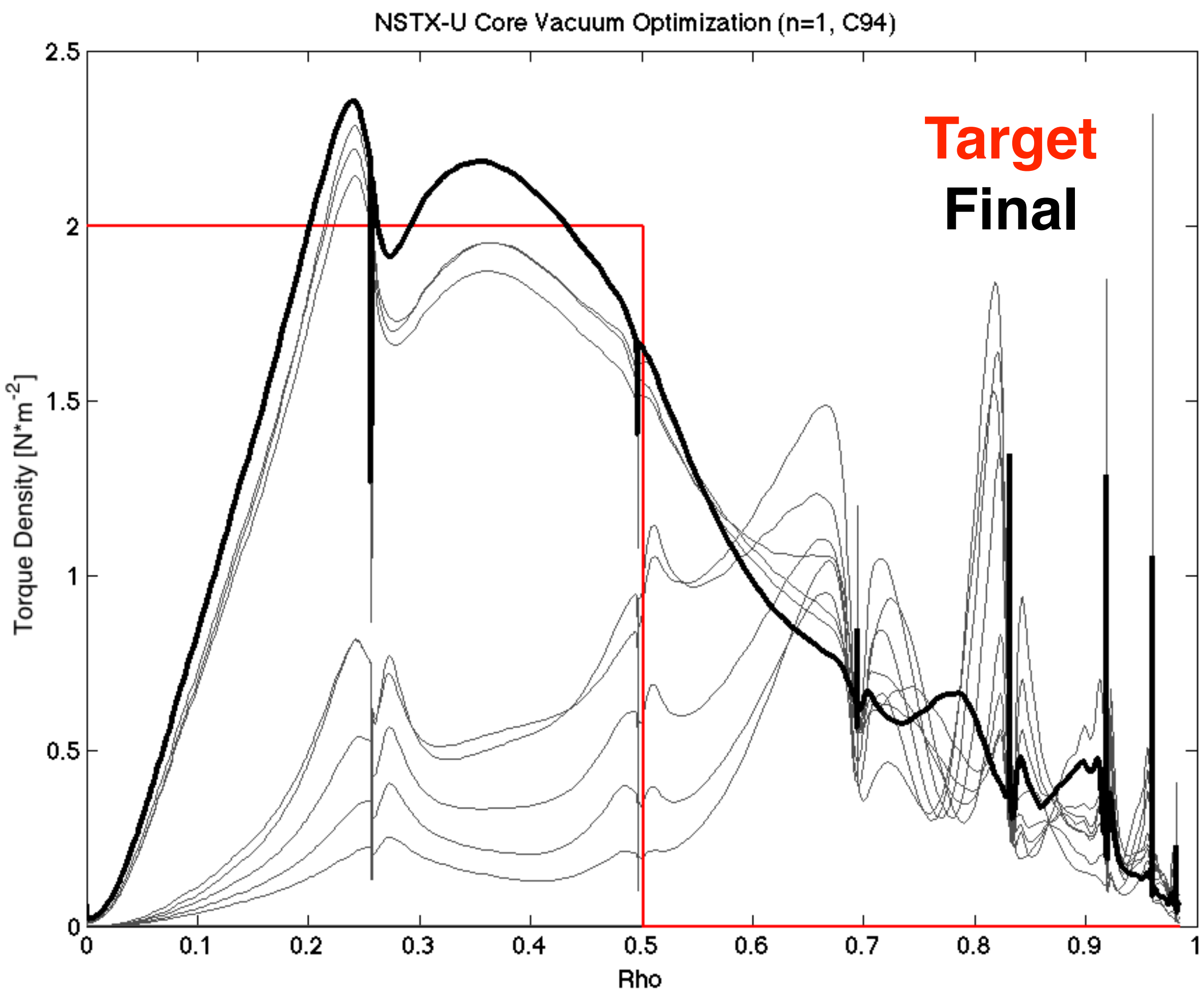
Work by J.K. Park

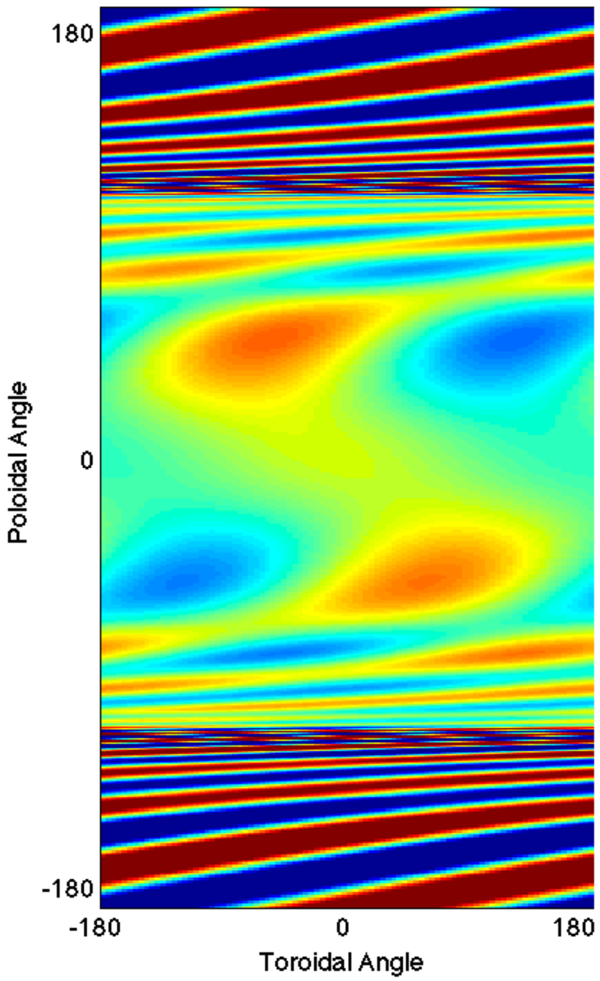
Total B-field optimization motivated continued work

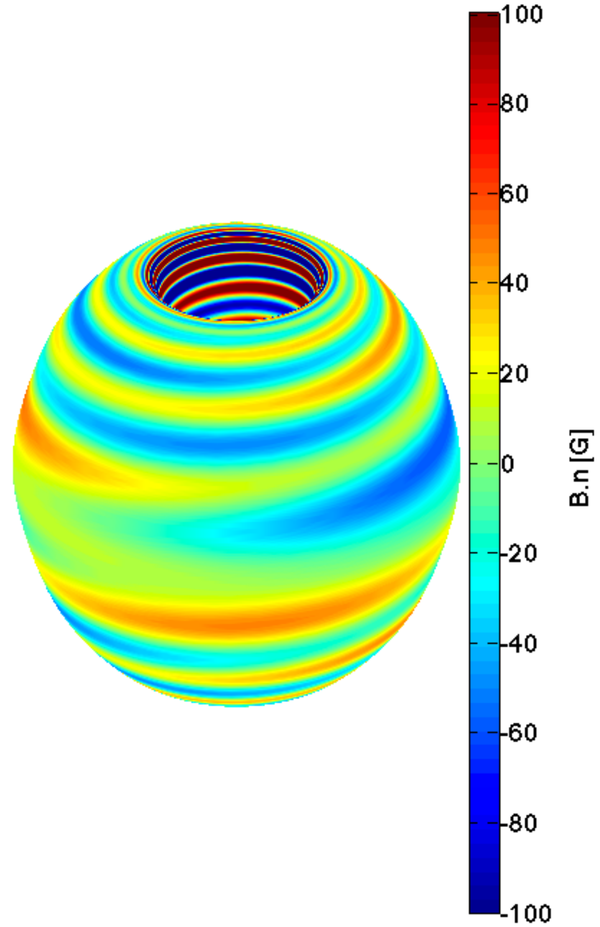
- Demonstrated that edge vs core torque may be controlled
  - Total response appears to be field line pitch crossing
  - Appears possible to reproduce with simple coils
- Motivated vacuum B-field optimizations (B-normal spectrum)
  - Larger target torques were considered
  - Here vacuum B-normal fields were optimized

Core torque control with n=1 was reexamined

- Larger core torque requires larger field amplitude
  - Pitch non-resonant behavior still present
  - Higher harmonics present

