# NCSX Physics Design Progress and Preparations for CDR

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# Outline

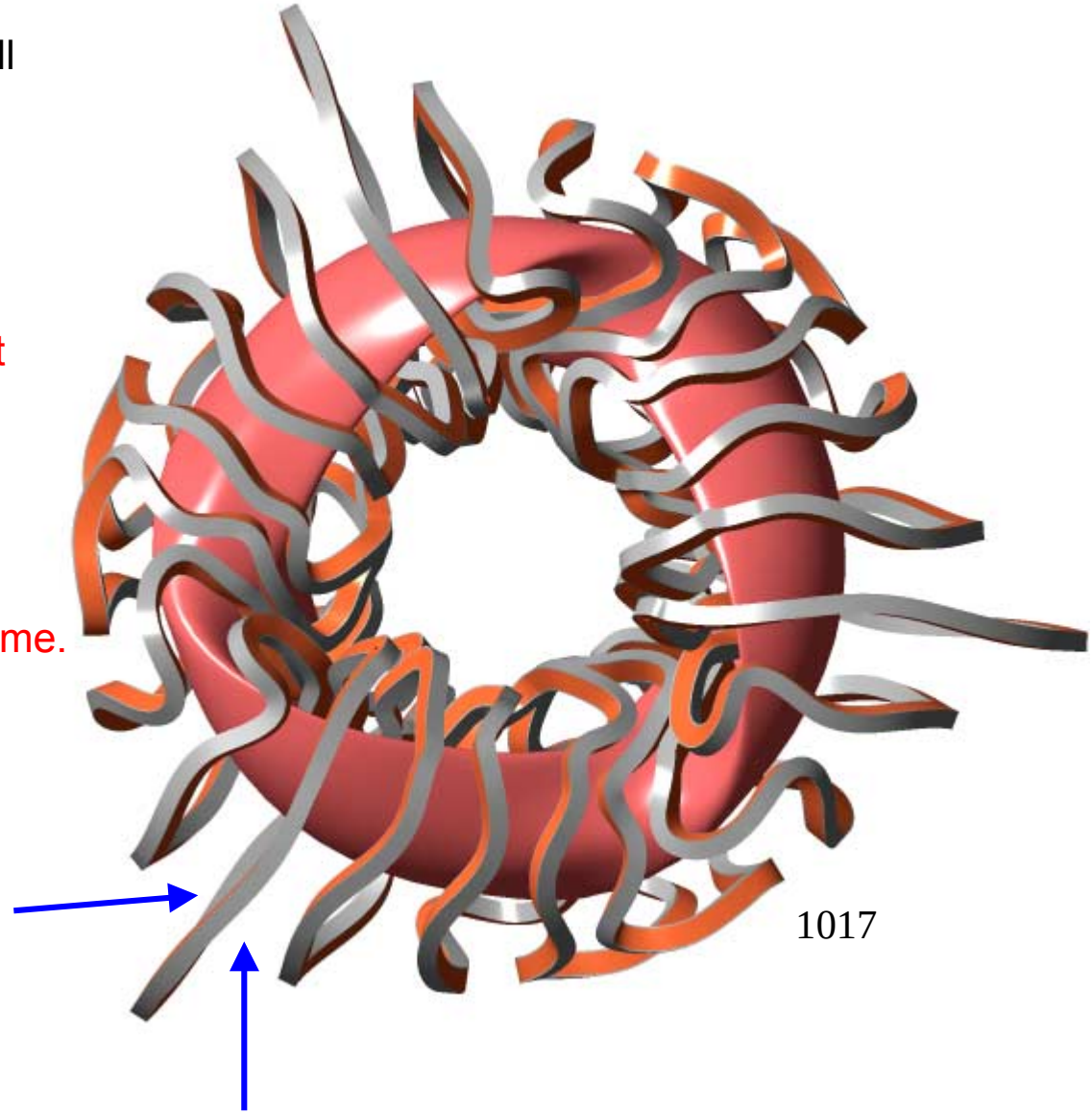
- Coil design progress
- Transport and flow damping
- Experimental mission and envisioned plan
- Conceptual design requirements
- Plans for CDR preparation

# Major Task Since PVR: Improve Coil Designs

PVR Coil designs did not accomplish all goals simultaniously

- 0907 coils had good physics reconstruction, island healing, did not allow beam access
- 1017 coils allowed beam access via displaced coil-leg, some increase in ripple, difficult to heal islands at the time. NB losses ~1.2 x fixed-boundary

- 21-coil designs constrained access
- Both were found to be very flexible β-limit > 6.5%



