NCSX Physics Design Progress and Preparations for PDR

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UCSD, Columbia, LLNL, ORNL, PPPL, SNL

NCSX PAC-6
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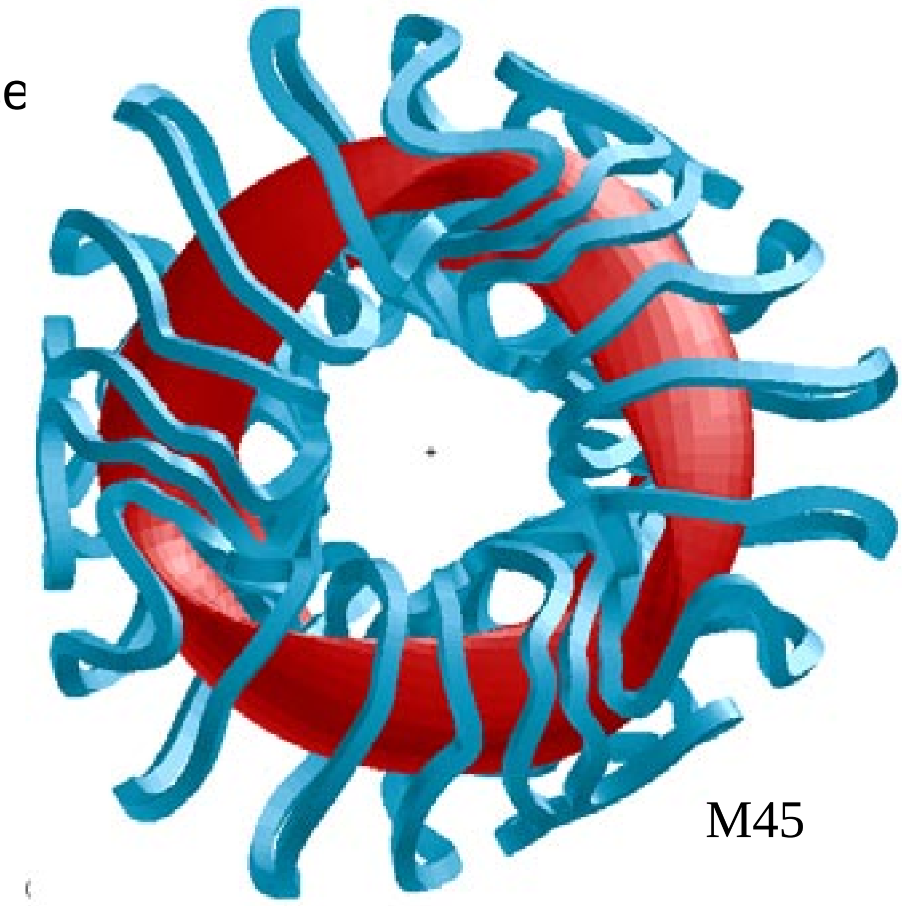
Outline

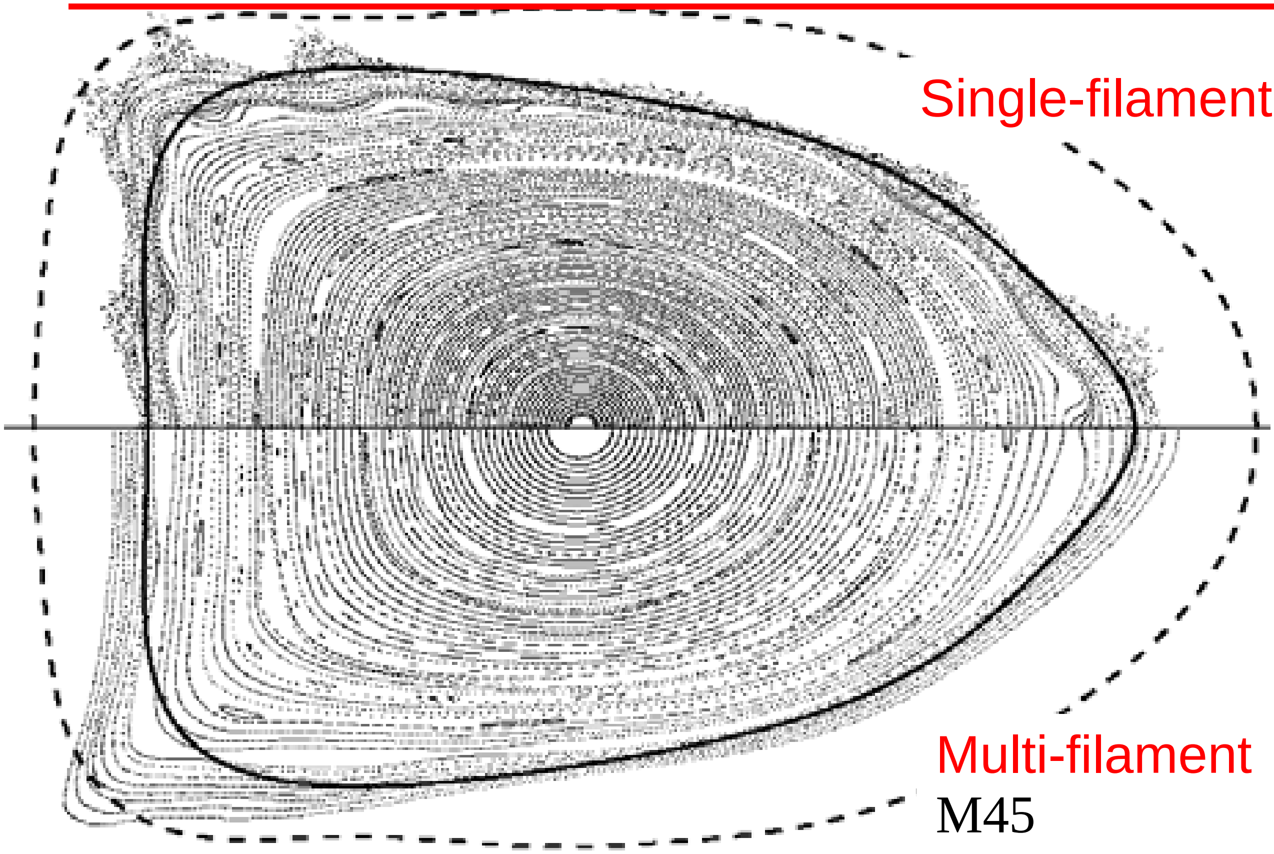
- CDR Design
- Design Progress since CDR
- Plan for Experiments
- Research Preparation Activities
- Experimental Collaborations
- Summary

CDR Coil Design Achieved Physics & Engineering Goals

- 3 periods, R/⟨a⟩=4.4, ⟨κ⟩~1.8, of transform from coils, ‘reverse shear’
- Quasi-axisymmetric
- Passively stable at β=4.1% to kink, ballooning, vertical, Mercier, neoclassical-tearing modes
- 18 modular-coils (3 shapes)
  Full coil set includes PF coils & weak TF coil for flexibility
- Coils meet engineering criteria:
  Bend radii & Coil-coil separation distance