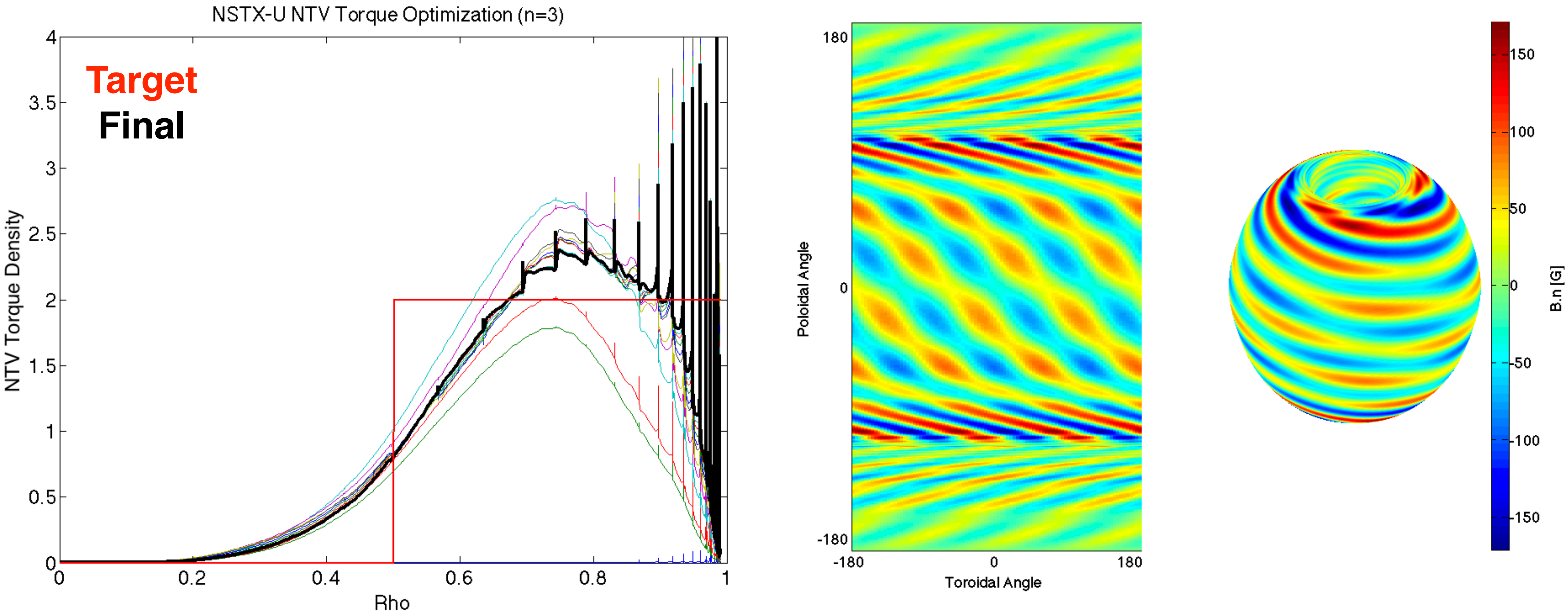






Vacuum fields were used to drive edge torque

- Relatively simple mode spectrum at larger torque amplitude
  - Edge torque targeted (~ 1 [Nm])
  - n=3 toroidal harmonics drive some edge resonances



IPECOPT can improve FOMs for NTV and RMP with NCC + mid-plane coils

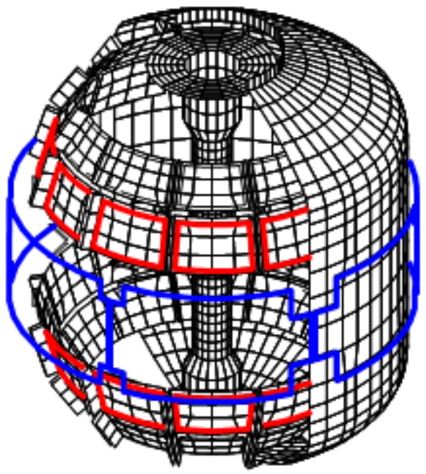
- Figures of merit (FOMs) for NTV and RMP were estimated without mid plane coils
- IPECOPT can be the best choice to perform 3-coil optimization and improve 2-coil FOMs

Figures of Merit	Favorable values	MID	12U	2x6-Odd	2x12
EF (n=1) $F_{N-R} \equiv \dfrac{T_{NTV}}{\sum_{\psi_N<0.85} \delta B_{mn}^2}$	High F	0.07	0.13	1.24	1.24
RWM (n=1) $F_\beta \equiv \dfrac{\beta_{active}}{\beta_{no-wall}}$	High F	1.25	1.54	1.61	1.70
NTV (n≥3) $\Delta\left(F_{N-N} \equiv \dfrac{T_{NTV}(\psi_N < 0.5)}{T_{NTV}(\psi_N < 1)}\right)$	Wide	1.00	1.44~6.08	1.75~11.33	6.38~59.4
RMP (n≥3) $F_{N-C} \equiv \dfrac{\left(C_{vacuum,\psi_N=0.85}\right)^4}{T_{NTV}}$	High F	0.25~0.30	0.31~1.04	0.43~0.77	1.18~3.53
	Wide	1.00	2.20~12.3	10.4~17.4	888~14400

