NSTX-U

Supported by U.S. DEPARTMENT OF ENERGY | Office of Science

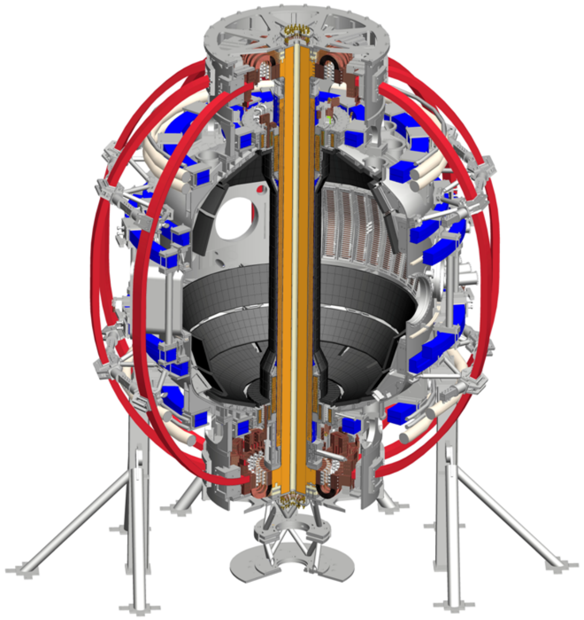
NCC Design/Analysis Update

Samuel Lazerson

J-K Park, N. Logan, A. Boozer,

and the NSTX Research Team

NSTX-U
B233
August 21, 2014



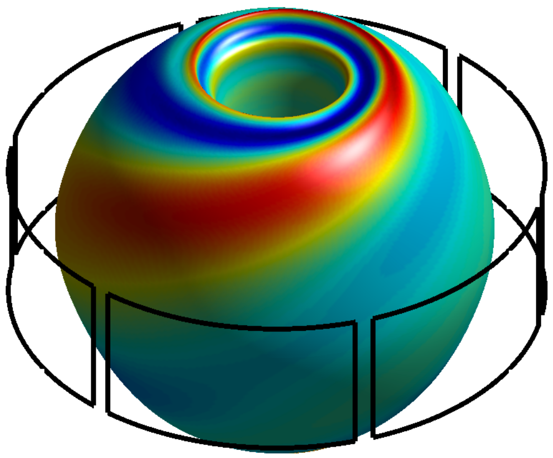
The application of 3D fields in Tokamaks is commonplace

- 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

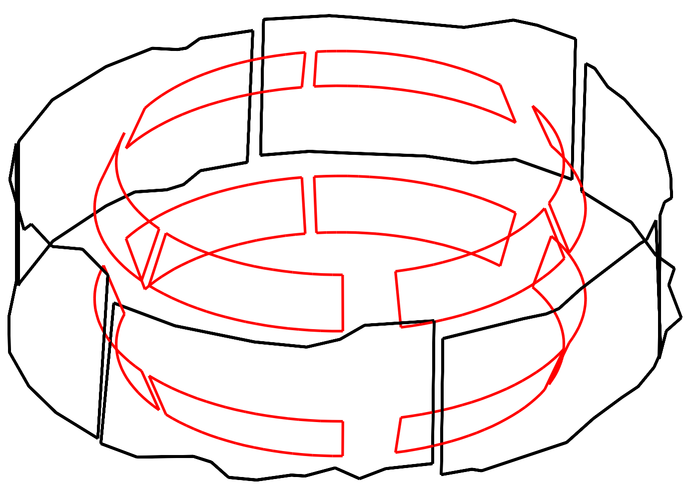
How do we design these coils?

- 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

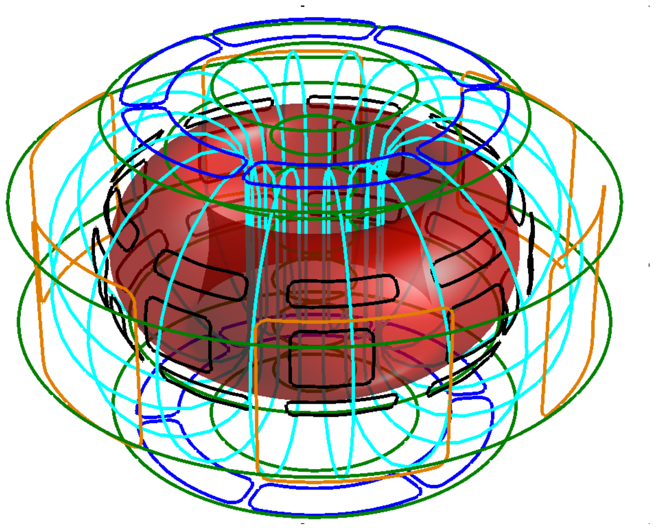
There is a better way!



NSTX



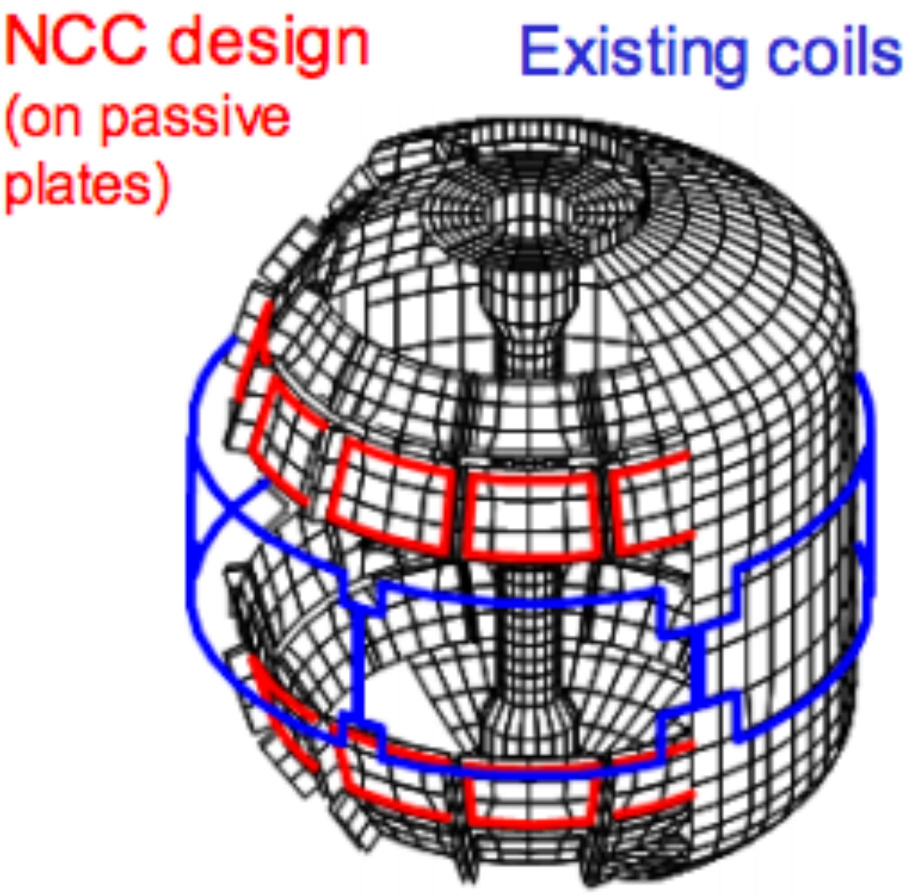
DIII-D



ITER

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)