CDR Coils Healed to Produce Good Flux Surfaces



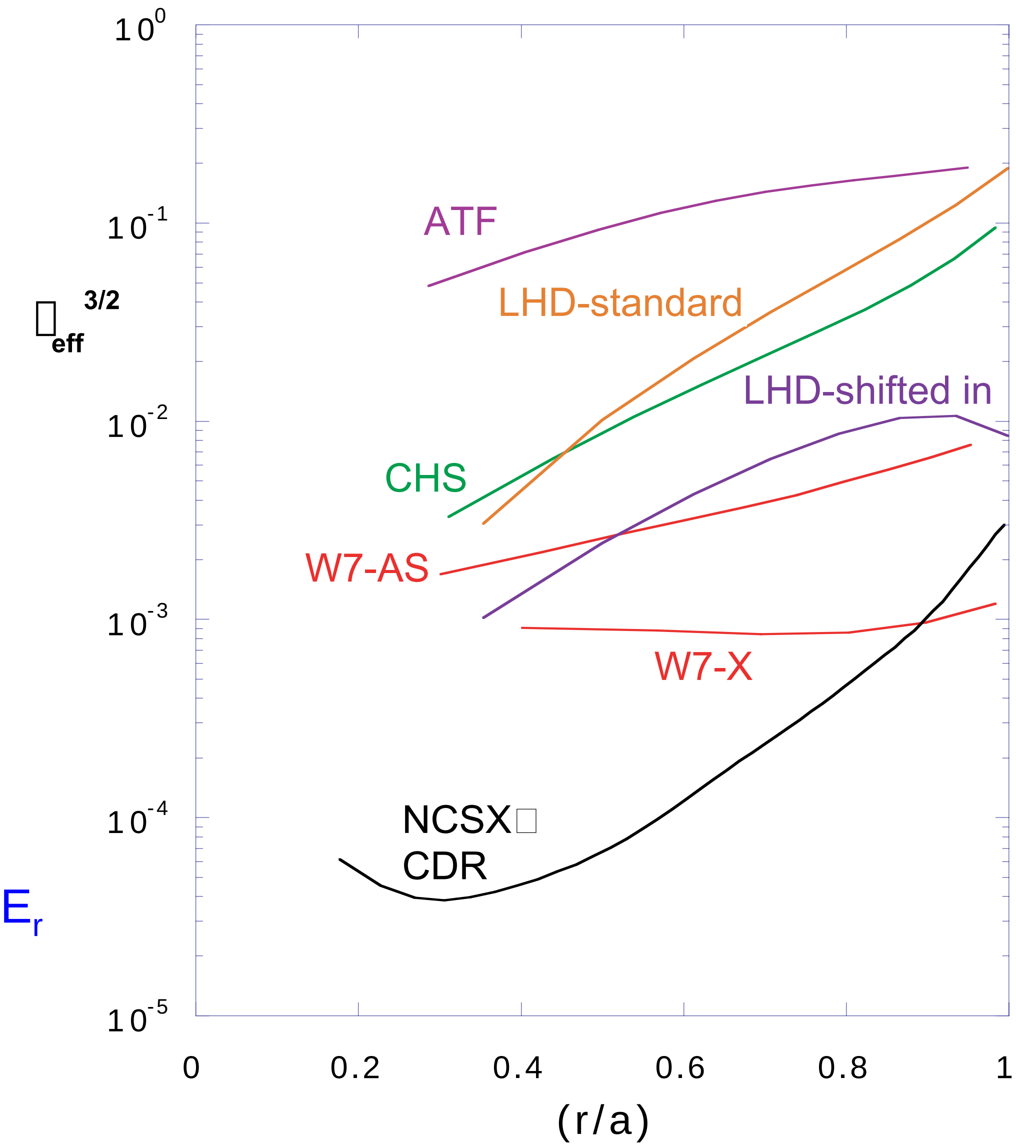
β=4.1% reference
Poincare: PIES
Dashed: first wall
Solid: VMEC boundary

<1% flux surface loss, including effects of neoclassical healing and || vs. ⊥ transport.

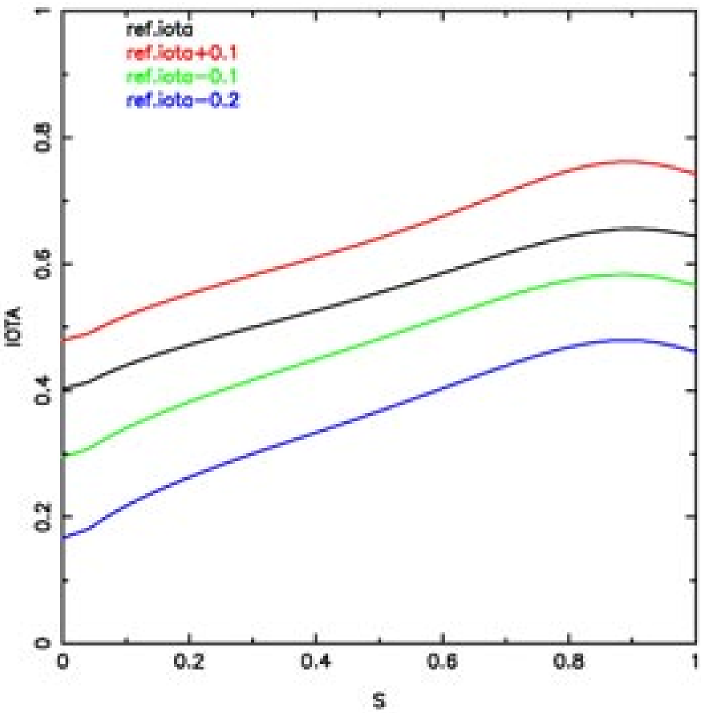
- Coils designed to eliminate resonant fields
- Flux surfaces improved with multi-filament model; stability and transport unaffected.
- Coils also produce good vacuum flux surfaces and for tested flexibility cases. Trim coil arrays will allow targeting of low-order resonances (upgrade)

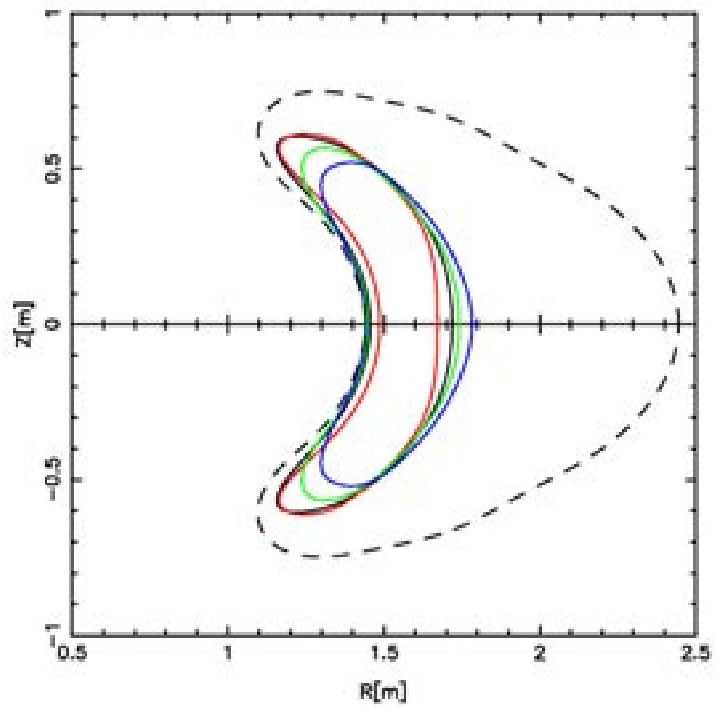
Quasi-Axisymmetric: Very Low effective ripple

- Edge ε_{eff} ~ 2%, ~ 0.1% in core
- In 1/ν regime, neoclassical transport scales as $\varepsilon_{eff}^{3/2}$
- Allows balanced-NBI 25% loss at 1.2T, drops as B↑
- Ripple thermal transport insignificant
- Gives low flow-damping allow manipulation of flows for flow-shear stabilization, control of E_r
- ε_{eff} from NEO code by Nemov-Kernbichler