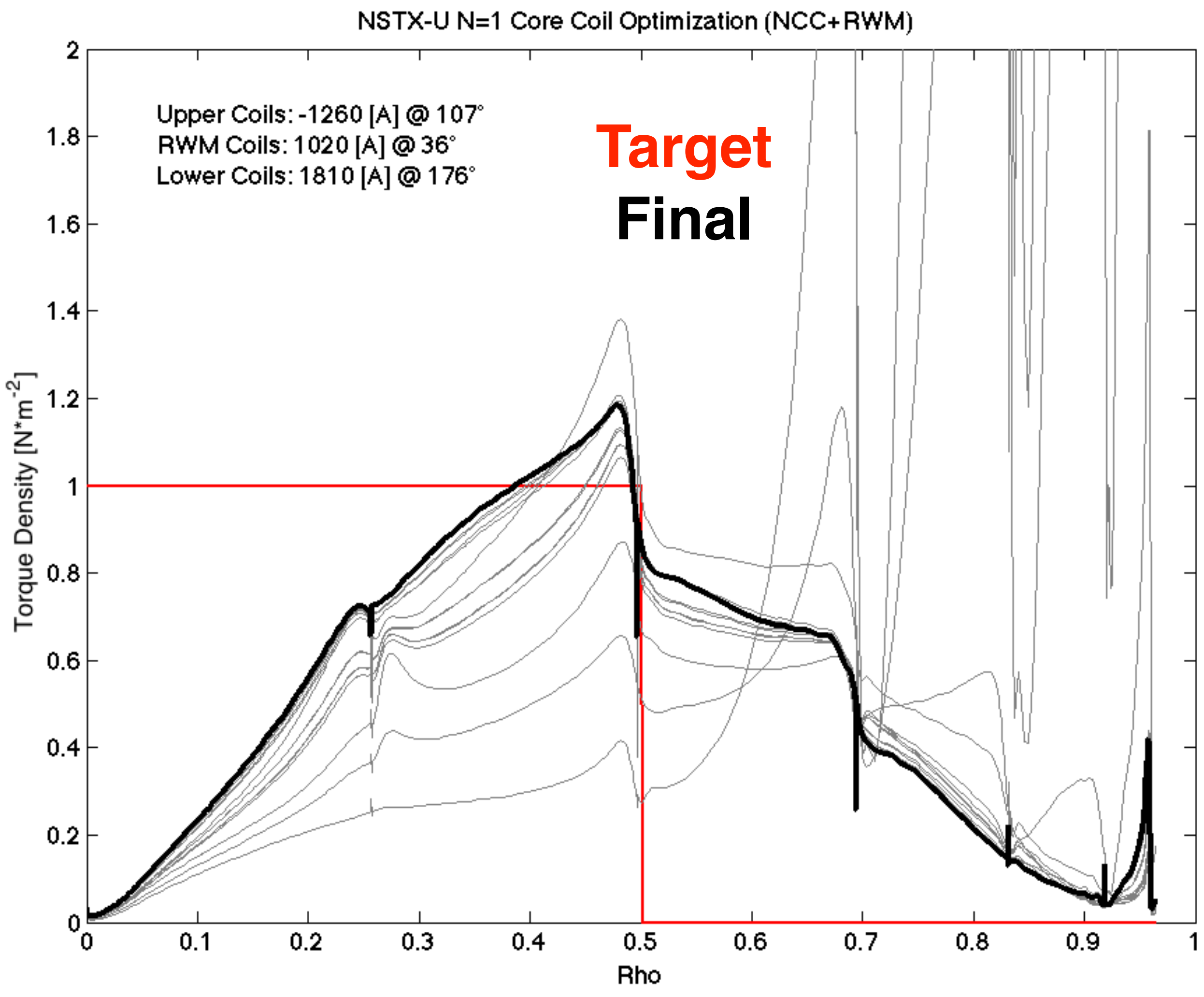
Table courtesy of J.K. Park

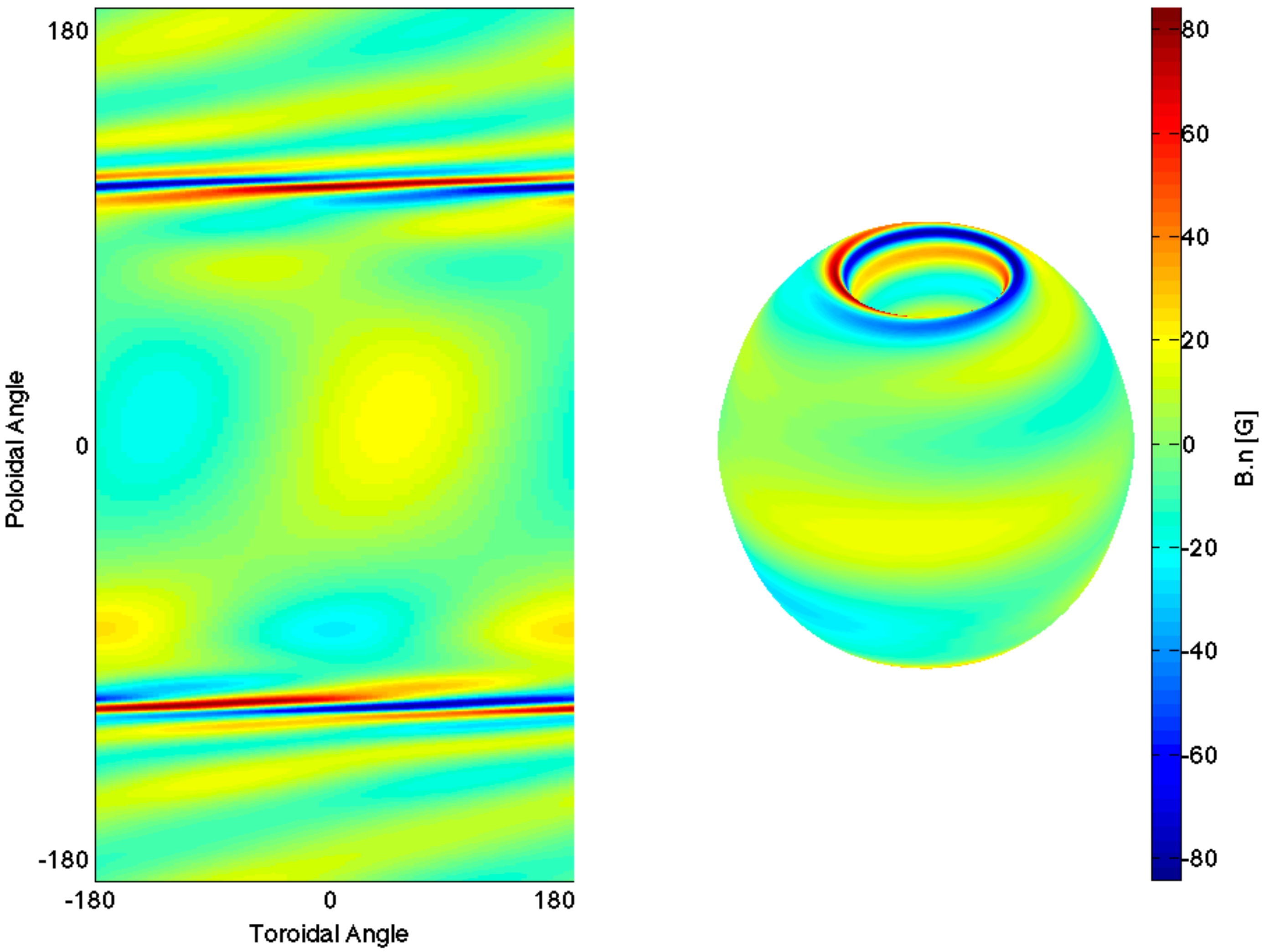
NCC+RWM coil currents optimized for core torque

- It is possible to drive meaningful core torque using the planned coil set with n=1 fields



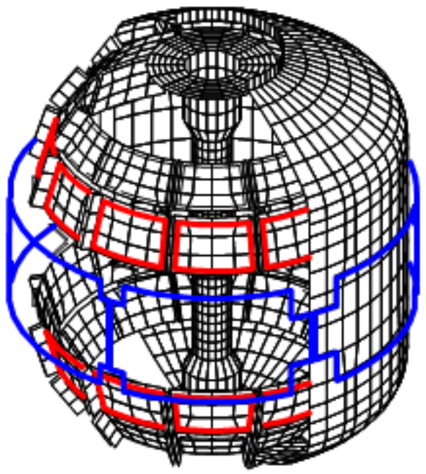
  - NCC + RWM coils optimized (6 free parameters)
  - Amplitude and phase of coil currents were optimized