# Coil Design Process Improved

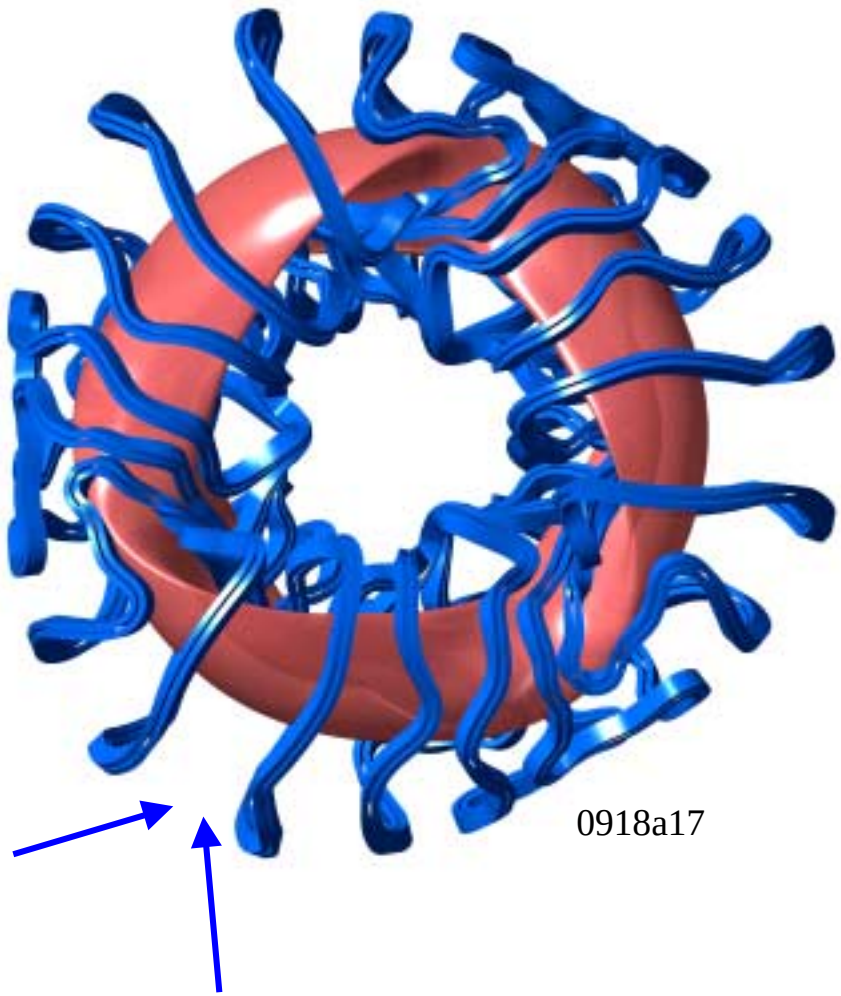
Main tool for coil-design: COILOPT

Optimizes coil shapes to match $B \cdot \hat{n}$ on plasma boundary

- COILOPT representation extended to use Fourier series for both u and v (“saddle representation”)
- COILOPT extended to optimize unequal Modular coil currents, TF bias field
- Improved targeting of engineering constraints

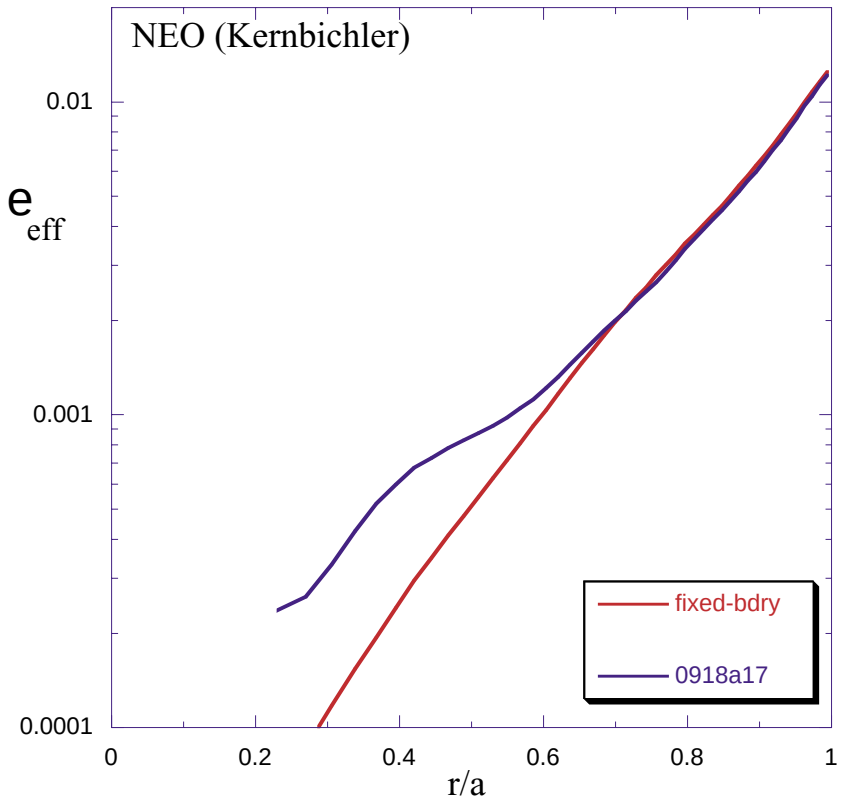
# NCSX Modular Coils Provide Good Physics Capability