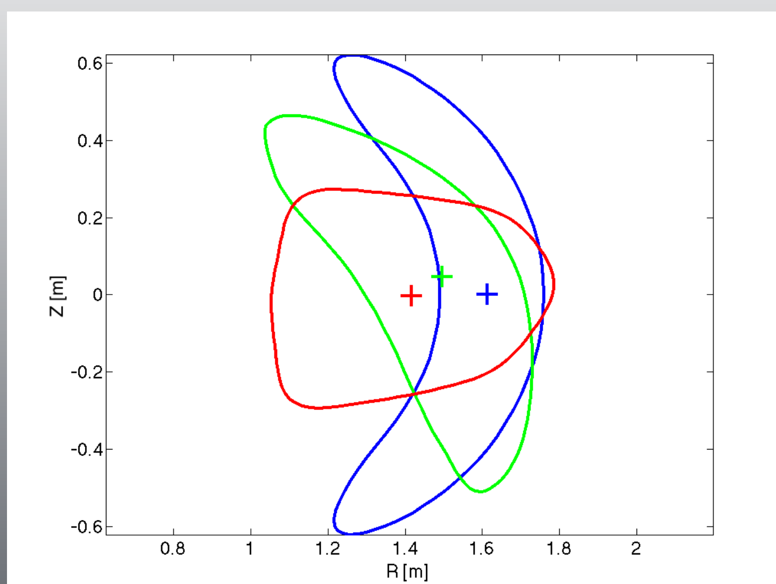
  - These coils clearly have a great deal of utility.
  - Could stellarator optimization techniques help us better understand the types of fields we'd like to apply?
  - Do the numerically optimized fields look anything like those we can produce with the NCC coils?
  - What do numerically optimized coils look like?
  - How close can the NCC coils get us to the numerically optimized physics parameters?

STELLARATOR optimization is a non-linear curve fit

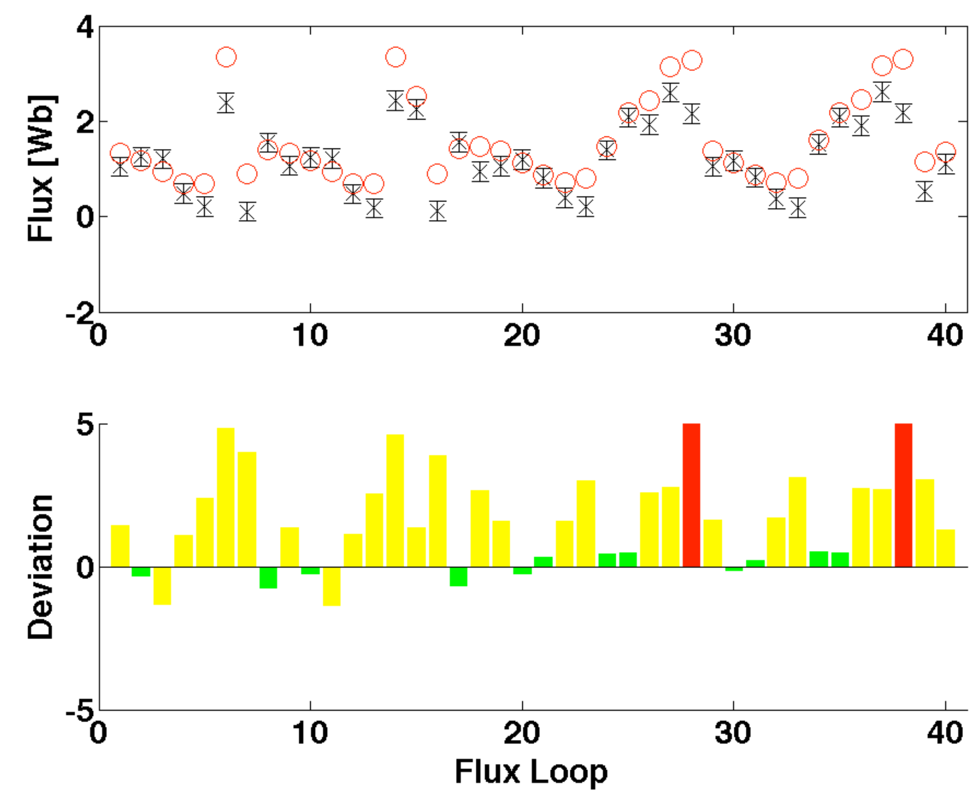
Input Parameters
- Boundary Coefficients
- Vacuum Fields
- Pressure, etc.

These need to result in a good match to these.

Equilibrium Model

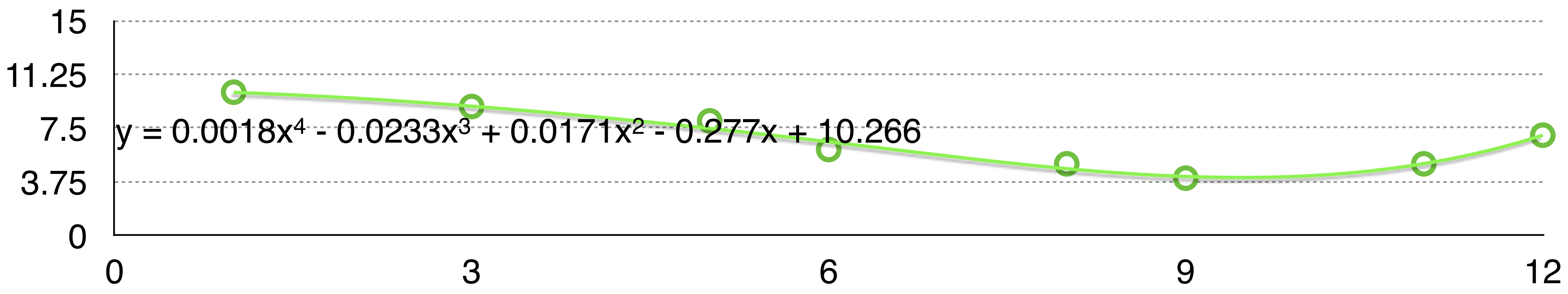


Modeled Values



Numerical Optimization Fits Model Inputs to Target Physics Parameters

- 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 are available to us?