CDR Modular Coils are Flexible





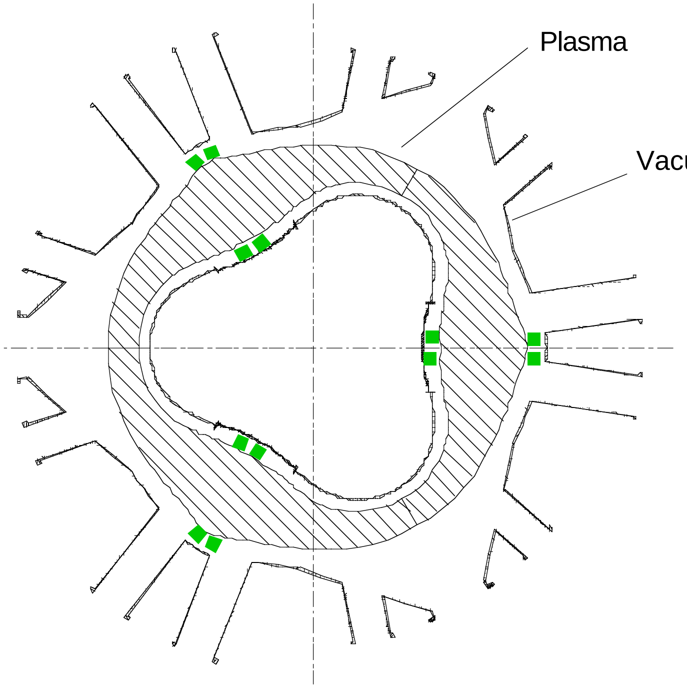
β=4.2%, full current

M45

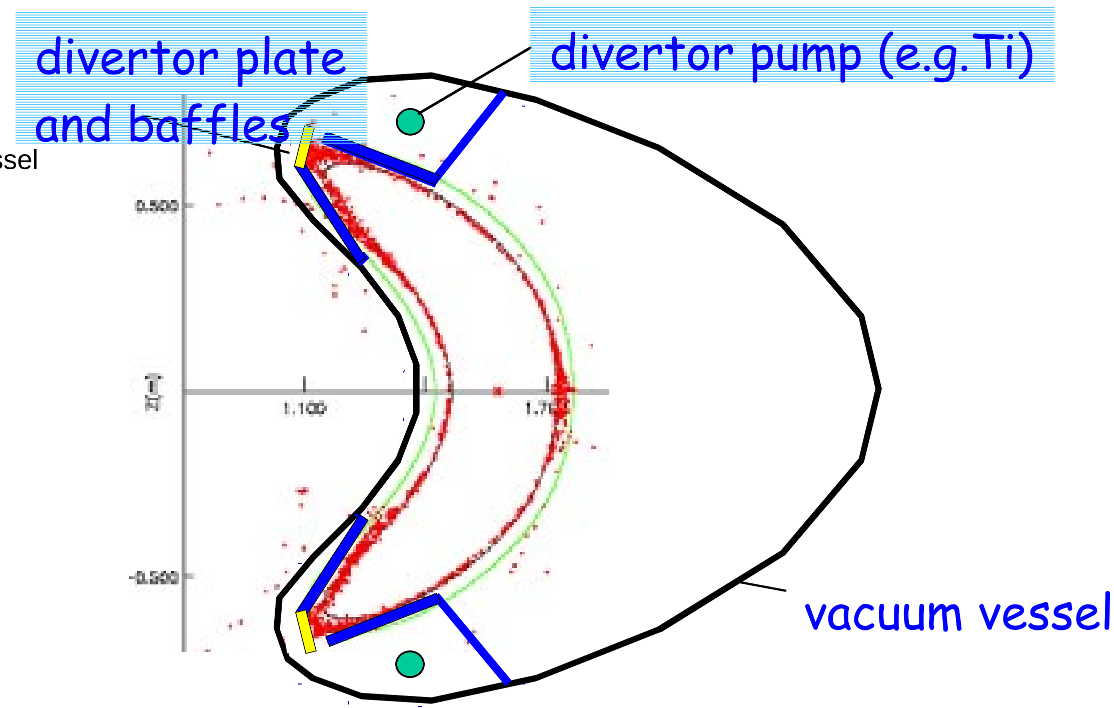
- External rotational transform controlled by plasma shape at fixed plasma current & profile.
- Can adjust to avoid iota=0.5, or hit it; can externally control shear
- Can accommodate wide range of p,j profiles
- Can use to test stability, island effects. Can lower theoretical β-limit to 1%
- Discharge evolution calculations show stable access to high β

Limiter and Divertor Designs

Initial Limiter Configuration (in TEC)

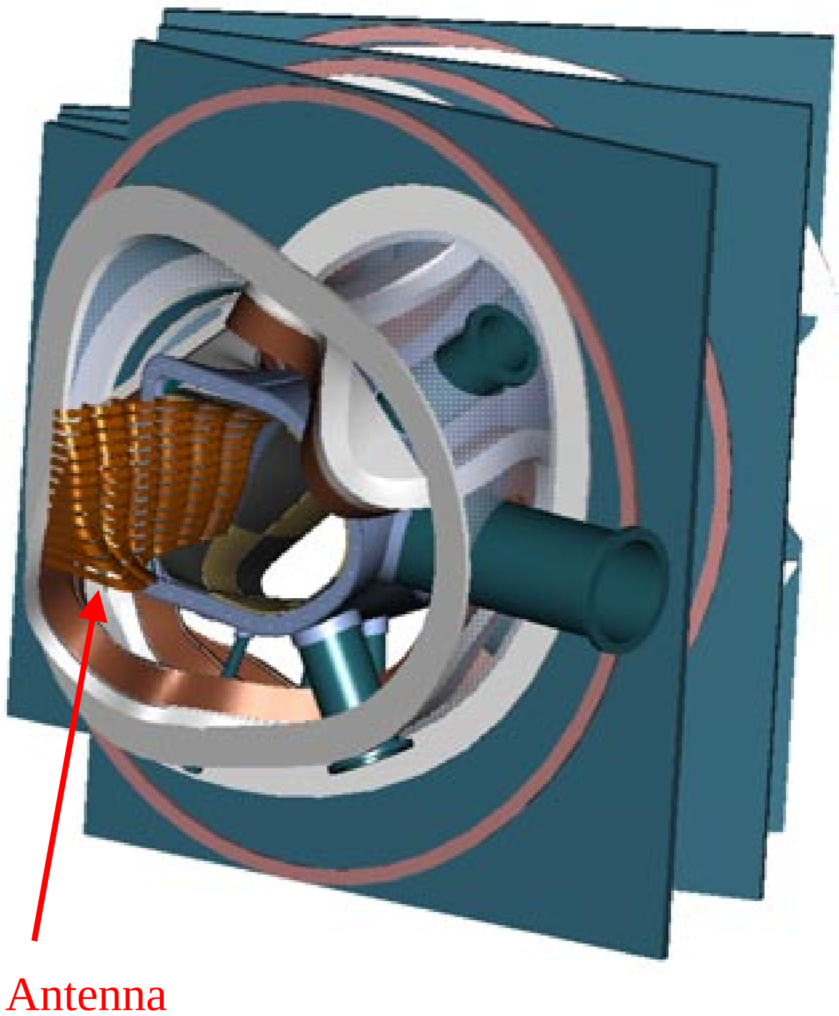


Upgrade Divertor Configuration

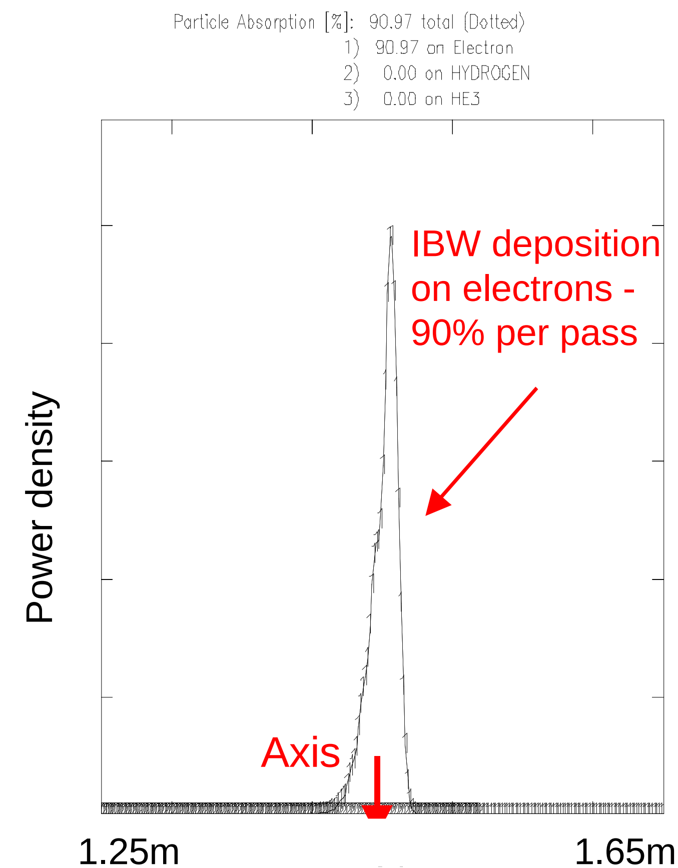


- Plan: start with limiters for Ohmic phase
- Add baffles and pumps as upgrades, starting in Auxiliary Heating Phase
- PFC design will be iterated during high-power experiments
- Neutral penetration calculations (DEGAS) show shielding of core with designed plasma contact (at elongated tips, or at bullet cross-section)

NCSX Can Accommodate High Field-side RF Antenna: IBW mode-conversion



- Three antennas planned for 6 MW, can be operated as combline
- localized electron and thermal ion heating with mixtures of D, H, ^{3}He



Post CDR Design Activities

- Modeling of scrape-off layer: desire 4 cm clearance between design LCFS and PFCs (away from divertor region)

- For CDR design (M45), requires significant local reduction of gap between PFCs and Vacuum Vessel
  - May not be compatible with inboard-launch RF antenna design