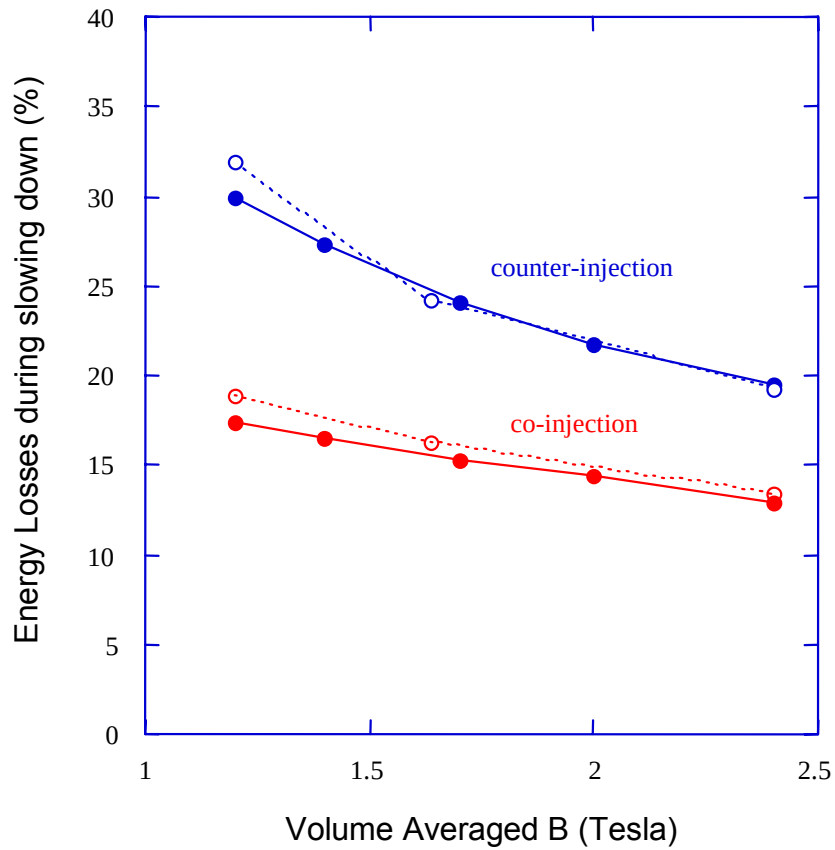
- New coil designs reproduce fixed-boundary physics properties:
  - stable at reference β (4%).
- 18-coil designs allow NB access without enlarged coil. Improved diagnostic access
- Also include Poloidal Field coils and weak Toroidal Field, for flexibility




— See N. Pomphrey for flexibility studies

# New Coils Satisfy Physics Requirements




- Modest ripple increase in core, no discernable effect on thermal transport
- Small increase in calculated beam losses, within Monte-Carlo uncertainty

# Major Task: Coils that satisfy Physics and Engineering

- Present physics coils do not satisfy engineering requirements:
  - Min coil-coil (filament) separation ~ 12 cm (want 16 cm)
- Coils adjusted to meet engineering constraint do not satisfy physics:

  For kink & ballooning stable equilibria ($\beta$=4.1%)
  - NB fast ion losses increase by factor of ~1.5
  - $\varepsilon_{eff}^{3/2}$ increased by factor of 15 in core, 3 at edge

- Further COILOPT improvements
  - B-spline representation, to better localize engineering constraints

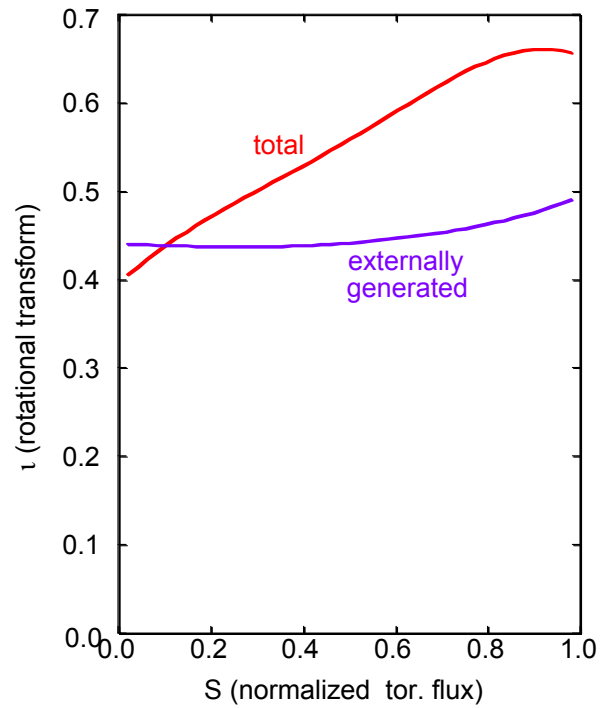
- 'Merged Optimizer' – optimize coil shapes, directly targeting physics properties

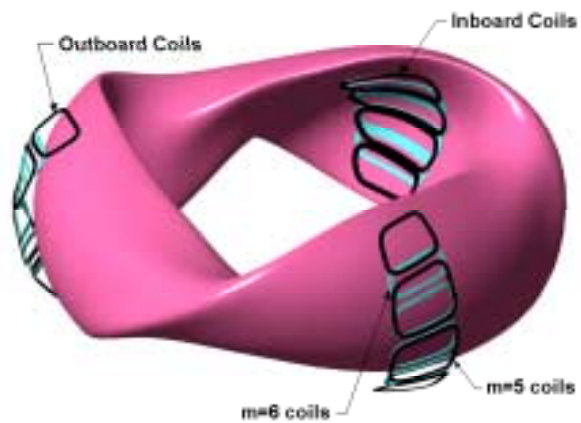
# Coil Design is Part of Good Surface Design

Flux surface quality is a significant issue.