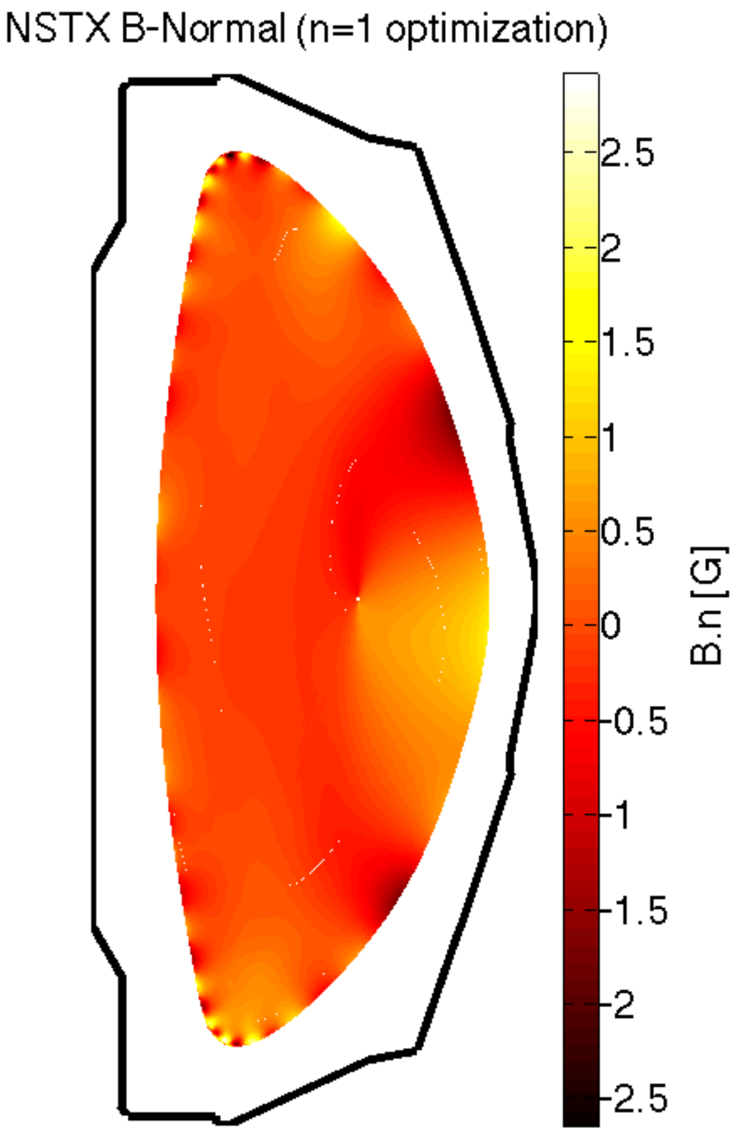
- The stellarator community has developed STELLOPT for this exact task
  - STELLOPT relies on VMEC and lacks experimental validation at this level
- The IPECOPT code utilizes experimentally validated models
  - The IPEC code computes the perturbed equilibrium model
  - The PENT code then calculates the 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

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

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

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

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
  - Coil current optimization under development