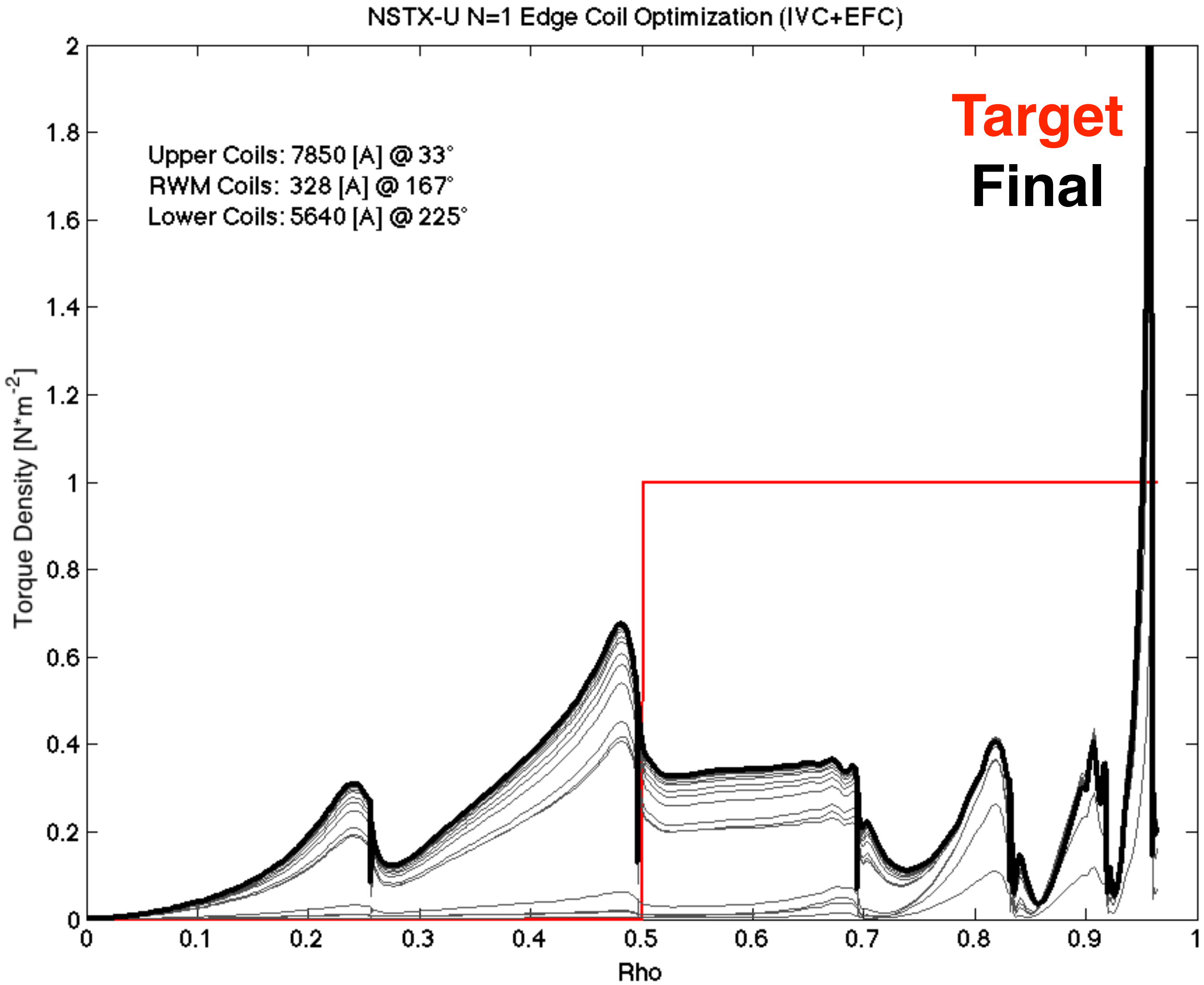


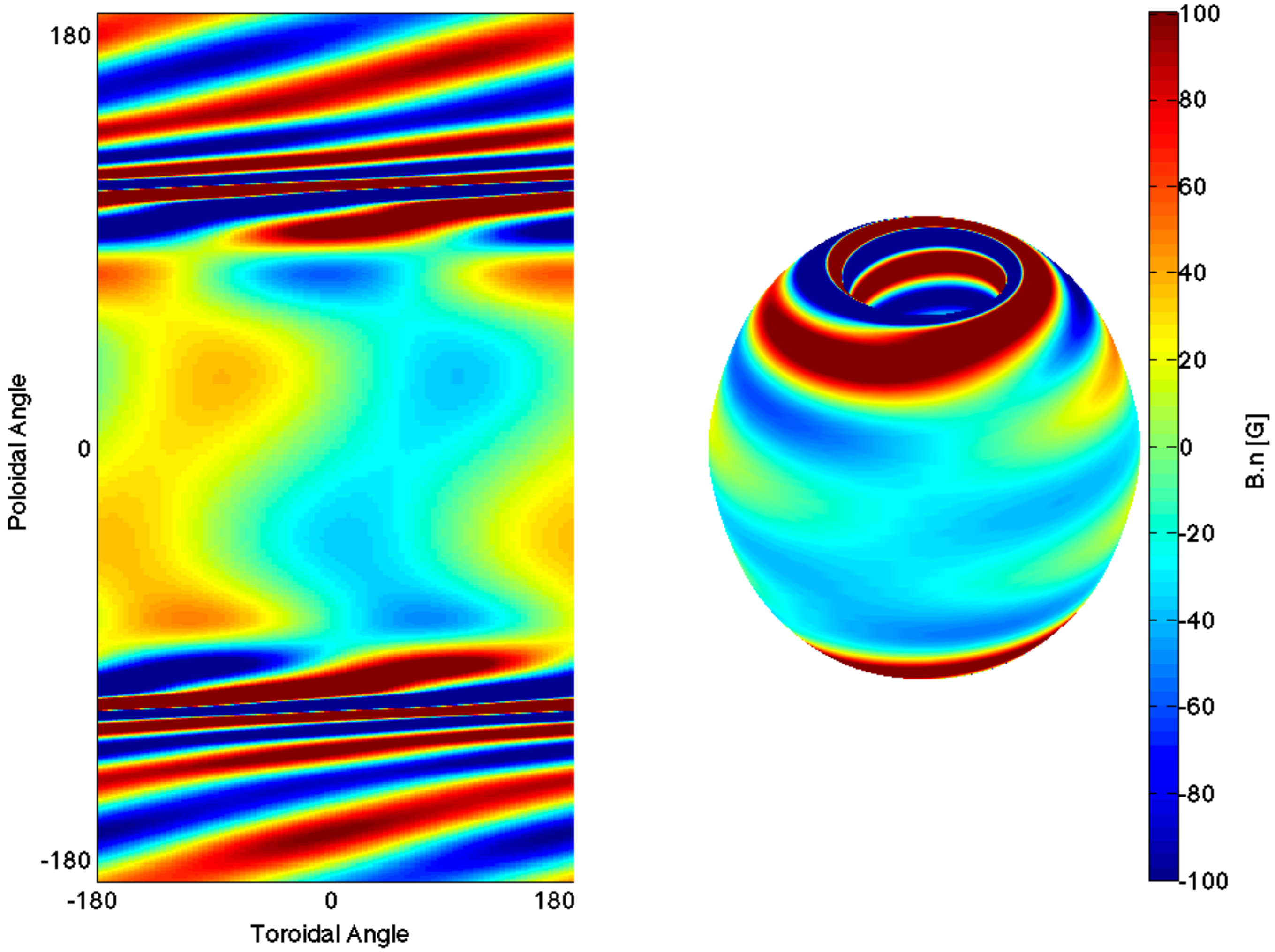


Difficult to drive edge torque with n=1

- The n=1 spectrum appears to drive edge torque
  - NCC coils were over-driven in amplitude
  - Difficult to drive edge torque over core with n=1