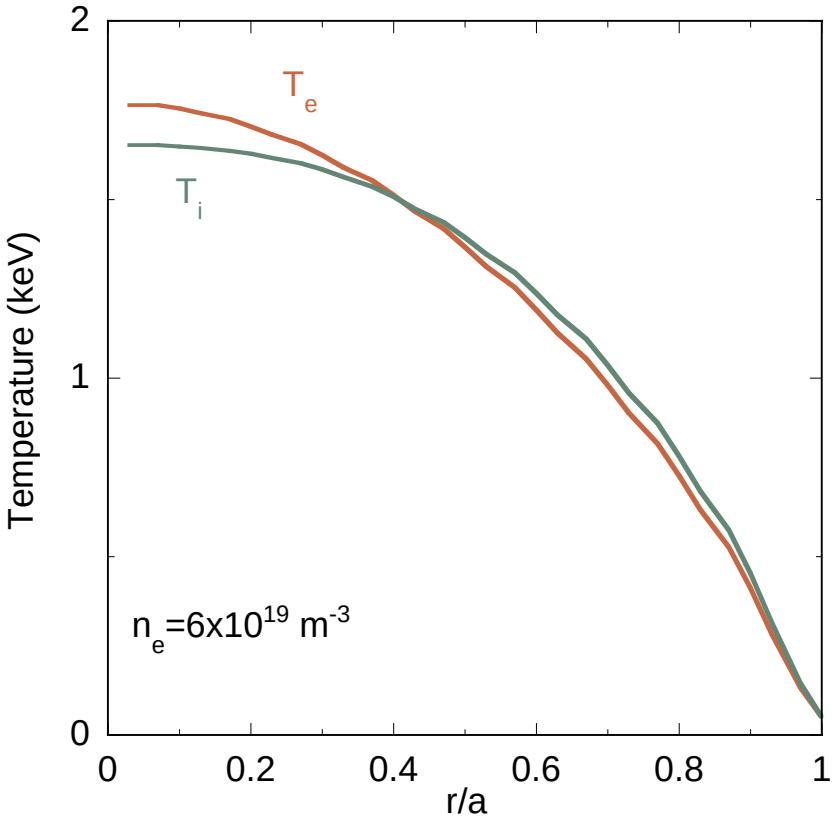
NCSX design uses three methods to attempt to ensure good flux surfaces:

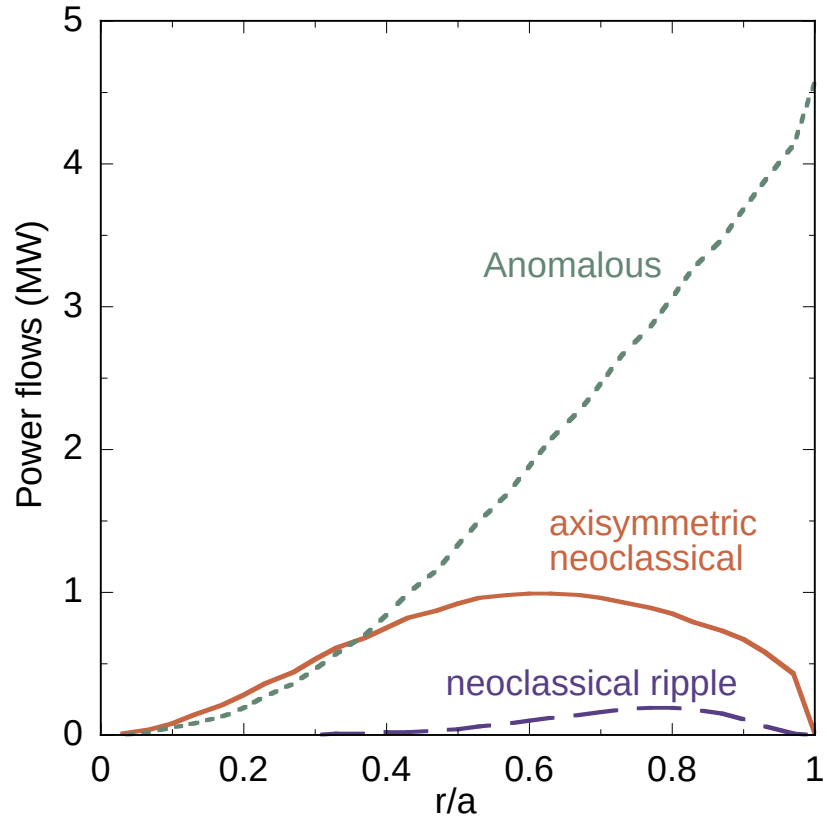
- Explicit design to eliminate resonant fields, in both fixed boundary target plasma, and in coil designs -- See A. Reiman
- 'Reversed shear' configuration ⇒ neoclassical healing of equilibrium islands and stabilization of tearing modes
- Trim coil arrays targetting low-order resonances