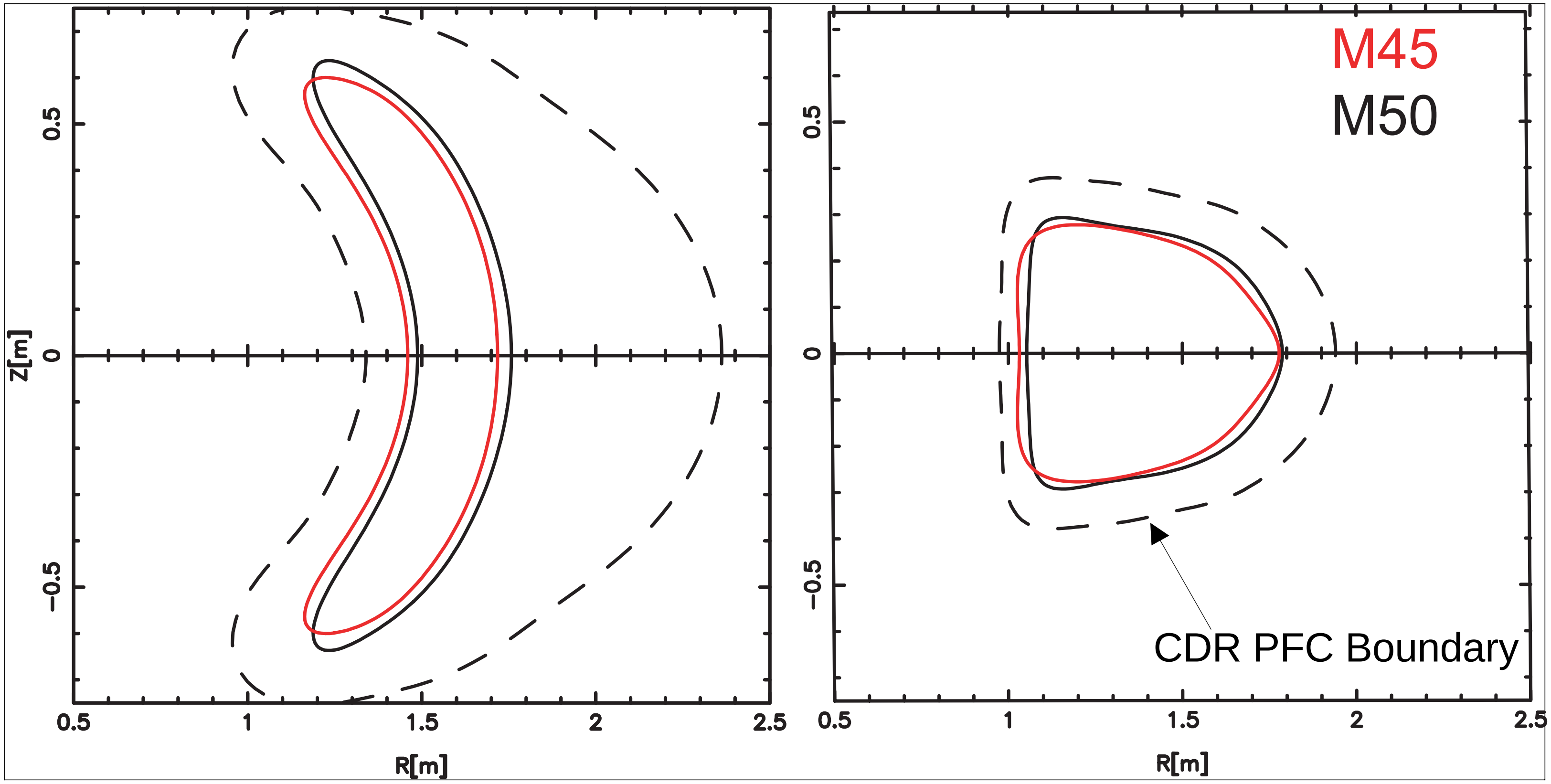
- Improved coil designs have been developed to increase the plasma-coil separation, allowing more plasma-PFC separation
  - M50 Coilset adopted. Final adjustments being made & runs done.
  - PDR Coil design will be provided to Engineering on 16 Dec ’02.

New Design Characteristics

	M45	M46	M48	M50
Min. Coil Separation (cm)	16.0	16.0	15.7	15.7
Min Coil Curvature Radius (cm)	10.5	9.5	10.0	10.5
Coil-Plasma Separation (cm)	18.5	20.9	21.6	21.1
Max Modular Coil Current (kA-t)	694	722	699	652
ε_{eff} (ρ = 0.56)	2.1e-3	2.0e-3	3.2e-3	2.2e-3
ε_{eff} (ρ = 0.97)	0.016	0.017	0.014	0.015

- M46 found more flexible than M45. M50 expected to be similar to M46.