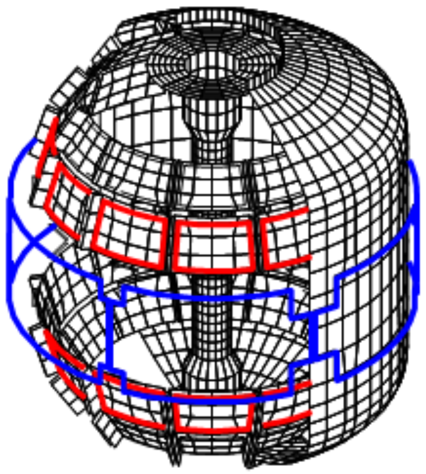


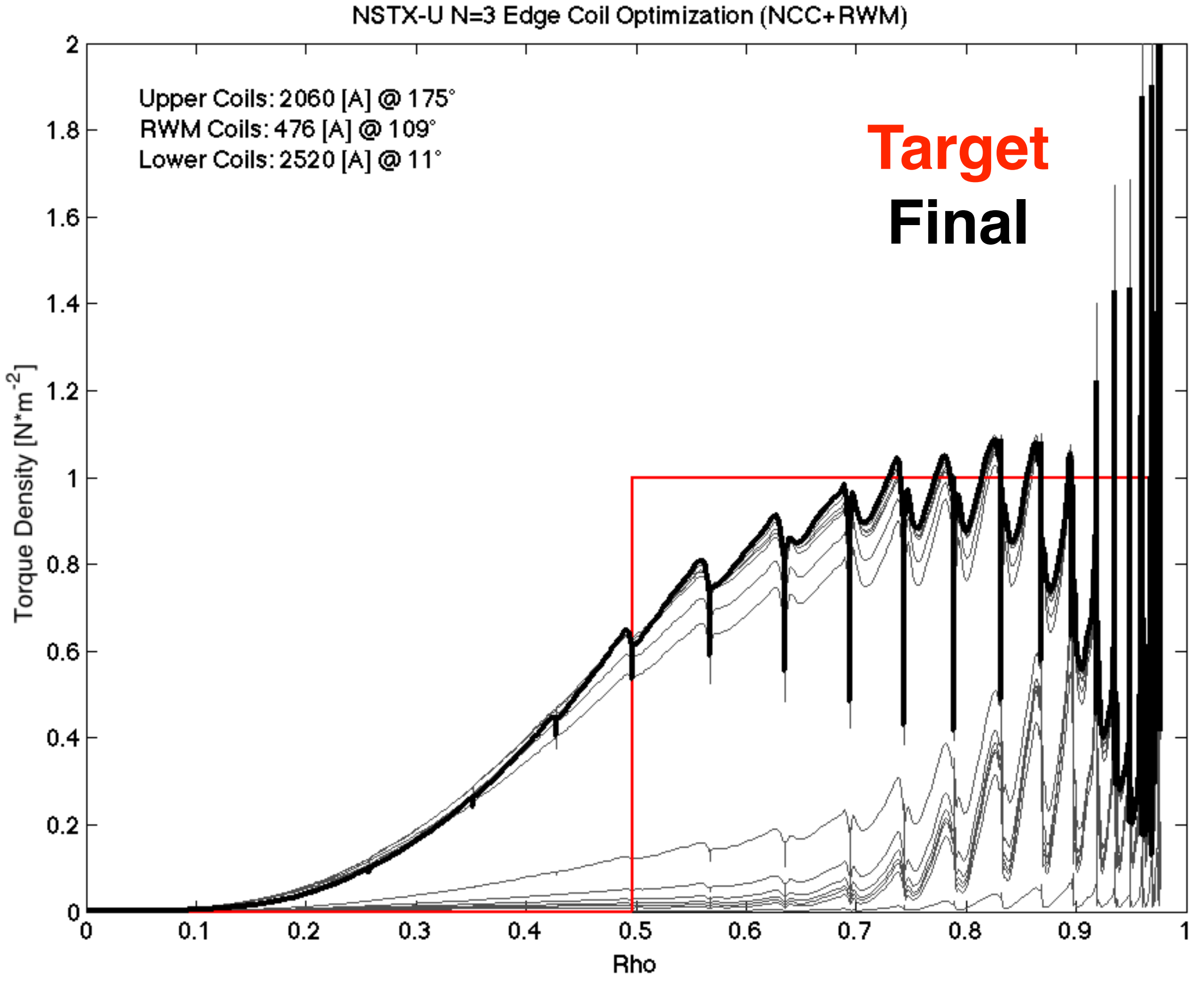


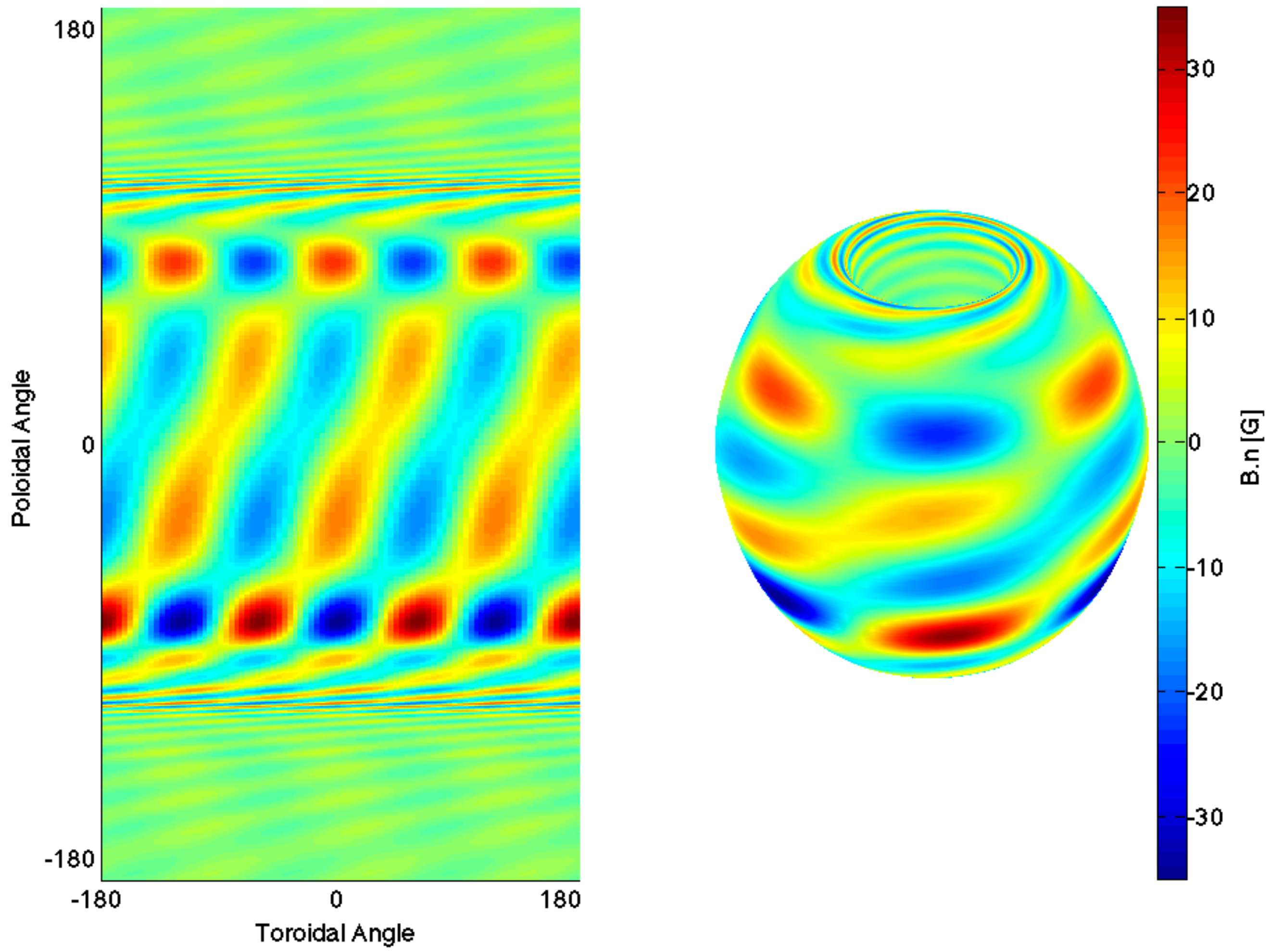


Edge torque driven with optimized n=3 coil currents

- Edge torque easily driven by n=3 fields
  - NCC coils provide the majority of the torque drive
  - RWM coils only have 2 phases for n=3