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

m: number of targets

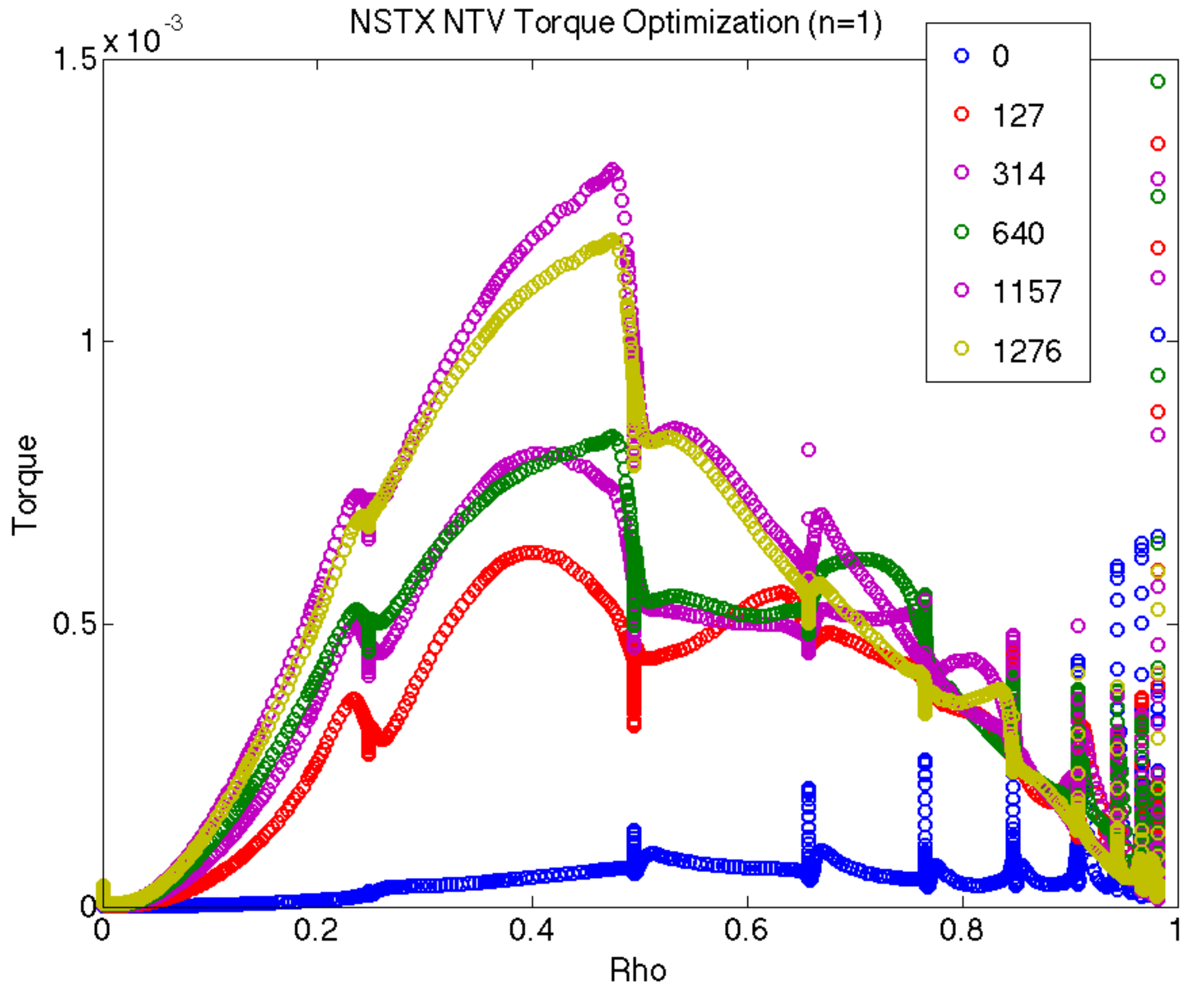
Y: target values

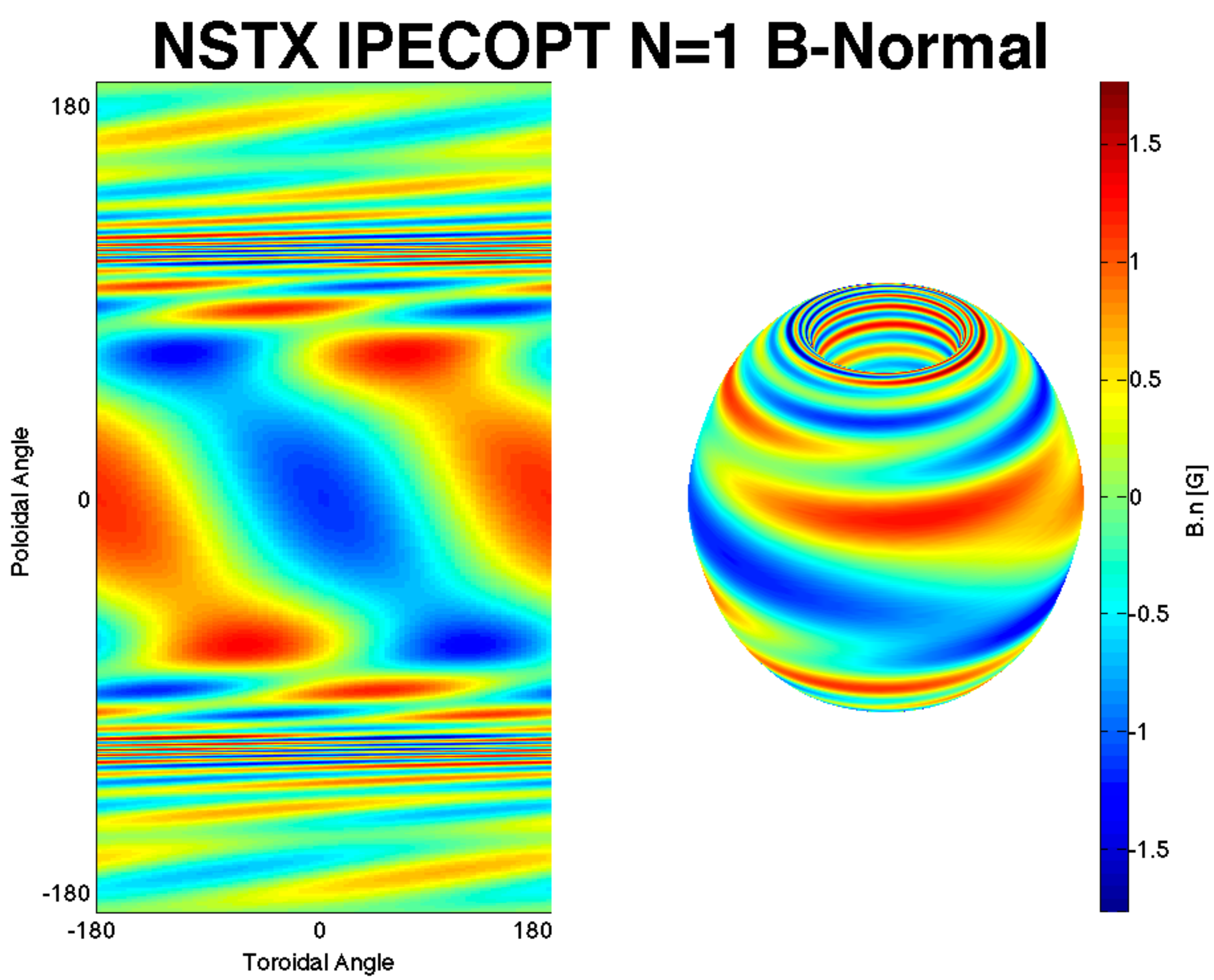
y: simulated values

sigma: weights

Core NTV Torque Optimization for NSTX-U

- As a first attempt the total B-Normal spectrum was optimized
  - Core Torque was targeted
  - n=1 toroidal harmonics