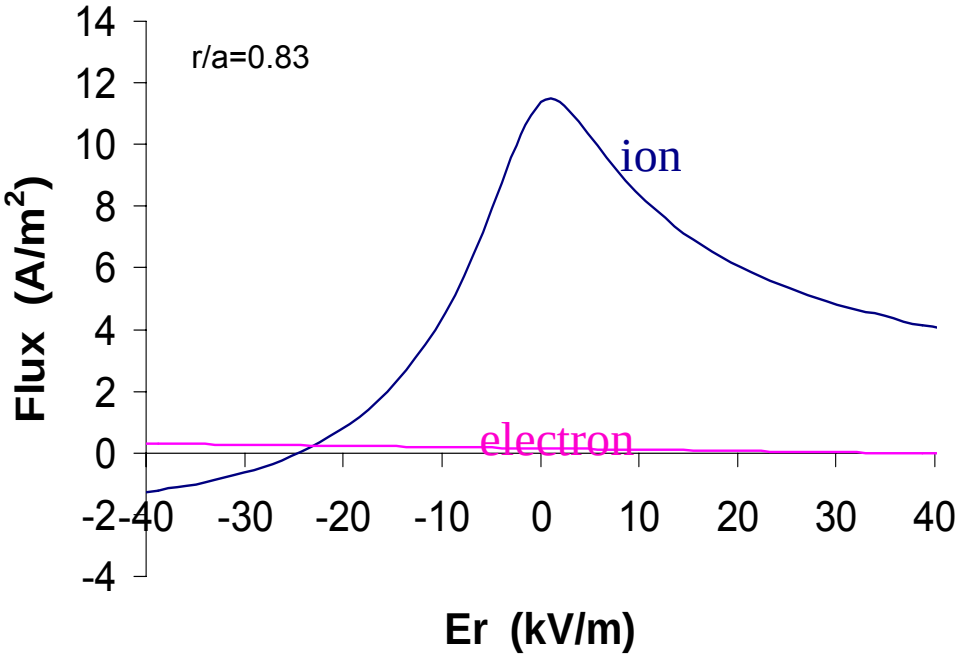
# Low $\varepsilon_{h,eff}$ $\Rightarrow$ Low Ripple Transport

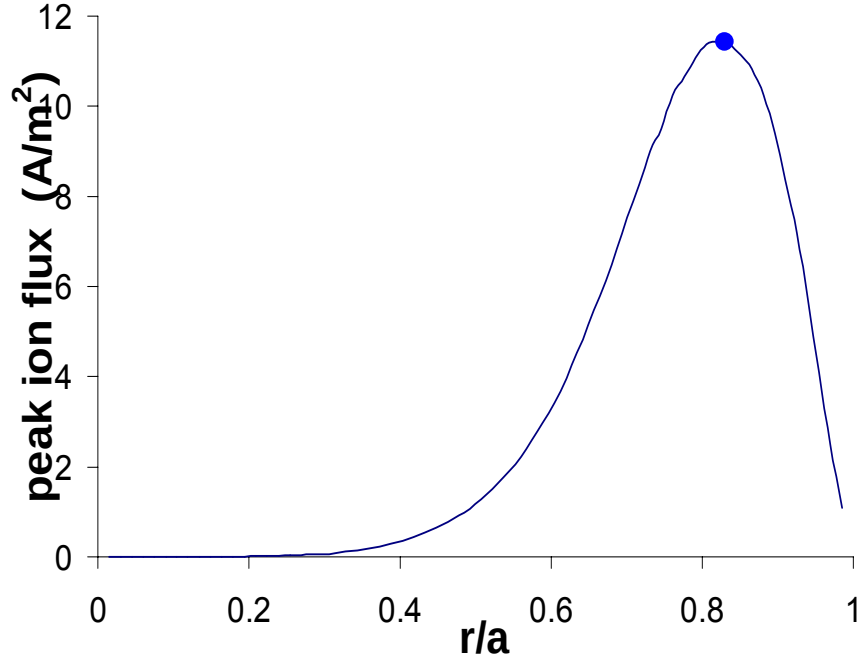



- Helical transport is negligible with self-consistent $E_r$
- $\beta$ = 4%, $\nu^*$ ~ 0.25 with B=1.2 T, $P_{inj}$=6 MW, $n_e$ = 6 x $10^{19}$ $m^{-3}$ requires $H_{ISS95}$=2.9 or $H_{ITER\text{-}97P}$=0.9 (L-mode) B=1.7T allows $\nu^*$ ~ 0.1, $T_i(0)$~2.3 keV
- Shaing-Houlberg for helical transport, benchmarked with Monte-Carlo.
- Uniform anomalous $\chi$ used. Similar results obtained with Lackner-Gottardi