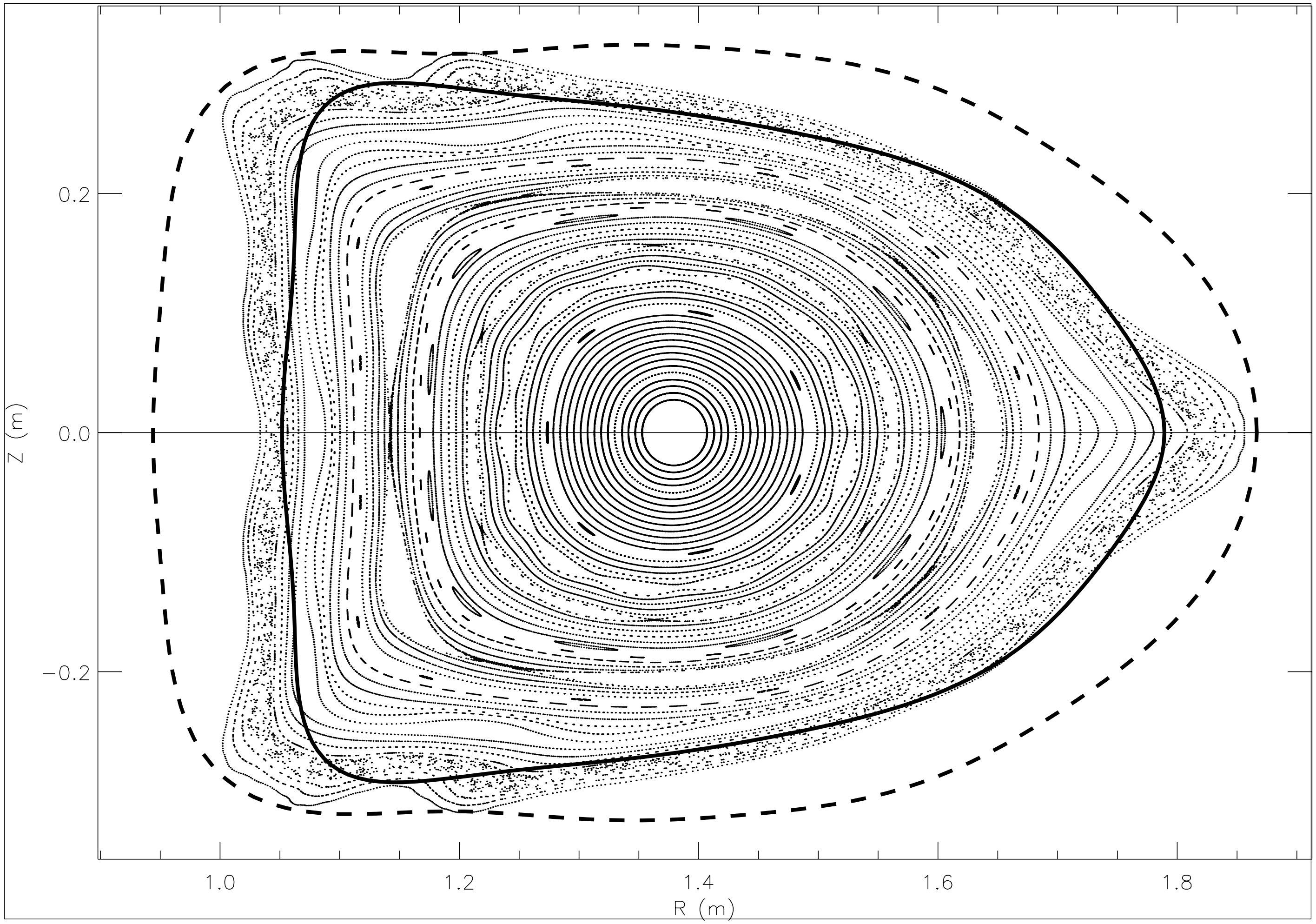
M50 similar to M45



β=4.2%,
full current

- ⟨R⟩ shifted outwards ~ 3 cm

M50 Flux Surfaces are Adequately Healed



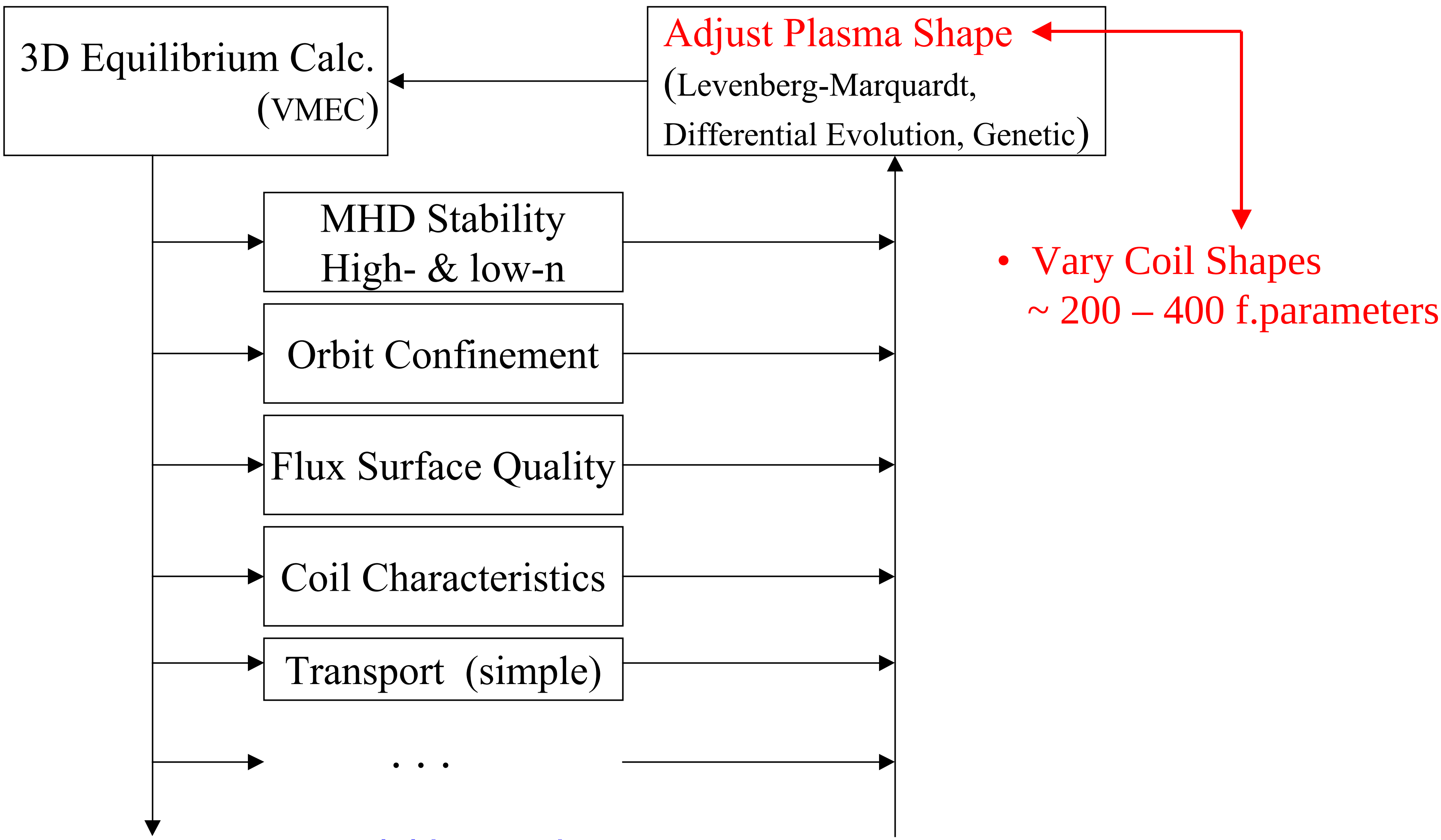
β=4.2%
Poincare: PIES
Dashed: first wall
Solid: VMEC boundary

Single-Filament Calculation

- m=5 island should have effective width < 3%, including neoclassical and || vs. ⊥ transport effects

Primary Tool: ‘Merged Optimizer’

Direct design of coil shapes to achieve desired physics properties



See Strickler et al, IAEA 2002.

NCSX Research Mission

Acquire the physics data needed to assess the attractiveness of compact stellarators; advance understanding of 3D fusion science. (FESAC-99 Goal)

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.
- Alfvenic-mode stability in reversed shear compact stellarator

Demonstrate…

- Conditions for high-beta, disruption-free operation

NCSX Research will Proceed in Phases

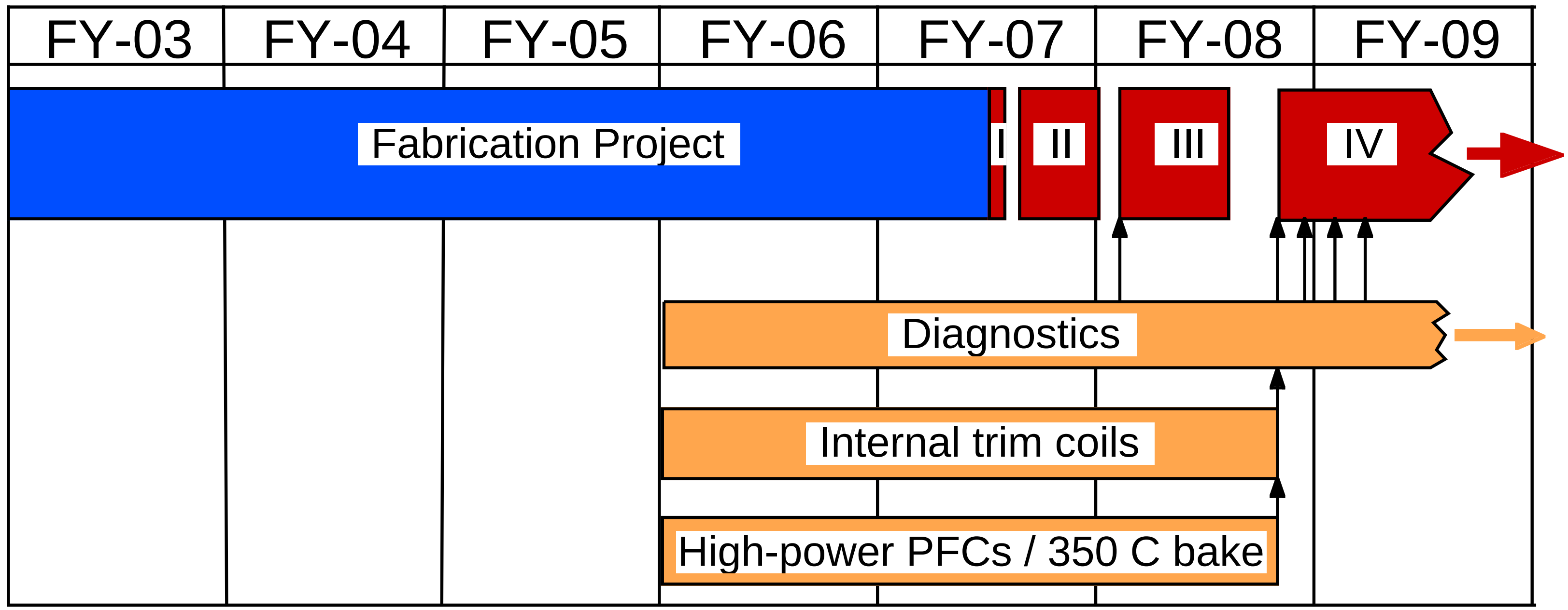
Planned as:

I. Initial operation - shake down systems
II. Field Line Mapping
III. Ohmic
IV. Auxiliary Heating - (3MW NBI, PFC liner)
V. Confinement and High Beta - (~6 MW, 3rd gen. PFCs)
VI. Long Pulse – (pumped divertor)

– Diagnostic upgrades throughout to match research goals
  - See D. Johnson's talk
– Phases IV – VI may last multiple years.