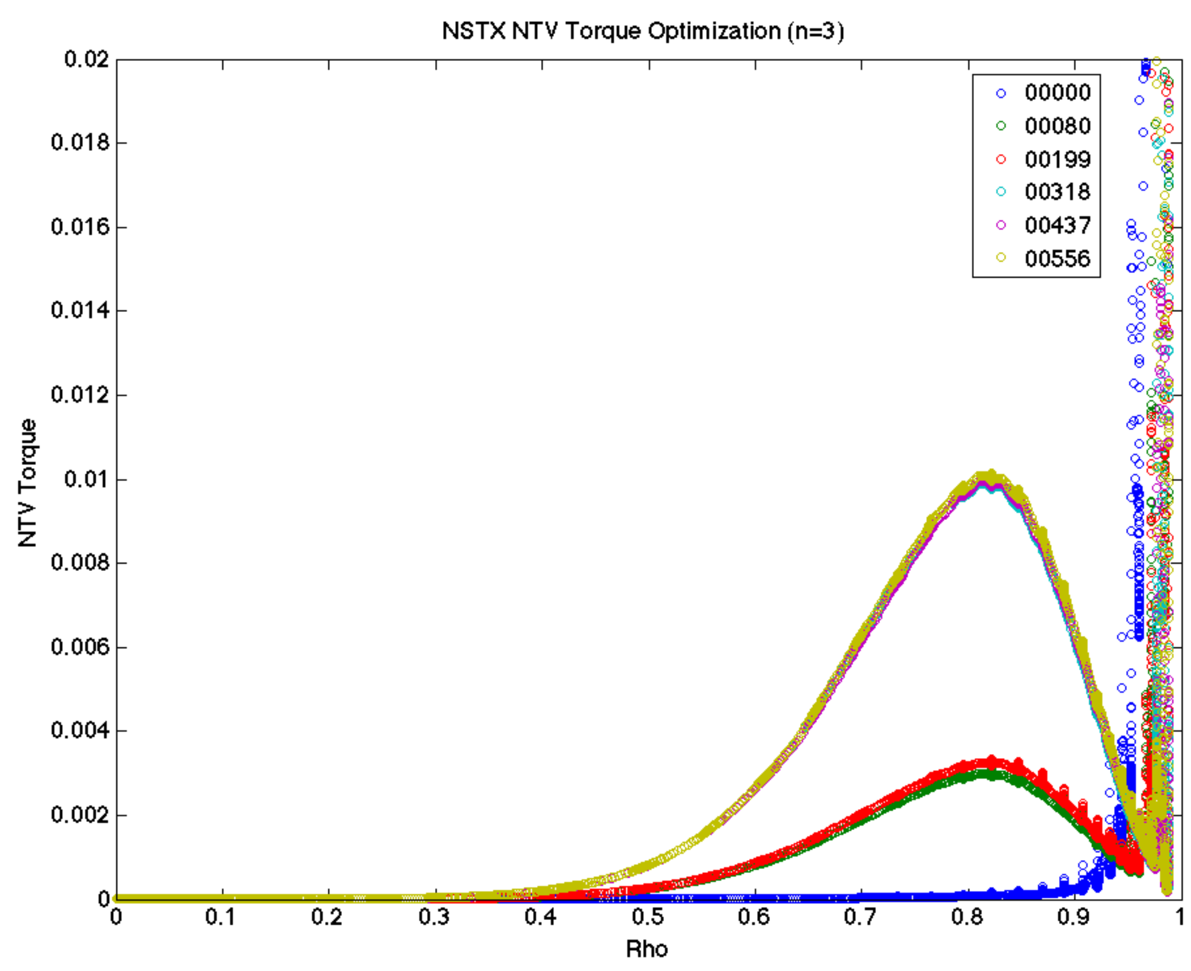


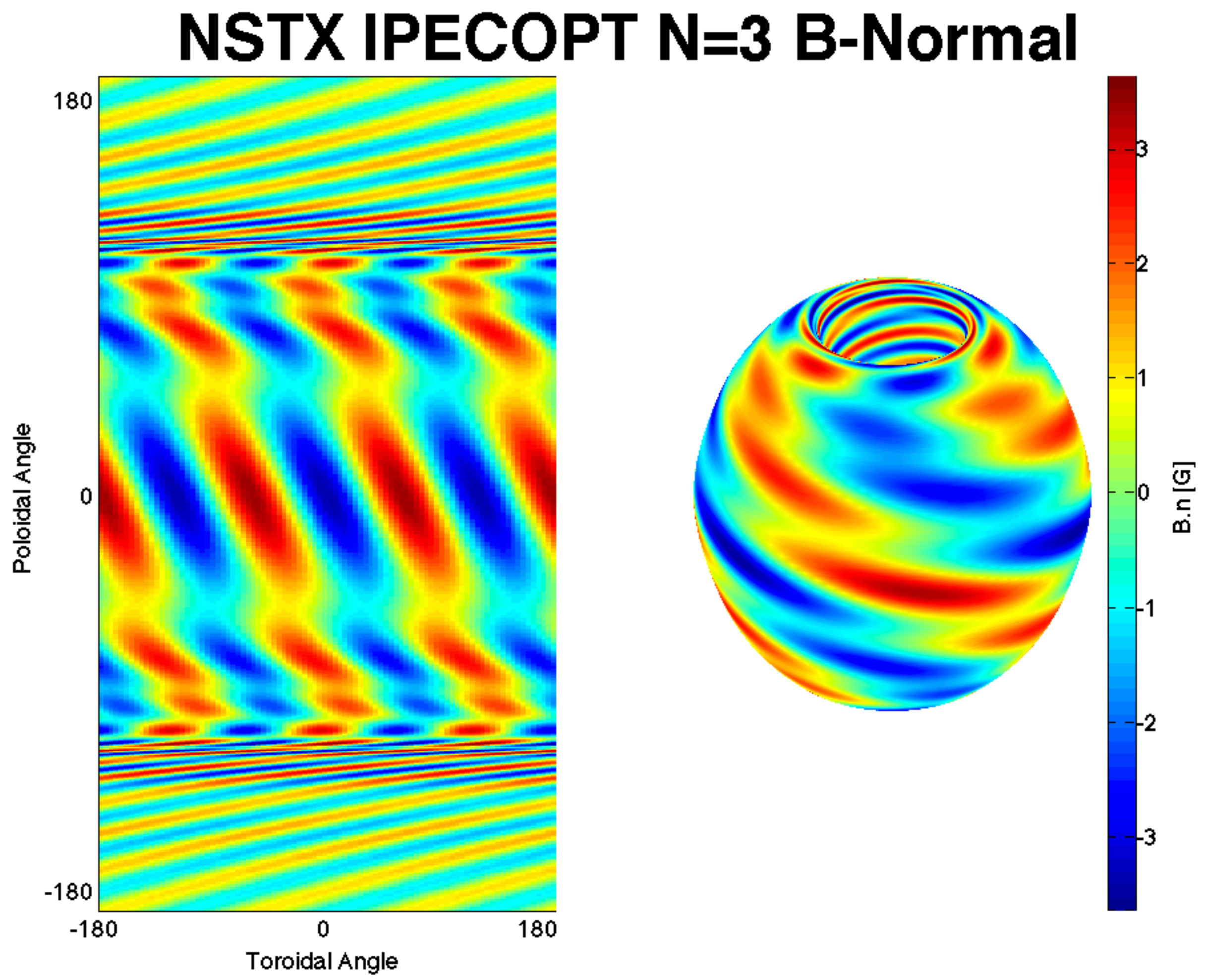
Edge NTV Torque Optimization for NSTX-U

- The phase are target were then changed

  - Edge torque

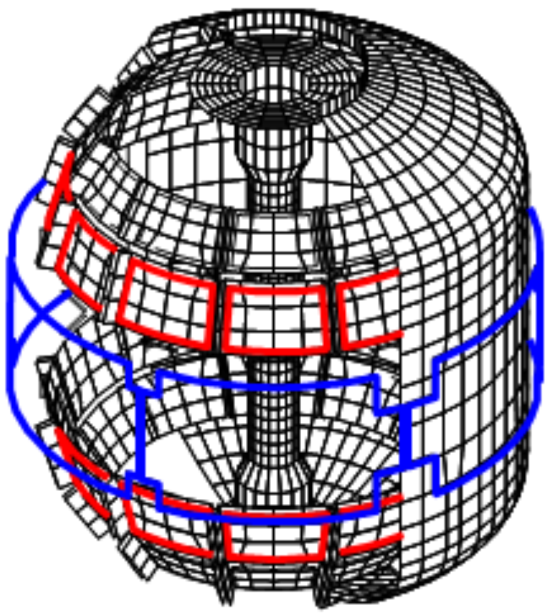
  - n=3 toroidal harmonics