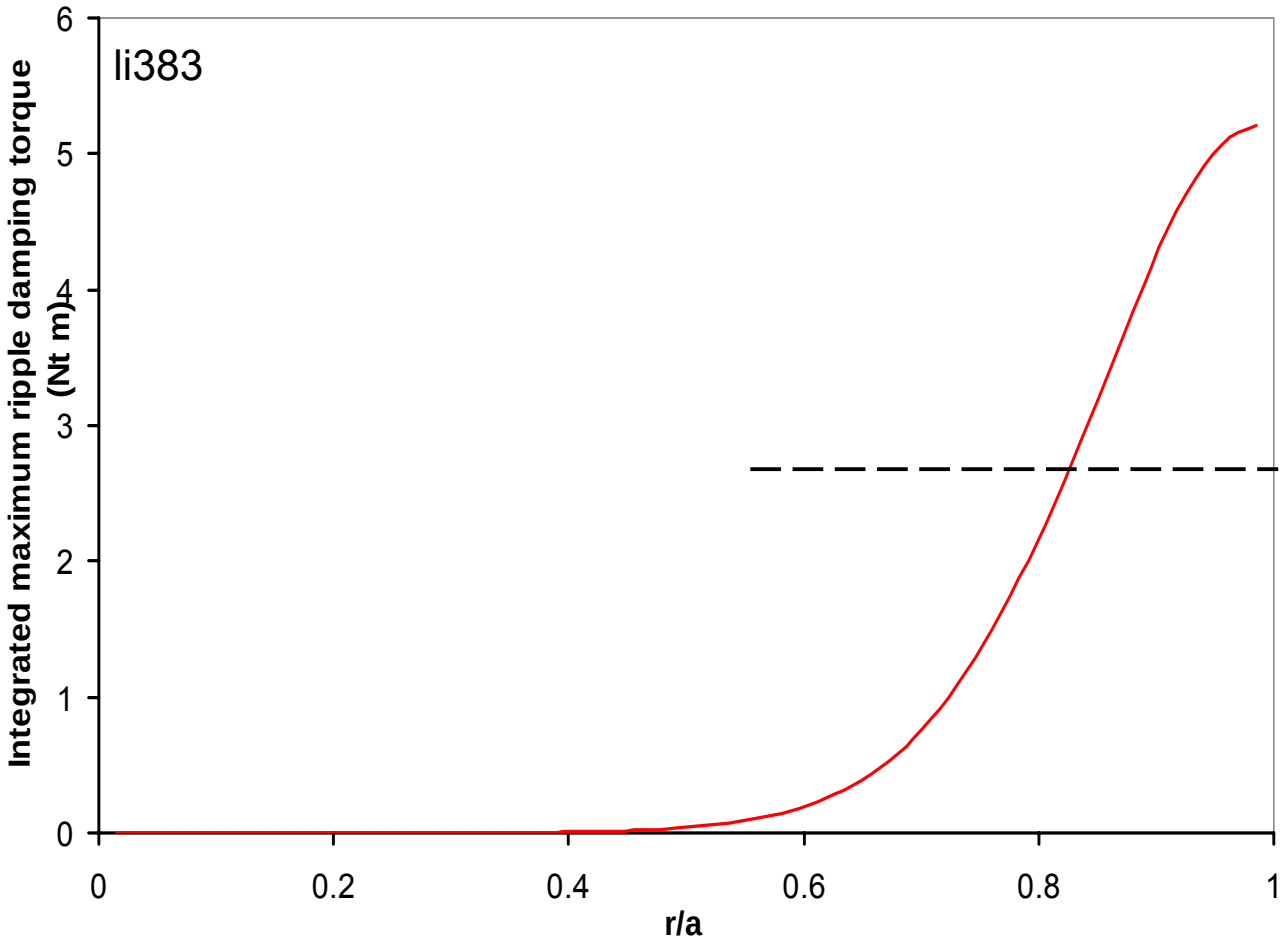
# Ripple driven flux peaks for $E_r$=0, near edge




- From Shaing-Houlberg ripple-neoclassical model, due to deviations from quasi-axisymmetry; benchmarked to Monte-Carlo (GTC)
- Ambipolar $E_r^{amb}$ where $\Gamma_i = \Gamma_e$
- For $E_r \neq E_r^{amb}$, $\Gamma_i \neq \Gamma_e$ acts to restore $E_r^{amb}$ and damp rotation back to ambipolar value.
- At each radius, peak $\Gamma_i - \Gamma_e \sim \Gamma_i$ occurs for $E_r = 0$