(equipment included in project cost-TEC)

Timeline for Initial Research & Preparation



Checkout Phases

I. Initial Operation	Heating	Measurement Requirements
• Initiate plasma; exercise coil set & supplies • Ip > 25 kA Checkout magnetic diagnostics Checkout vacuum diagnostics Initial wall conditioning	Ohmic GDC 150 bake	Plasma current Magnetic diagnostics Plasma / wall imaging Line-integrated density
II. Field Line Mapping		
• Map flux surfaces (cold & room temperature) Verify iota and QA Verify coil-flexibility characteristics		Electron-beam mapping apparatus Variable energy electron-beam

III. Ohmic

Topic	Heating	Measurement Requirements
• Plasma control, plasma evolution control	Ohmic	Core ne & Te profiles
• Global confinement & scaling, effect of 3D shaping		Radiated power profile
Density limit & mechanisms		Magnetic axis position
Characterize Te and ne profiles vs iota, current,		Low (m,n) MHD (< 50kHz)
• Vertical stability		Flux surface topology
Current-driven kink stability		Impurity sources &concentrations
• Effect of low-order rational surfaces on flux-surface topology		Zeff
Initial study of effect of trim coils, both signs		Hydrogen recycling
• Effect of contact location on plasma plasma performance		
Control of plasma contact location		

IV. Auxiliary Heating

Topic	Upgrades	Measurement Requirements
• Plasma and shape control with NB heating, CD	3MW NBI	Core Ti profile
• Test of kink & ballooning stability at moderate beta	PFC liner	Tor. & pol. rotation profiles
Effect of shaping on MHD stability	350 bake	Iota profile
Initial study of Alfvenic modes with NB ions		Er profile
• Confinement scaling		Fast ion losses
Local transport & perturbative transport measurements		Ion energy distribution
• Effect of quasi-symmetry on confinement and transport		First wall surf. temperature
• Density limits and control with auxiliary heating		High frequency MHD
Use of trim coils to minimize rotation damping		Edge neutral pressure
Blip meas. of fast ion confinement and slowing down		SOL temp. & density
Initial attempts to access enhanced confinement		
• 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		
Low power RF loading and coupling studies (possible)		

V. Confinement and High Beta

Topic	Upgrades	Measurement Requirements
• Stability tests at β >~ 4%	6 MW total	Core fluctuations & turbulence
• Detailed study of β limit scaling	Divertor	Core helium density
• Detailed studies of beta limiting mechanisms		Edge/div. Radiated power profile
Disruption-free operating region at high beta		Divertor recycling
Active mapping of Alfvenic mode stability (with antenna)		Edge Te, ne profiles
• Enhanced Conf.: H-mode; Hot ion regimes; RI mode; pellets		Divertor target temperature
• Scaling of local transport and confinement		Target Te, ne
Turbulence studies		Divertor impurity concentration
Scaling of 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		

VI. Long Pulse

Topic	Upgrades	Measurement Requirements
Long pulse plasma evolution control Equilibration of current profile 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	Long pulse Divertor pumping 12 MW?	More detailed divertor profiles

Research Preparation

Before operation (FY2003-07), need to do long-term development to prepare for operation (similar to NSTX)

- Development of discharge control strategy & algorithms
- Design and begin fabrication of long-lead diagnostic upgrades for Phase III and IV.
- Develop improved edge models, apply them to design Phase IV PFCs
- Finish modeling and design for internal trim coils for Phase IV.
- Conceptual design of low-power RF loading study, for Phase IV.

Research Preparation – FY03

- Initial investigation of control strategies, implications for magnetics design
  - Requirements (e.g. position, shape, iota control)
  - Filament code? Parametric interpolation?

- Integration of envisioned upgrade diagnostics with port design
  - See D. Johnson's talk

- Improved edge models, implications for PFC design
  - Extend edge field-line topology & connection length studies
  - 3D neutral calculations
  - Continue collaborative development of BORIS with IPP-Greifswald

Preparation of NCSX Research Team

NCSX will be operated as a National Collaboration, including members from many institutions

Plan to start Research Forums in FY2005/06 to

- Identify groups interested in developing needed diagnostics
- Nucleate the research team
- Develop detailed research plans and responsibilities

During the fabrication period: NCSX will collaborate with existing US & International stellarators on topics of mutual interest, to debug analysis methods, and prepare potential team.

- Already started…

Experimental Collaborations

Strong collaborations being formed to prepare for NCSX and participate in experiments -- already very fruitful

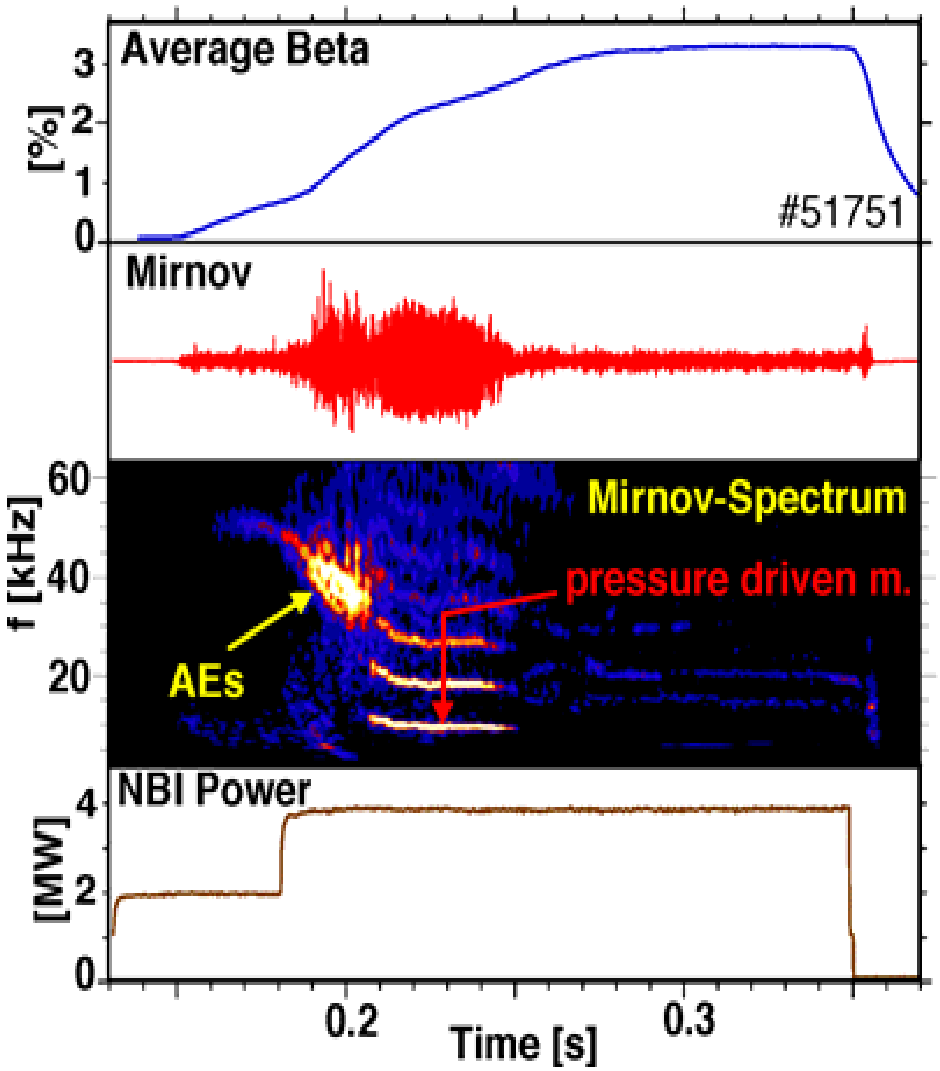
- W7-AS
  - High-beta experiments (Zarnstorff, Fredrickson)
  - Theoretical analysis - see A. Reiman
- W7-X
  - Transport modeling and analysis (Mikkelsen)
  - Diagnostic development (A. Werner)
- LHD
  - Diagnostics (Takahashi, Darrow, Medley)

- HSX, CTH, CNT – expect to establish collaborations

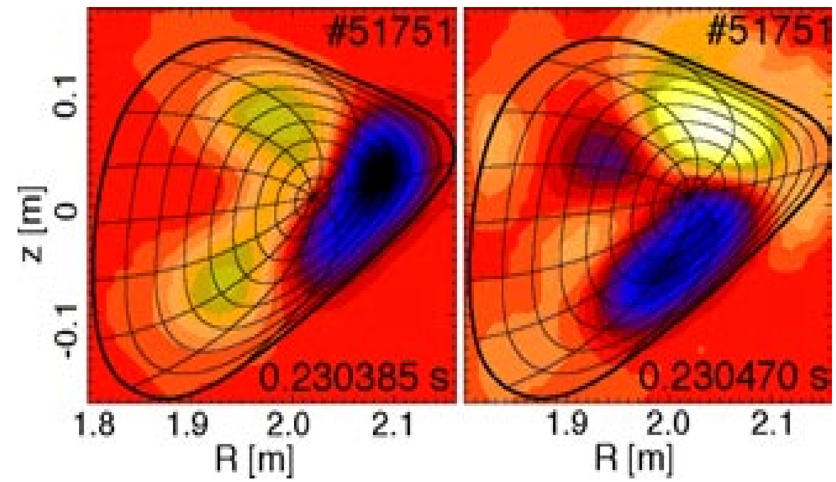
- NCSX (!) - starting to explore possible incoming collaborations