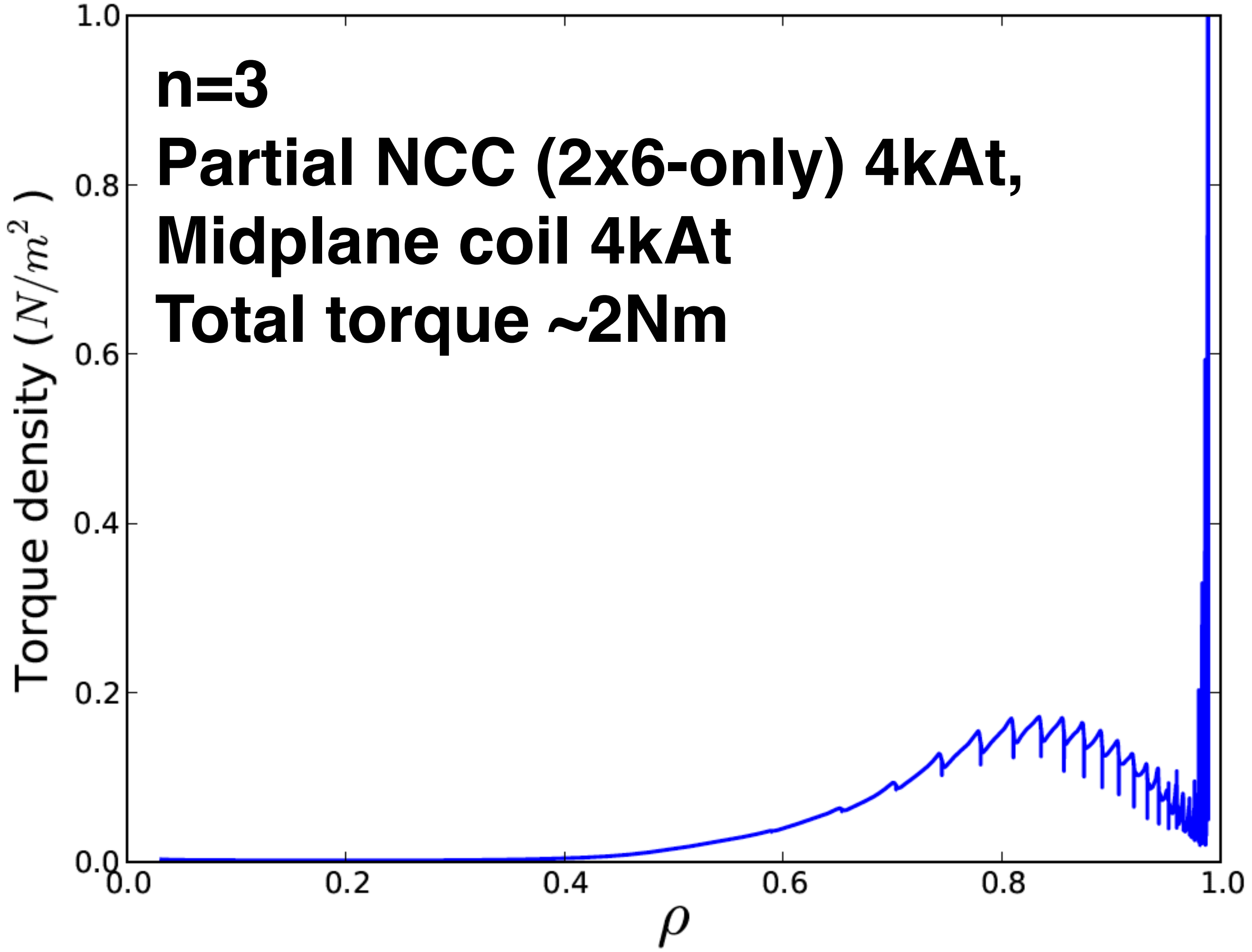


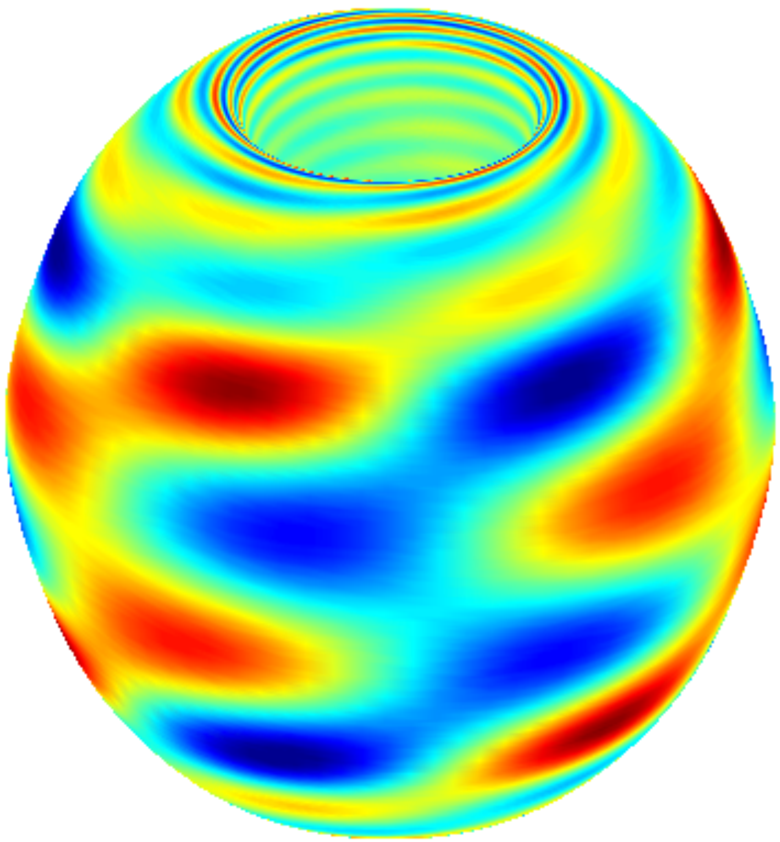


Planned NCC coils can recapture the n=3 features

- Initial attempts to mimic optimized result show some promise
  - Partial-NCC and mid-plane coils used
  - No numerical optimization performed