# Core rotation should be un-damped



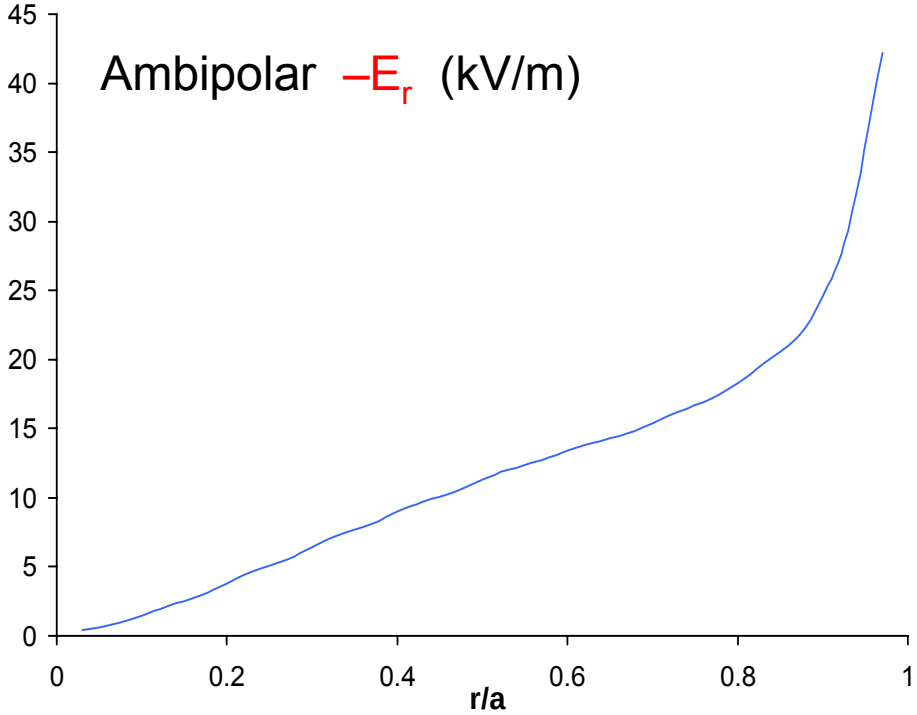

- 6MW balanced NBI planned
- 3MW unidirectional NBI ~ 2.7 Nt-m

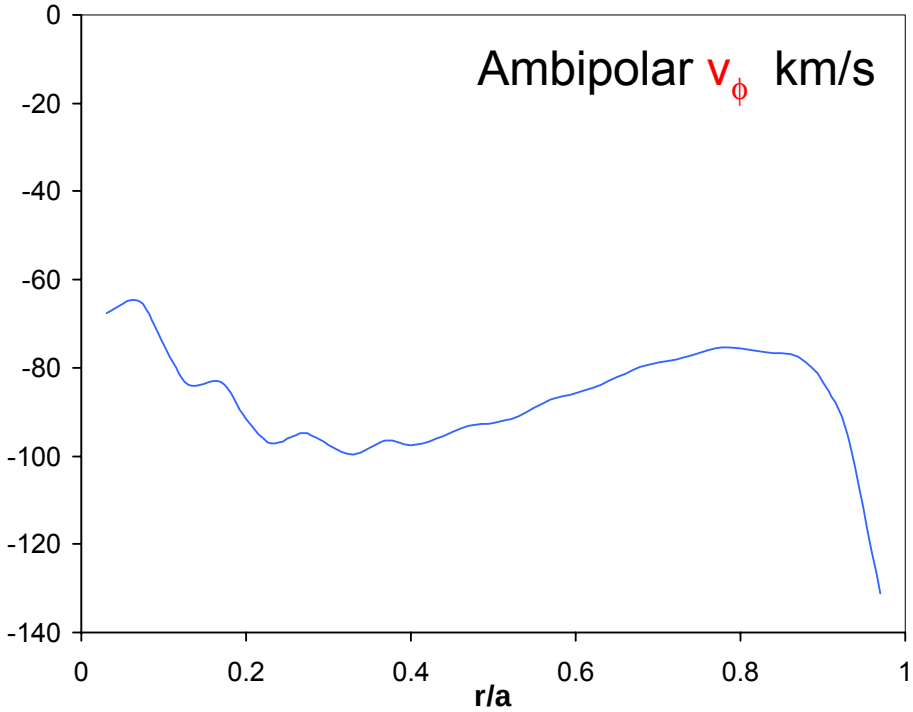
- Estimated integrated ripple-damping toroidal-torque from axis to given radius

$$\int_0^r J_r\, B_P\, R\, d\underline{v}' \sim \int_0^r \overline{J}_r(r')\, \overline{B}_P(r')\, R_0\, d\underline{v}'$$

- Edge velocity will probably be constrained to counter-rotation

# Ambipolar $E_r \Rightarrow$ large $v_\phi$




- No applied torque
- Ambipolar $E_r$ peaks at edge due to edge ripple
- poloidal damping much faster than toroidal, should have tokamak-like solution $v_\phi \sim E_r/B_P$
- $v_\phi$ preliminary: want to verify with Monte-Carlo codes
- large $E_r$ shear at edge

# Program & Requirements Preparation for CDR

- Need to understand priorities in experimental mission
  - needed to develop diagnostic plans and requirements

- Need to clarify and document physics requirements for engineering design

# NCSX Mission

**Understand…**

- Beta limits and limiting mechanisms in a low-A current carrying stellarator
- Effect of 3D fields on disruptions
- Reduction of neoclassical transport by QA design.
- Confinement scaling; reduction of anomalous transport by flow shear control.
- Equilibrium islands and neoclassical tearing-mode stabilization by choice of magnetic shear.
- Compatibility between power and particle exhaust methods and good core performance in a compact stellarator.
- Explore Alfvenic-mode stability in reversed shear compact stellarator

**Demonstrate…**

- Conditions for high-beta, disruption-free operation

**Acquire the physics data needed to assess the attractiveness of compact stellarators.** (adopted as 10-year goal by FESAC-1999)

# NCSX Reseach will Proceed in Phases

| Phase | Topic | Heating Power |
|---|---|---|
| 1. Initial Operation | initiate plasma; exercise coil set & supplies | Ohmic |
| | control plasma evolution | |
| | Initial wall conditioning | |
| 2. Field Line Mapping | map flux surfaces | |
| | verify iota and QA | |
| 3. Initial Ohmic | Improved plasma control, plasma evolution control | Ohmic |
| | global confinement & scaling, effect of 3D shaping | |
| | density limit & mechanisms | |
| | study of Te and ne profiles. | |
| | vertical stability | |
| | current-driven kink stability | |
| | effect of low-order rational surfaces on flux-surface topology | |
| | initial study of effect of trim coils, both signs | |
| | effect of contact location on plasma plasma performance | |
| | control of plasma contact location | |
| | Plasma edge and exhaust characterization | |