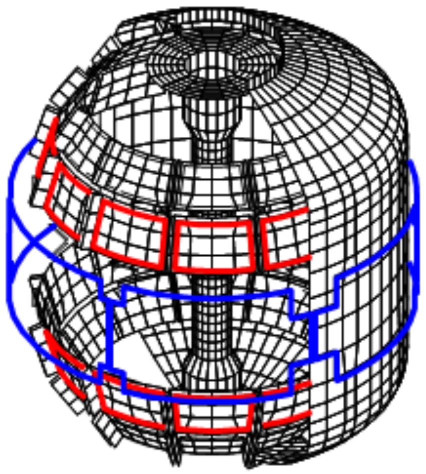


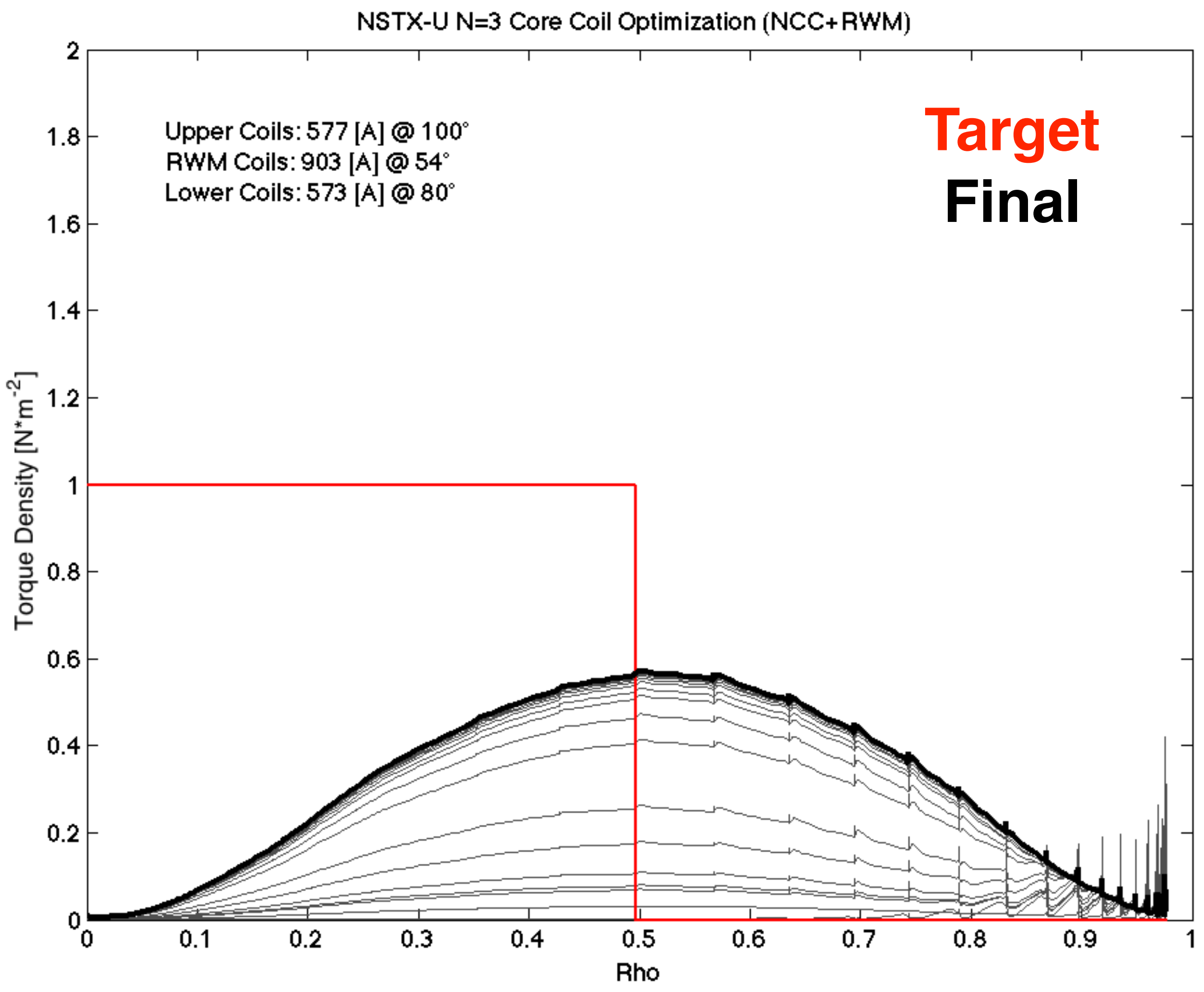


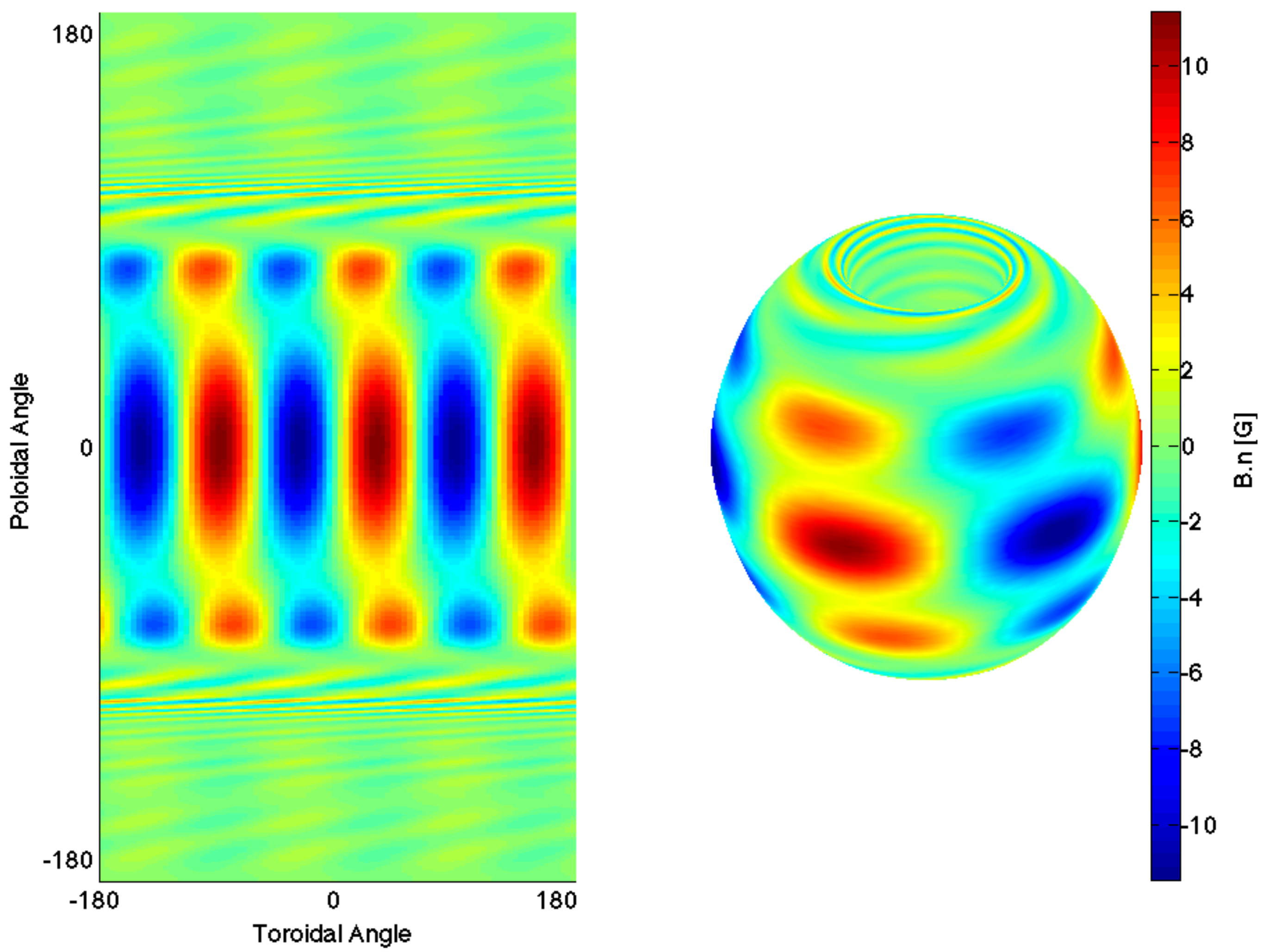


Limited ability to control core torque with n=3

- Broad torque density is driven
  - n=3 fields do not penetrate as well
  - Edge resonance control becomes key

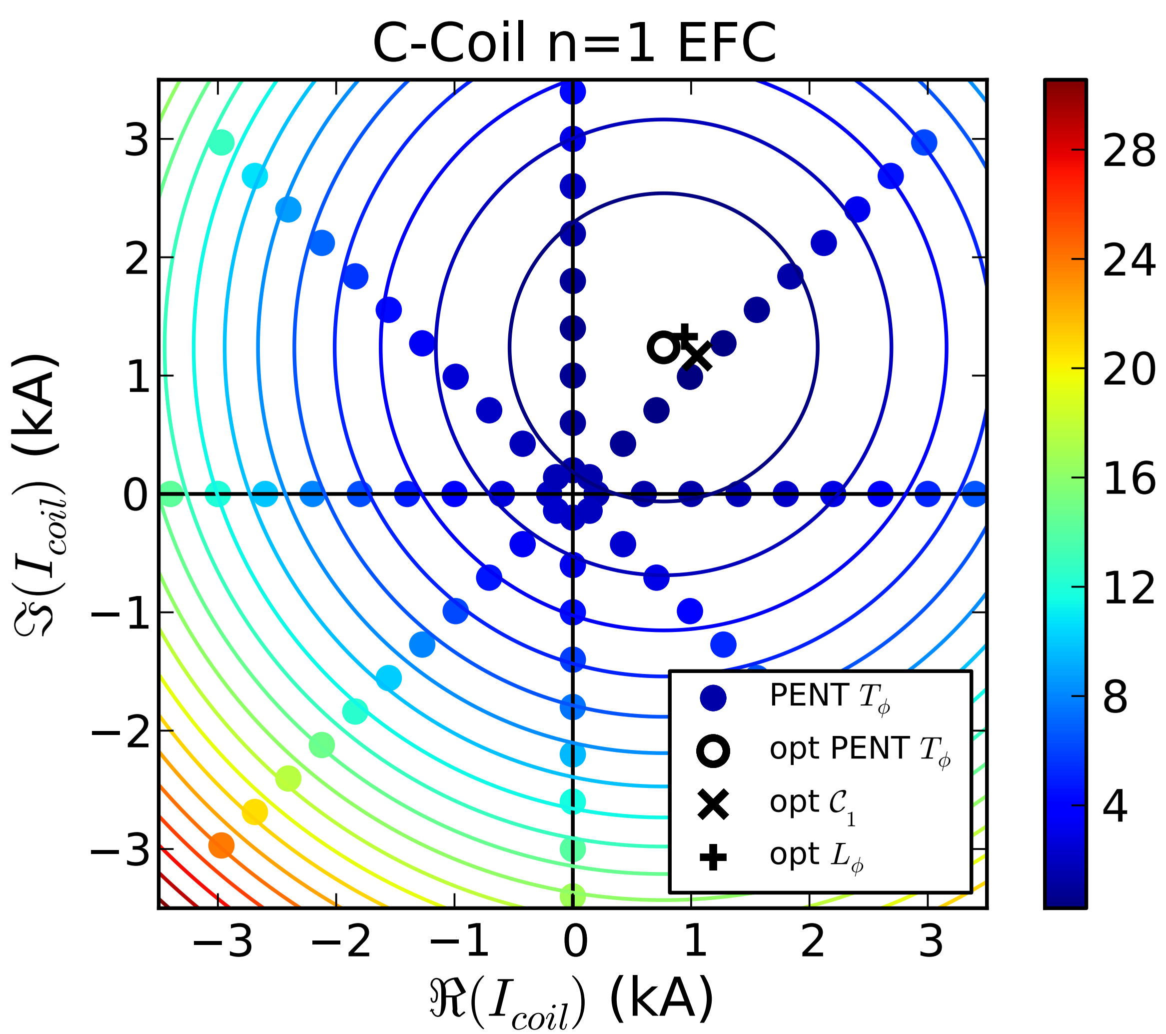


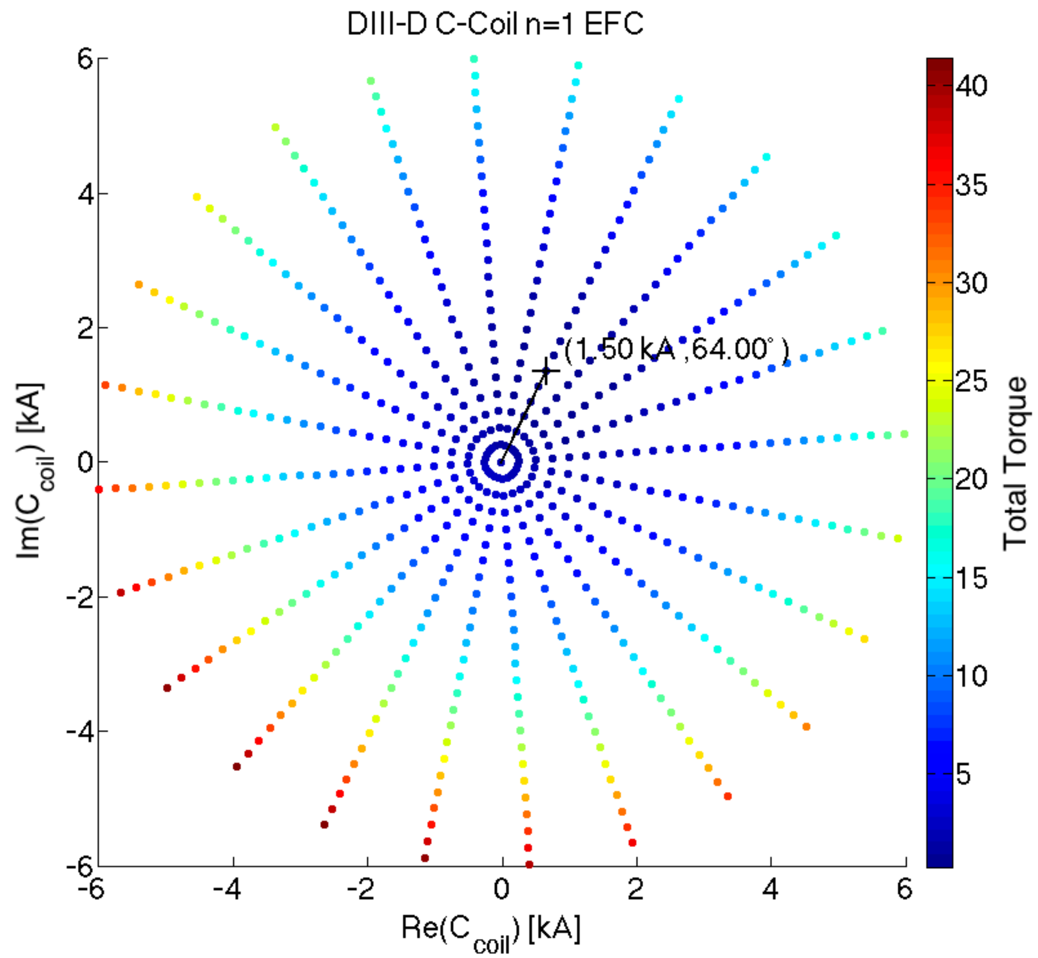




Optimization of coil currents motivated a validation

- DIII-D C-coil rotation scan experiment
  - C-coil phase and amplitude scan performed (2D parameter space)
  - IPEC/PENT to conduct similar numerical experiment using SURFMN error field model