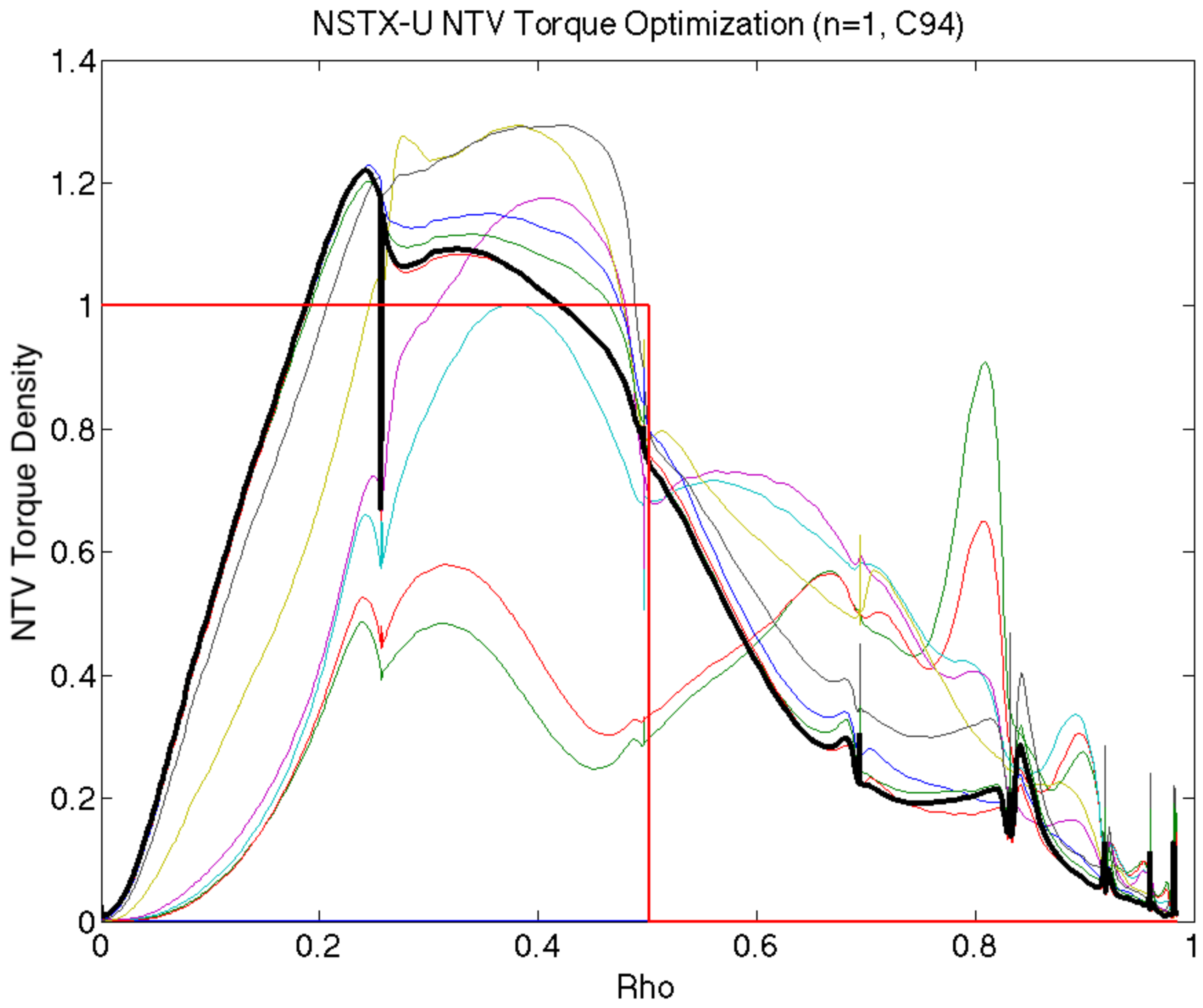
Work by J.K. Park

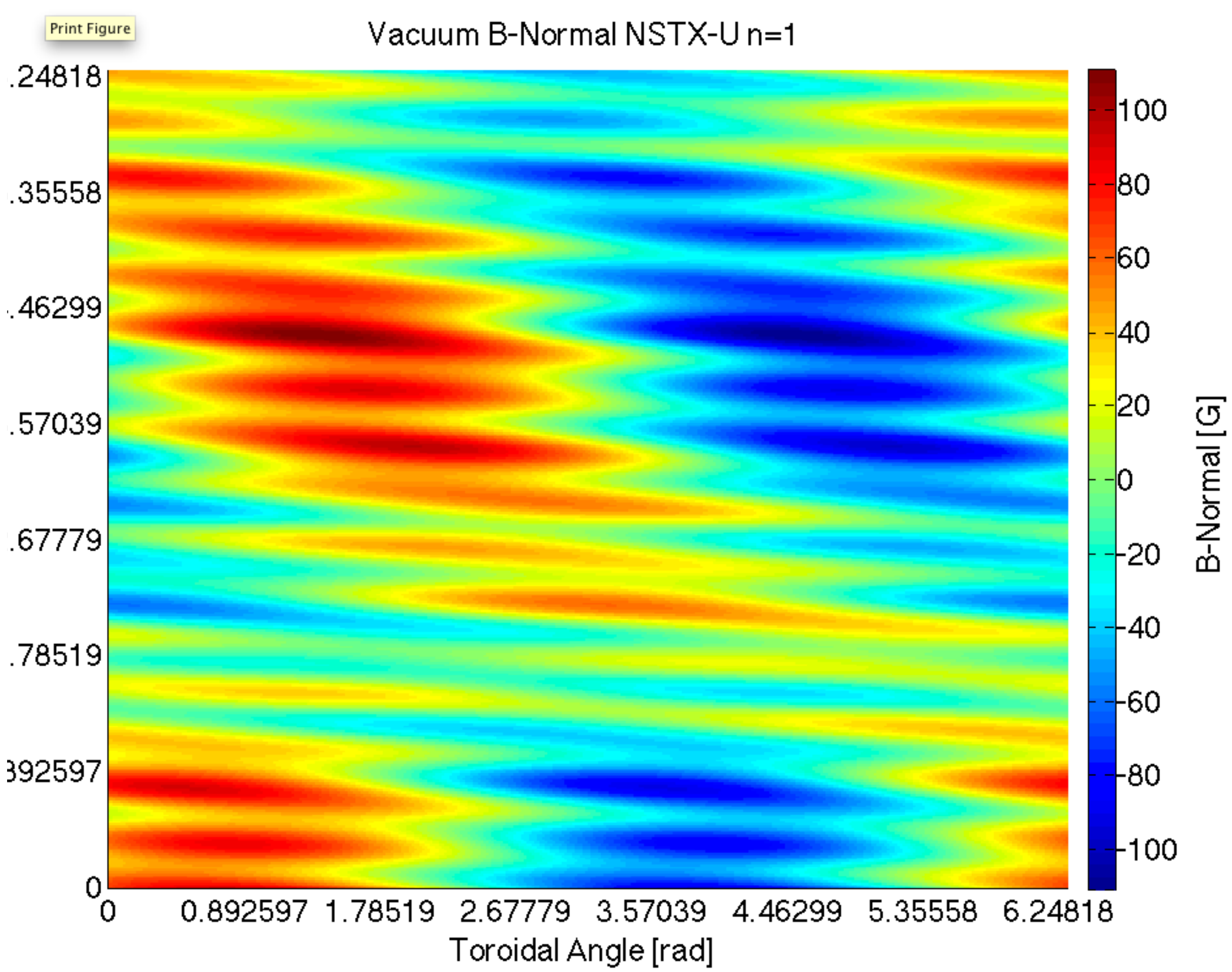
Fixed boundary optimization motivated continued work

- 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 free boundary optimizations (B-normal spectrum)
  - Larger target torques were considered
  - Here vacuum B-normal fields were optimized

Optimization of vacuum field spectrum possible

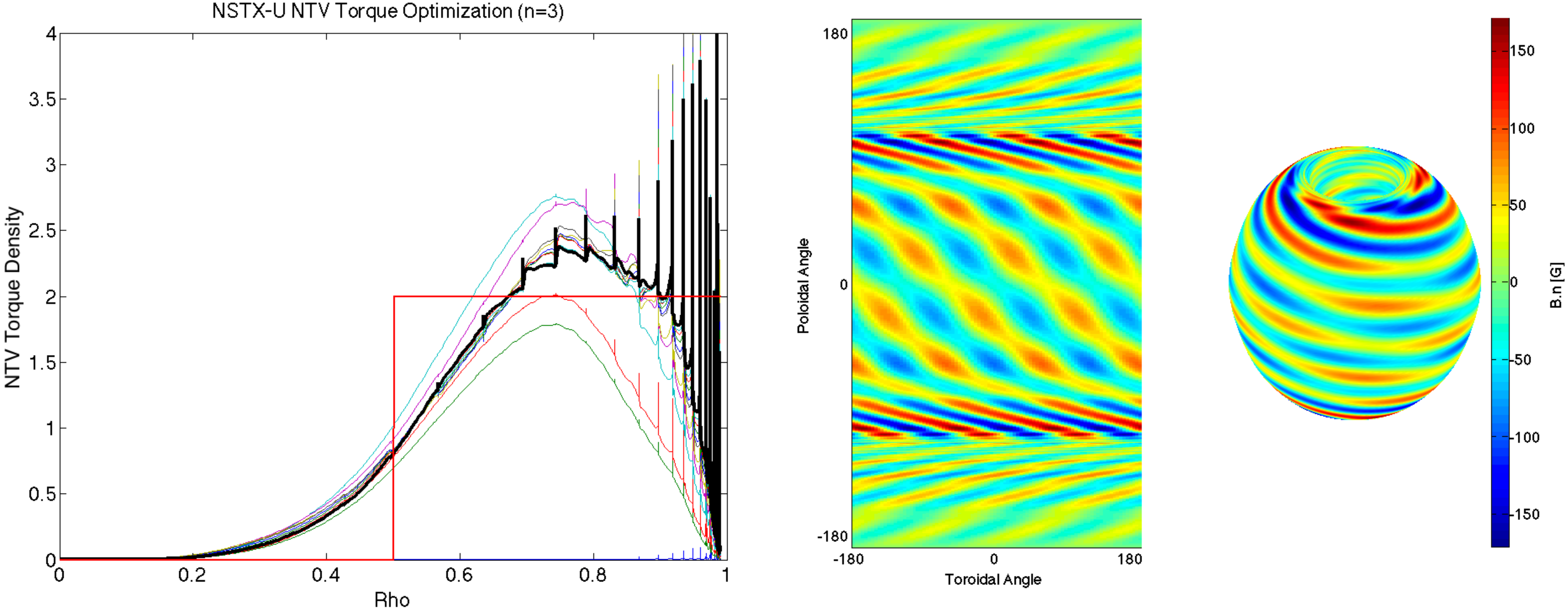
- The applied vacuum B-normal spectrum was optimized
  - Core Torque (~ 0.5 [Nm] total torque)
  - n=1 toroidal harmonics