# Expected NCSX Reseach (2)

| Phase | Topic | Aux. Power |
|---|---|---|
| 4. Initial Aux. Heating | Plasma and shape control with NB heating, CD | 3MW NBI |
| | test of kink & balooning stability at moderate beta | |
| | effect of shaping on MHD stability | |
| | initial study of Alfvenic modes w/ NB ions | |
| | confinement scaling w/ iota, B, … | |
| | local transport measurements, perturbative transport meas. | |
| | test of quasi-symmetry on confinement and transport | |
| | density limits and control with heating | |
| | use of trim coils to minimize rotation damping | |
| | blip measurements of fast ion confinement and slowing down | |
| | initial attempts to obtain enhanced confinement regimes | |
| | pressure effects on surface quality | |
| | controlled study of neoclassical tearing using trim coils | |
| | wall coatings with aux. Heating | |
| | Plasma edge and exhaust characterization, w/ aux. heating | |
| | Attempts to control wall neutral influx | |
| | wall biasing effects on edge and confinement | |

# Expected NCSX Reseach (3)

| Phase | Topic | Upgrades |
|---|---|---|
| 5. Confinement & beta push | Stability tests at beta >~ 4% | 6 MW total |
| | detailed study of beta limit scaling | 2nd gen. PFCs |
| | detailed studies of beta limiting mechanisms | More diags. |
| | disruption-free operating region at high beta | |
| | active mapping of Alfvenic mode stability (with antenna) | |
| | Enhanced Conf.: H-mode; Hot ion regimes; RI mode; pellets | |
| | Scaling of local transport and confinement | |
| | turbulence studies | |
| | scaling of power or other thresholds for enhanced confinement | |
| | ICRF wave propagation, damping, and heating (possible) | |
| | perturbative RF measurements of transport (possible) | |
| | Divertor operation optimized for power handling and neutral control | |
| | trace helium exhaust and confinement | |
| | scaling of power to divertor | |
| | control of high beta plasmas and their evolution | |
| 6. Long Pulse | long pulse plasma evolution control | Long pulse |
| | equilibration of current profile | Divertor pumping |
| | beta limits with ~ equilibrated profiles | |
| | edge studies with 3rd generation PFC design, pumping | |
| | long-pulse power and particle exhaust handling with divertor pumping | |
| | compatibility of high confinement, high beta, and divertor operation | |

# Physics Requirements for CDR Engineering

**Selected Highlights**

## Coils

- Produce reference plasma parameters and physics properties of li383.
- Provide flexibility in internal iota, external iota, shear, beta limit, quasi-symmetry, profile shapes.

## Electromagnetics

- Vacuum vessel time constant <10 ms, far from plasma (LFS) to avoid kink-mode stabilization.
- Loop voltage and vertical field penetration time constants short enough to maintain adequate magnetic surface quality.
- Be able to withstand EM forces due to disruptions (plasma disappearance).
- Magnetic diagnostics for equilibrium reconstruction

# NCSX Physics Requirements, continued

## Plasma facing components

- Long connection lengths (≥120 m).
- Reconfigurable, with provision for future divertor hardware:
  - plates for heat removal (12 MW / 1 s) with minimum impurity generation.
  - baffles and pumps for neutrals control.
- Carbon-based materials bakable to 350 C.
- Coverage expandable to 100%.
- Can electrically isolate regions for edge biasing.
- Accommodate plasma shaping flexibility.

## Vacuum and wall conditioning

- Glow discharge cleaning at bakeout temperatures or between shots.
- Boronization, lithiumization (upgrade).

# NCSX Physics Requirements, continued

## Heating

- Neutral Beam Injection: 6 MW (3 MW initially)
  - Balanced tangential injection: 2 co- / 2 counter (1 co- / 1 counter initially).
- Ion Cyclotron Heating: 6 MW upgrade.
  - Inboard-launch mode conversion scenario @ 20-30 MHz using available system.
- Port space for alternate NBI arrangements, high-frequency fast wave ICH, or ECH.

## Fueling

- Gas injection: programmable, with density feedback.
- Pellet injection upgrade: pre-installed inside-launch guide tubes.

# Plans for Proceeding to CDR

- **Highest priority is designing coilset that satisfies physics and engineering.**

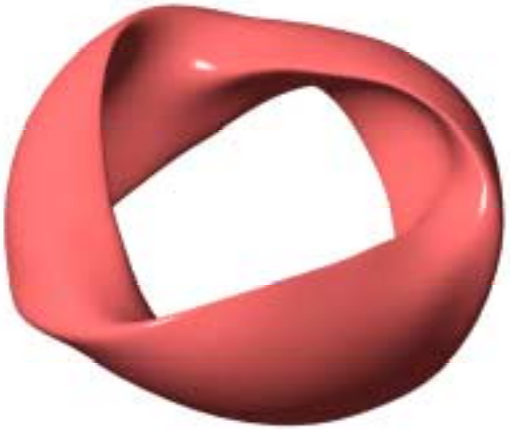
- **Complete documentation of physics requirements**

- **Redocument physics properties of final coil design, including full coil build**
  - Transport & NB loss
  - Flexibility
  - Startup evolution
  - Flux surface quality

**Update PVR document for re-issue at CDR (and publication)**

# Summary

- Significant advance in coil design since PVR
  - Narrowed gap between physics and engineering
  - Coil designs now give adequate physics and allow NB access.
  - Continue working on resolving remaining issues.

- Flow damping estimates indicate core damping is very low.
  - Edge damping may prevent access to co-rotation.
  - Ambipolar rotation rate is significant, has large flow-shear at edge

- Experimental plans and machine requirements have been developed to support CDR