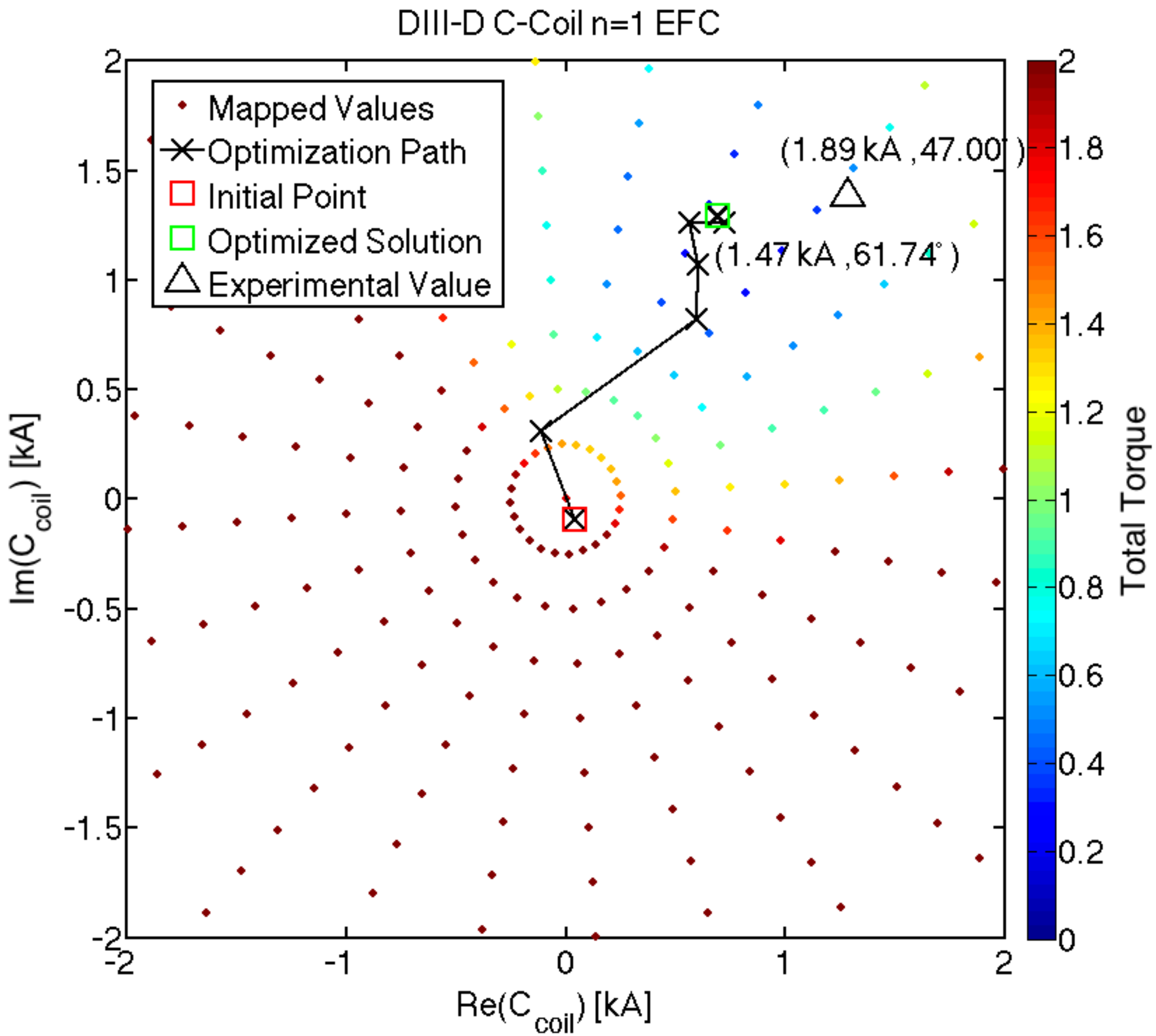




Work by N. Logan

IPECOPT agrees with experimental results

- Optimization of C-coil currents to minimize total torque
  - Phases match with 15°
  - Amplitude within 23%
  - Optimizer agrees with mapped space
  - More detailed error field model necessary



Conclusions

- The IPECOPT code can optimize applied 3D field for NTV torque
  - Total or vacuum field optimization demonstrated for NSTX-U
  - Core or edge torque profiles may be targeted
  - Coil current optimization demonstrated for NSTX-U as well
- Initial experimental validation is underway
  - Rotation scans on DIII-D seem to agree with IPECOPT predictions
- Future work will focus on coil design and target expansion
  - Separate resonant mode drive from NTV torque drive
  - Stellarator tools for coil design

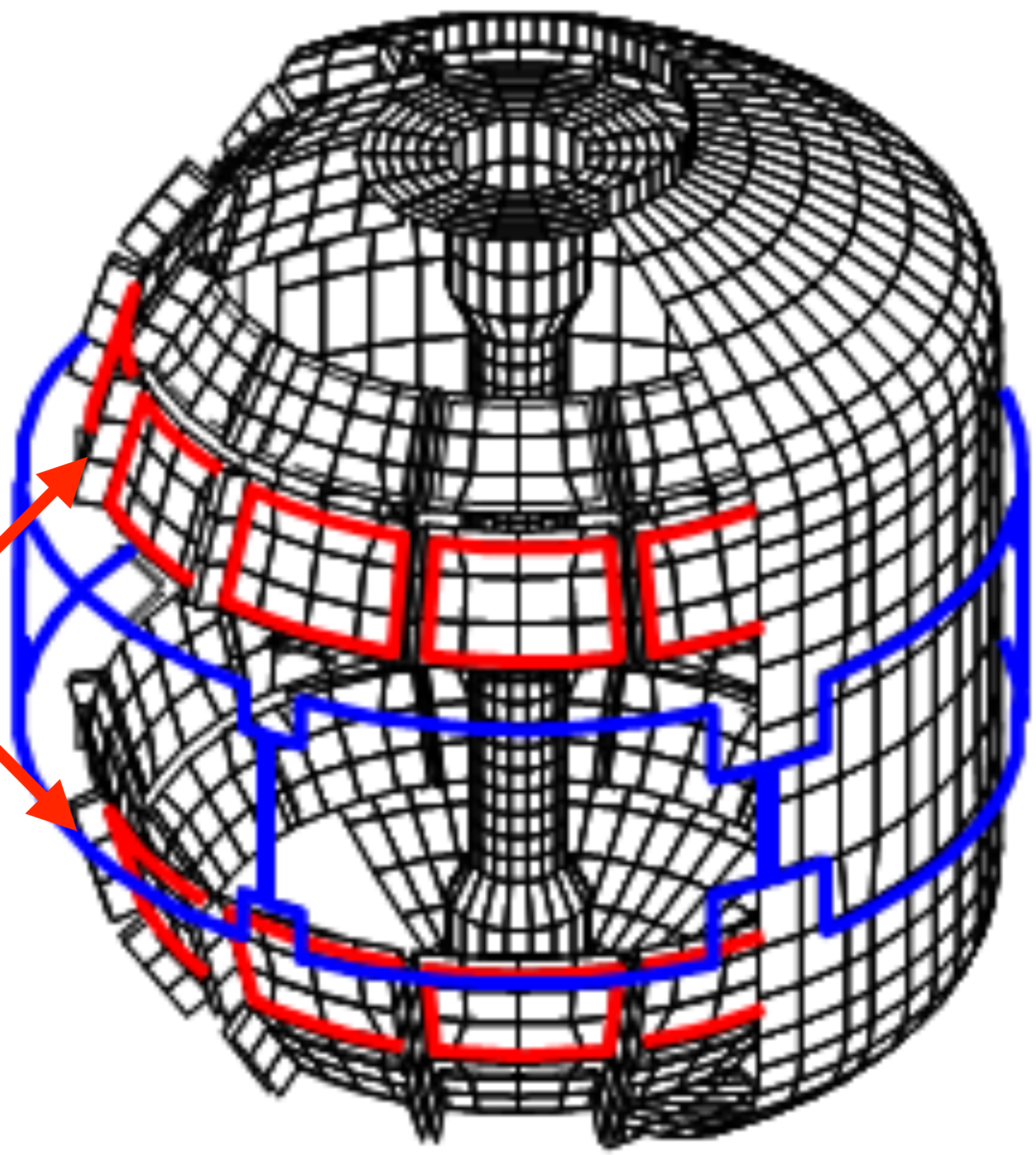
Design of coils from optimized spectrums is the next step

- Stellarator coil design requires the specification of the plasma B-normal on a plasma surface
  - This is already provided by the IPEC code
- Codes like NESCOIL[1] calculate the current potential on an encompassing surface which shield out that plasma B-normal
  - This provides a sanity check on possible coils.
- Code such as COILOPT++[2] allow us to design discrete coils with engineering constraints
  - This includes coil location and shape constraints.