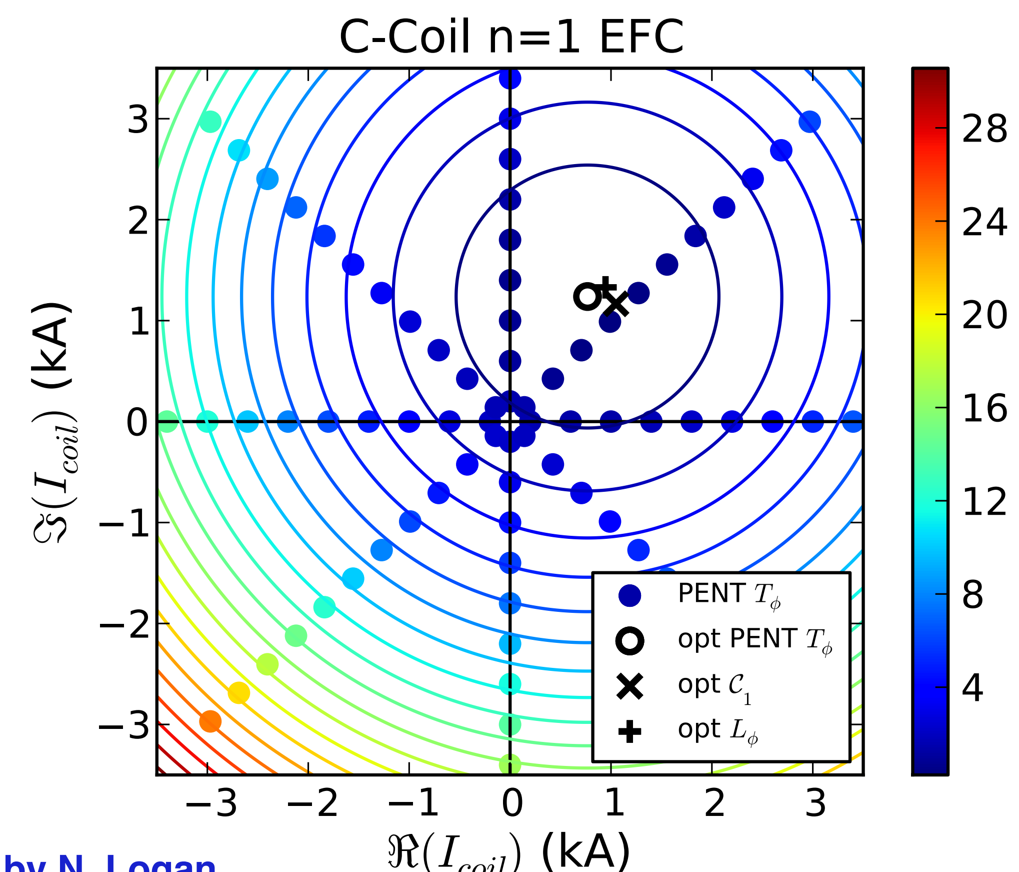
Edge optimization conducted with n=3

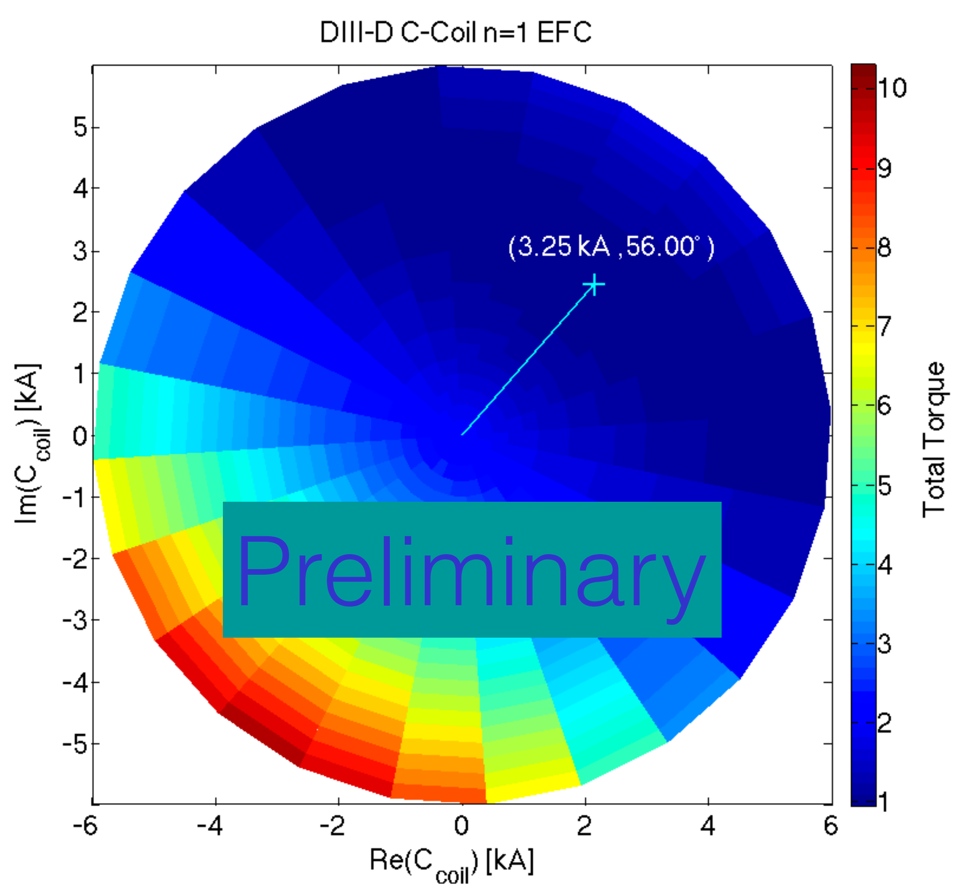
- The applied vacuum B-normal spectrum was optimized
  - Edge torque targeted (~ 1 [Nm])
  - n=3 toroidal harmonics drive some edge resonances



Simple validation on DIII-D performed using error fields

- 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
  - IPECOPT is being used to map this 2D space in more detail





Work by N. Logan

IPECOPT will be used to 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) $F_{N-R} \equiv \frac{T_{NTV}}{\sum_{\psi_N<0.85} \delta B_{mn}^2}$	High F	0.07	0.13	1.24	1.24
RWM (n=1) $F_\beta \equiv \frac{\beta_{active}}{\beta_{no-wall}}$	High F	1.25	1.54	1.61	1.70
NTV (n≥3) $\Delta\left(F_{N-N} \equiv \frac{T_{NTV}(\psi_N < 0.5)}{T_{NTV}(\psi_N < 1)}\right)$	Wide	1.00	1.44~6.08	1.75~11.33	6.38~59.4
RMP (n≥3) $F_{N-C} \equiv \frac{\left(C_{vacuum,\psi_N=0.85}\right)^4}{T_{NTV}}$	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

Near Term Plans (3 months)

- Fixed boundary optimization of NSTX-U
  - Larger target NTV torques
- Free boundary optimization is underway
  - Specify vacuum B-normal spectrum
- Evaluation of existing coils being developed
  - A true free boundary capability where coil phases and amplitudes is being optimized
  - This could be done for DIII-D allowing us to experimentally validate the optimization in the near term

Long Term Plans

- Development of new optimization targets
  - Island overlap parameter
  - Energetic particle confinement effects
  - Alfven eigenmode calculations
- Experimental validation
  - Possible DIII-D NSTX-U joint experiments
- Design of new highly optimized 3D coils