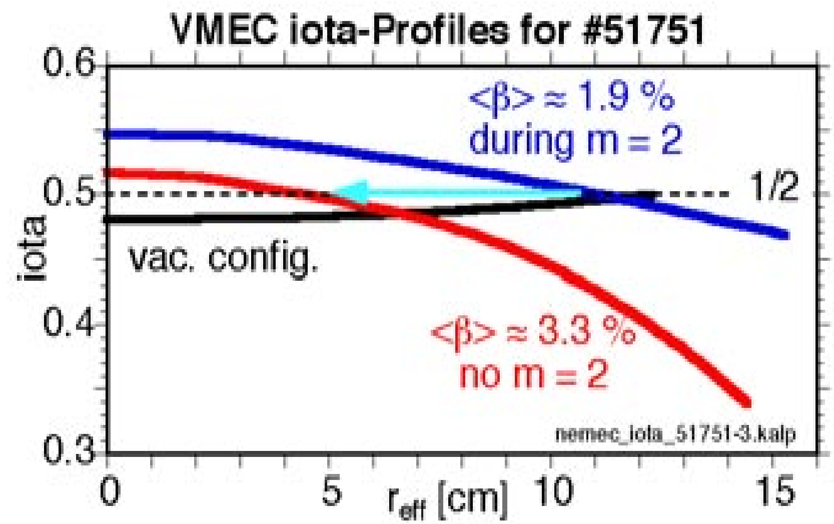
Global Modes close to low order rational Surfaces

pressure driven (m,n) = (2,1) modes around iota = 1/2



X-Ray Tomograms reveal
Ballooning Type Perturbation





- **Modes dissappear at high β**
  (magn. well + inward shift of iota = 1/2)

- A. Weller, IAEA 2002

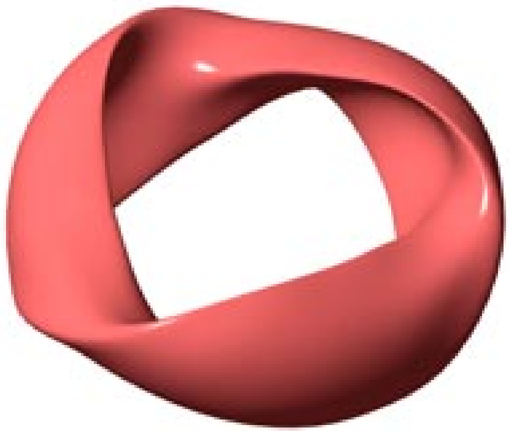
Conclusions

A sound physics design has been established for NCSX

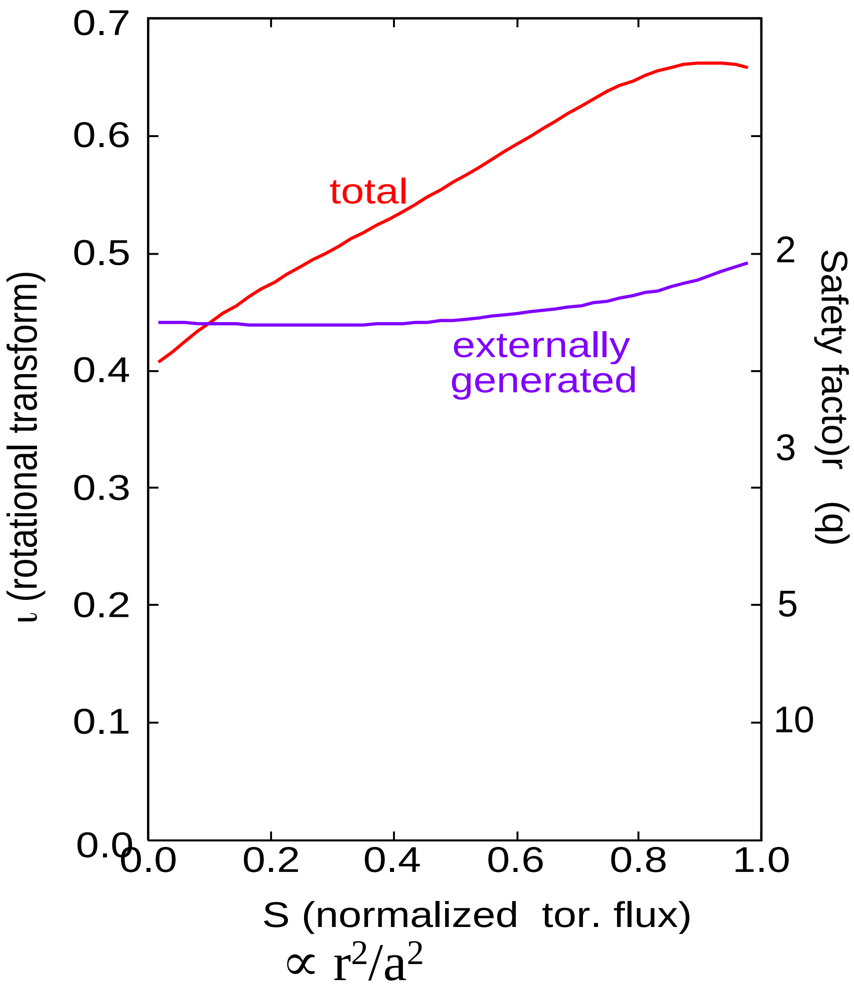
- Attractive coil configuration has been identified
  - passive stability to kink, ballooning, vertical, Mercier, neoclassical tearing with $\beta > 4\%$
  - very good quasi-axisymmetry
  - Healed to give good flux surfaces
- Robust, flexible coil system for testing understanding and exploring
- Coil design improved over CDR

NCSX will be a valuable national facility for the fusion science program. Starting long-lead design and R&D, preparing for research.

Ready for the next phase: preliminary & final design.



Hybrid Configuration Combines Externally-Generated Fields with Bootstrap Current

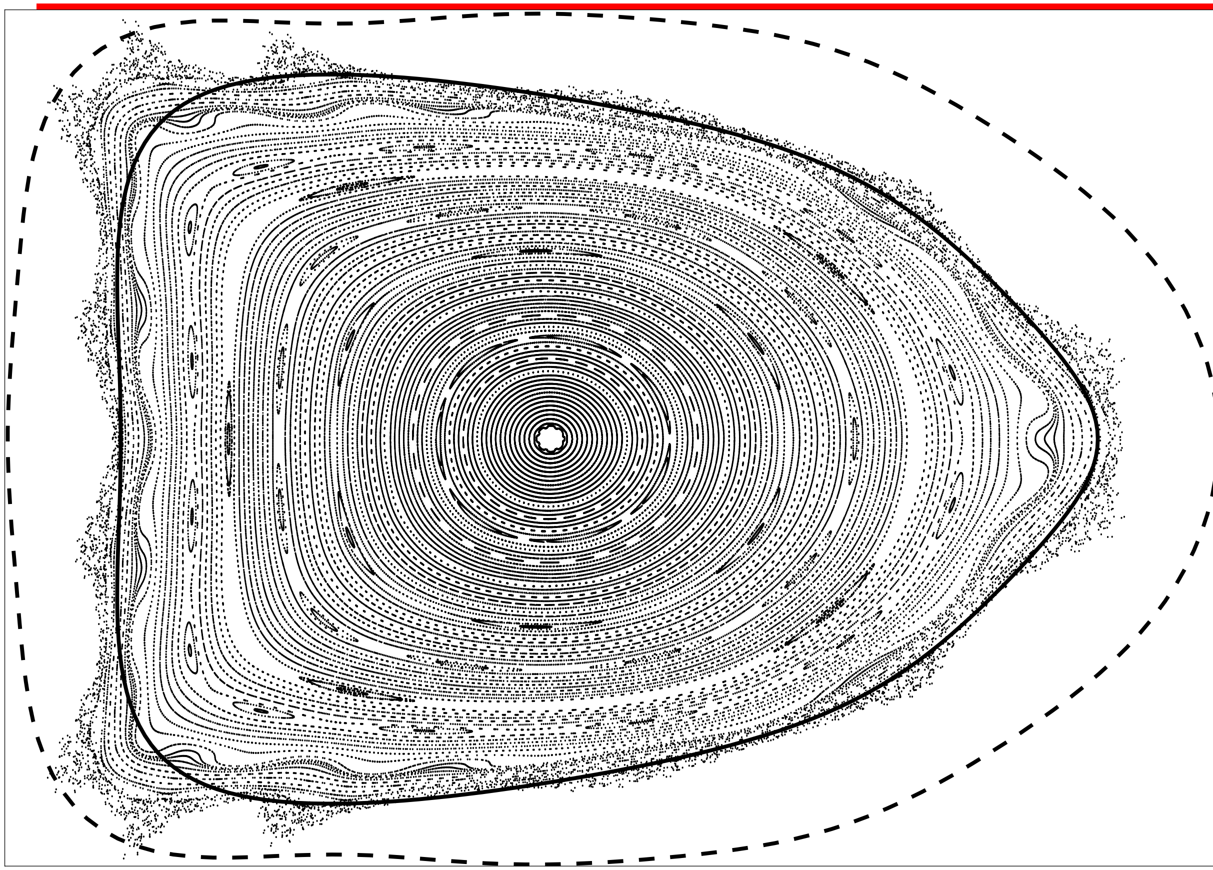


- Quasi-axisymmetry
⇒ tokamak like bootstrap current

- ~3/4 of transform (poloidal-B) from external coils ⇒ externally controllable

- 'Reversed shear' stabilizes neoclassical tearing and trapped particle modes ⇒ reduced turbulence drive as in reversed shear tokamak regimes?