[1] P. Merkel 1987 Nucl. Fusion 27 867
[2] J. Breslau (under development at PPPL)

EXTRA SLIDES

The NSTX-U Non-axisymmetric Control Coils (NCC)

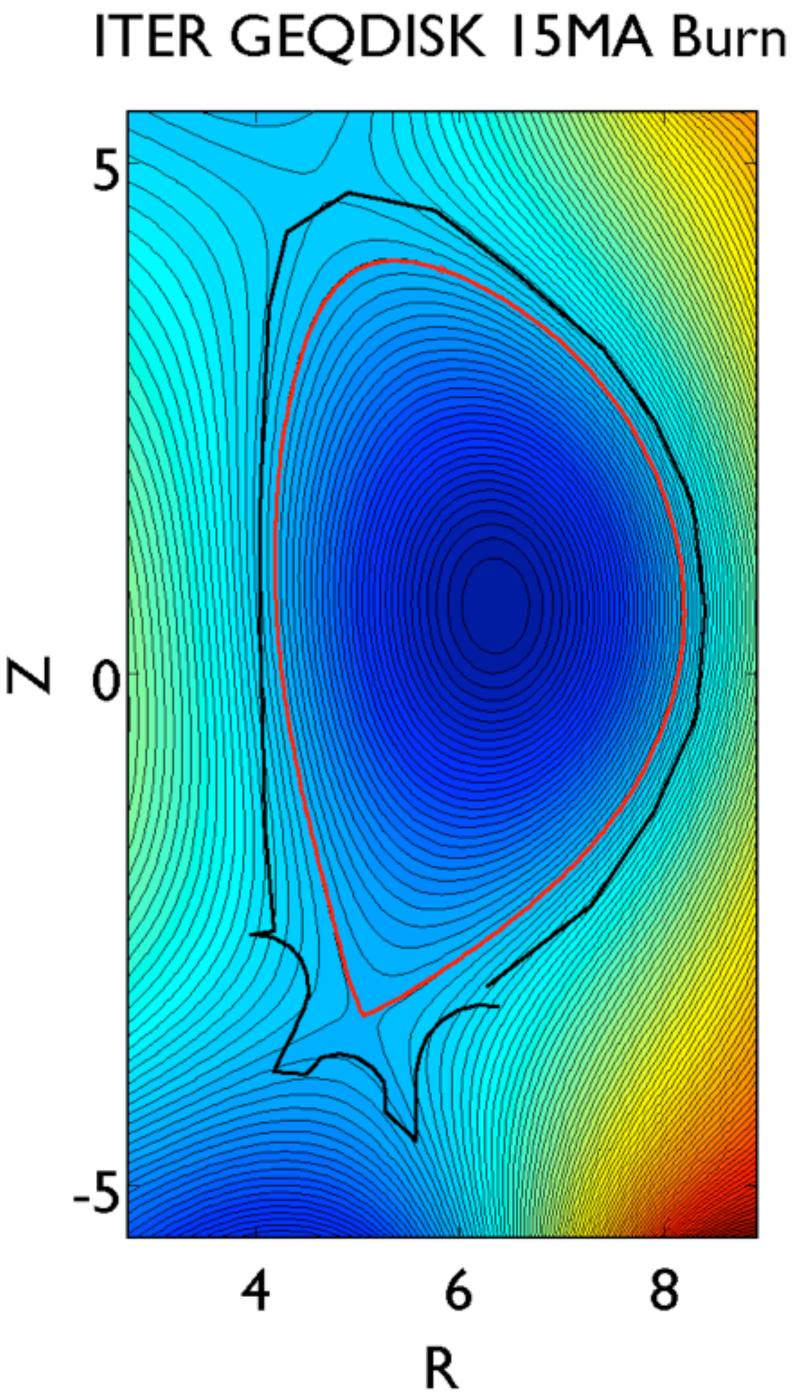


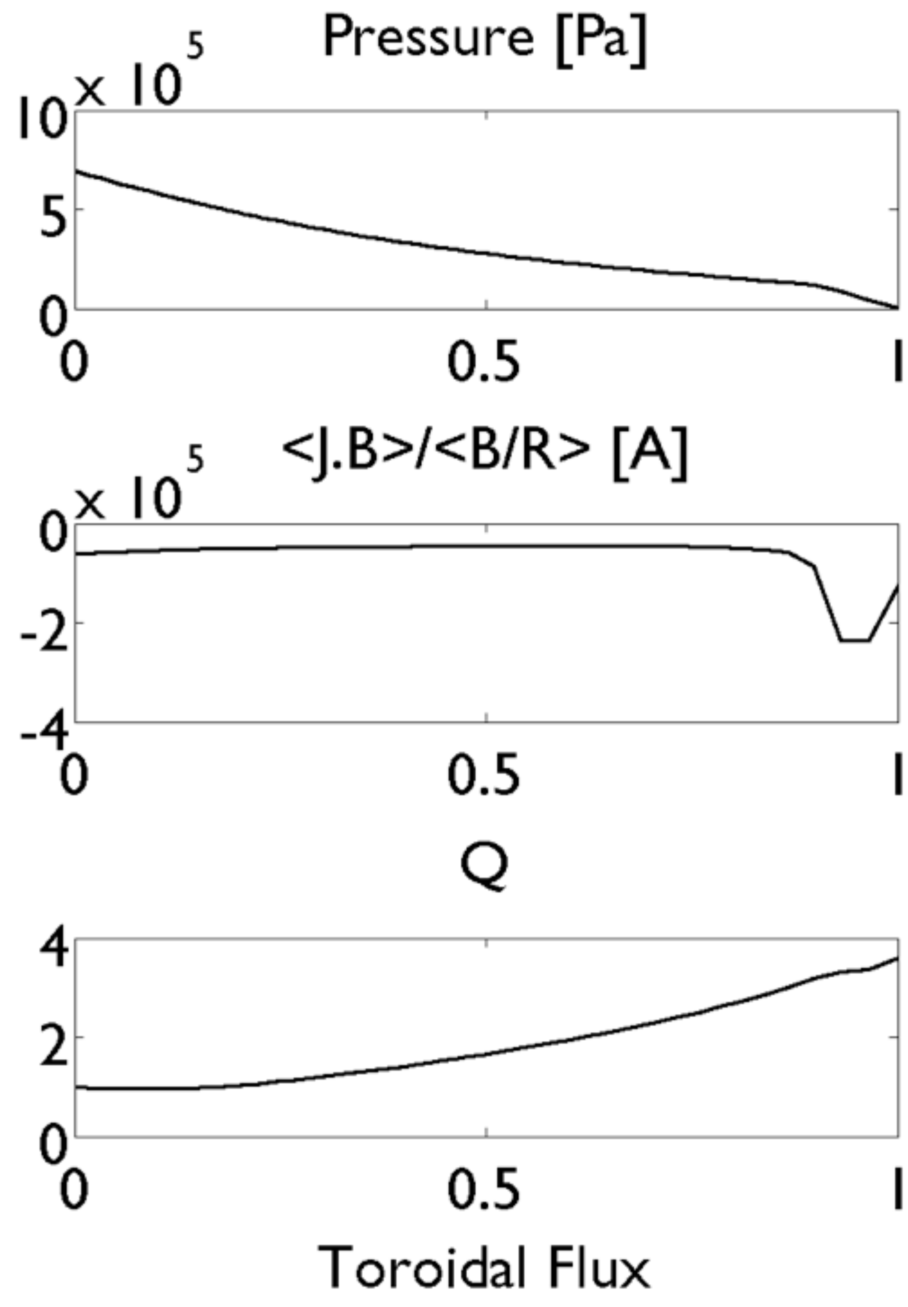
24 new coils

6 existing RWM coils

Can we preform a similar analysis for an ITER equilibrium?

- 15 MA H-mode scenario at full burn





Parameter	Value
Beta(pol)	0.713
Beta(tor)	0.029
I [A]	-1.49E+07
R0 [m]	6.35
Z0 [m]	0.67

Core torque difficult to drive with n=1 in ITER

- 12 dimensional parameter space should provide greater flexibility
  - Assumed very low rotation profile
  - Amplitude of applied fields within coil limits [A-t]