Multiple Methods used to Produce Good Flux Surfaces

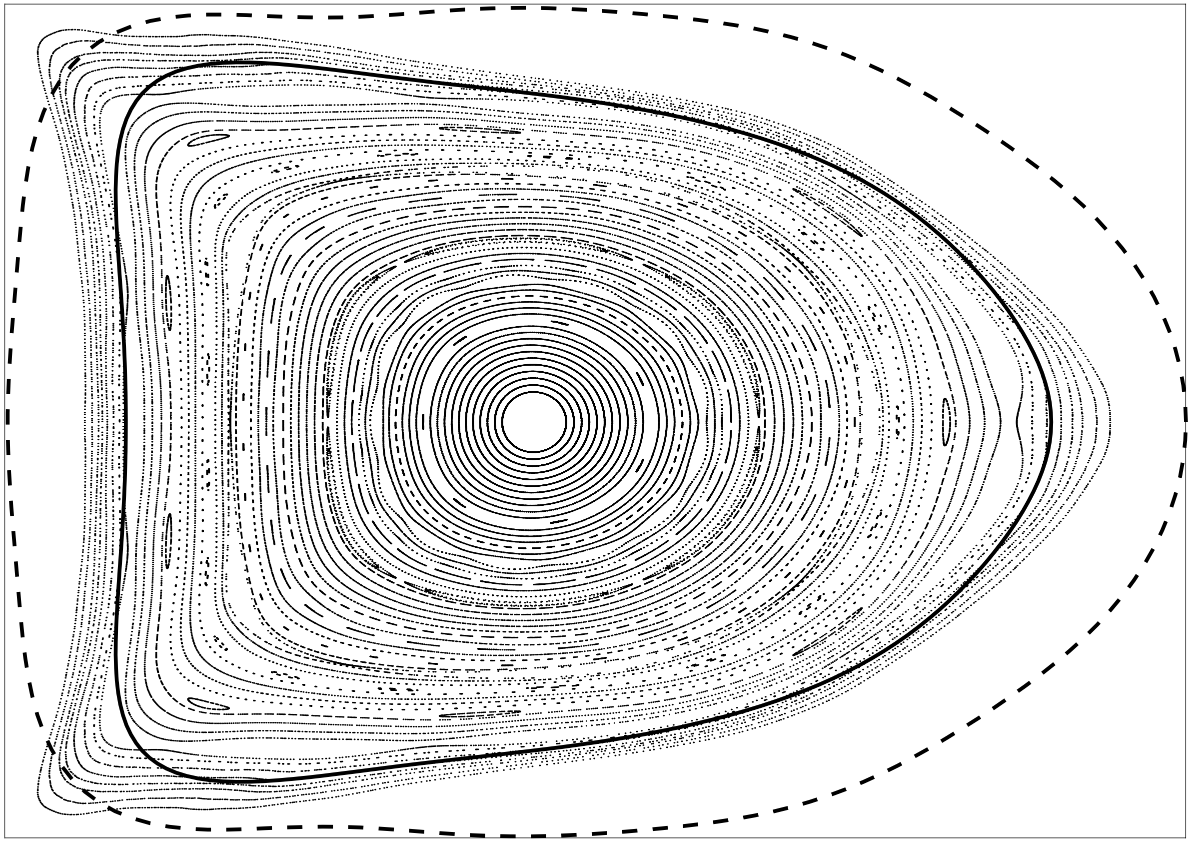


β=4.1% reference
Poincare: PIES
Dashed: first wall
Solid: VMEC boundary

'Healed' coils:
- Infinite-n ballooning unstable on 5/49 surfaces for reference profiles.
- Finite-n ballooning stable thru n=45
- Ok for simulated profiles, flexibility studies.

- Explicit design to eliminate resonant fields, in both fixed boundary target plasma, and in coil designs.
- 'Reversed shear' configuration $\Rightarrow$ neoclassical healing of equilibrium islands and stabilization of tearing modes
- Trim coil arrays targeting low-order resonances (upgrade)

Good Properties Maintained with Multi-filament Coil Model



Dashed: first wall
Solid: VMEC boundary

Goal: < 10% loss of flux surfaces

Result: <1% flux surface loss, including effects of neoclassical healing and || vs. ⊥ transport.

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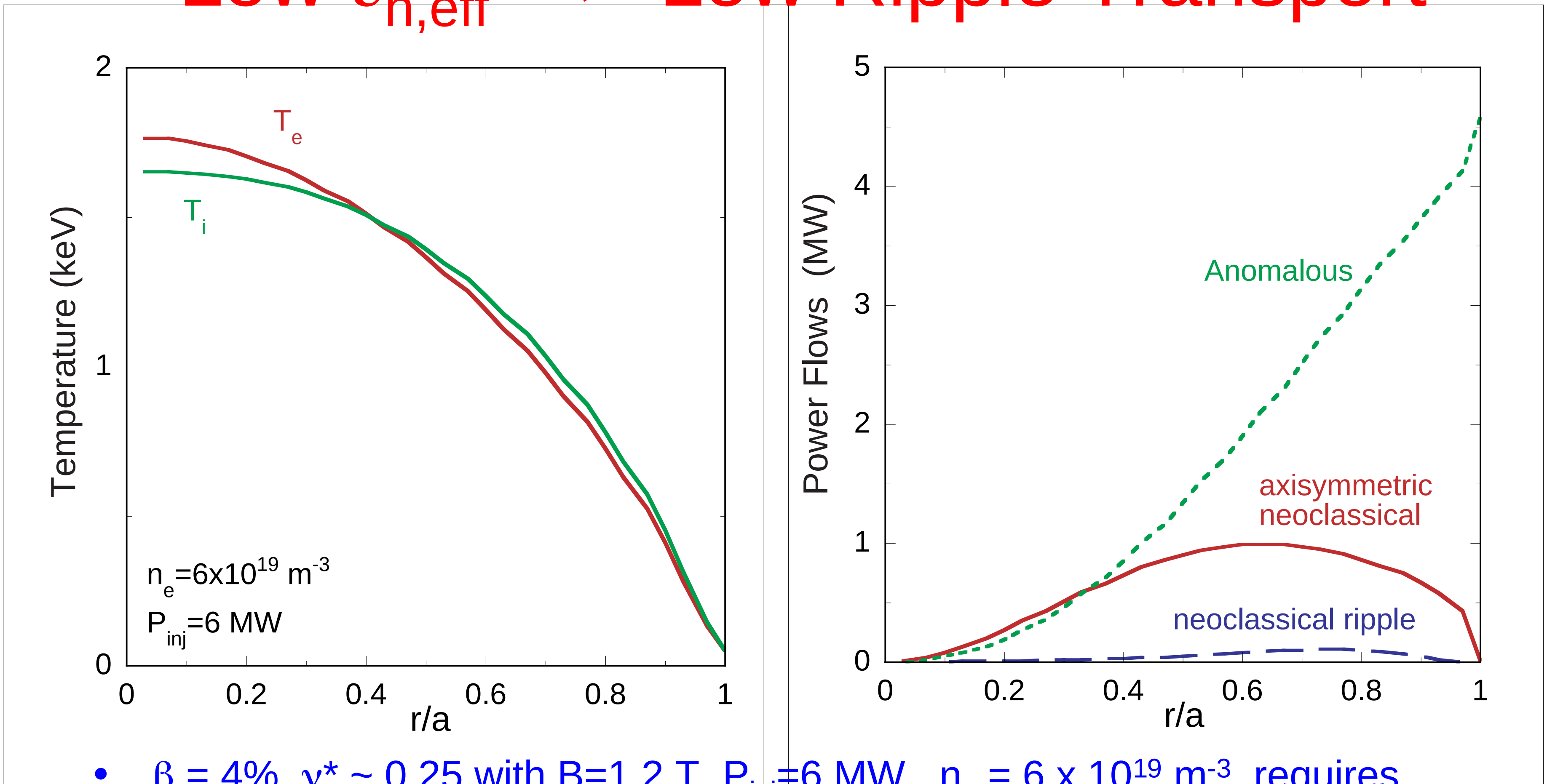
- Calculated flux surfaces improved in multi-filament model
- Stability and transport properties unaffected

Coils also produce good vacuum flux surfaces.

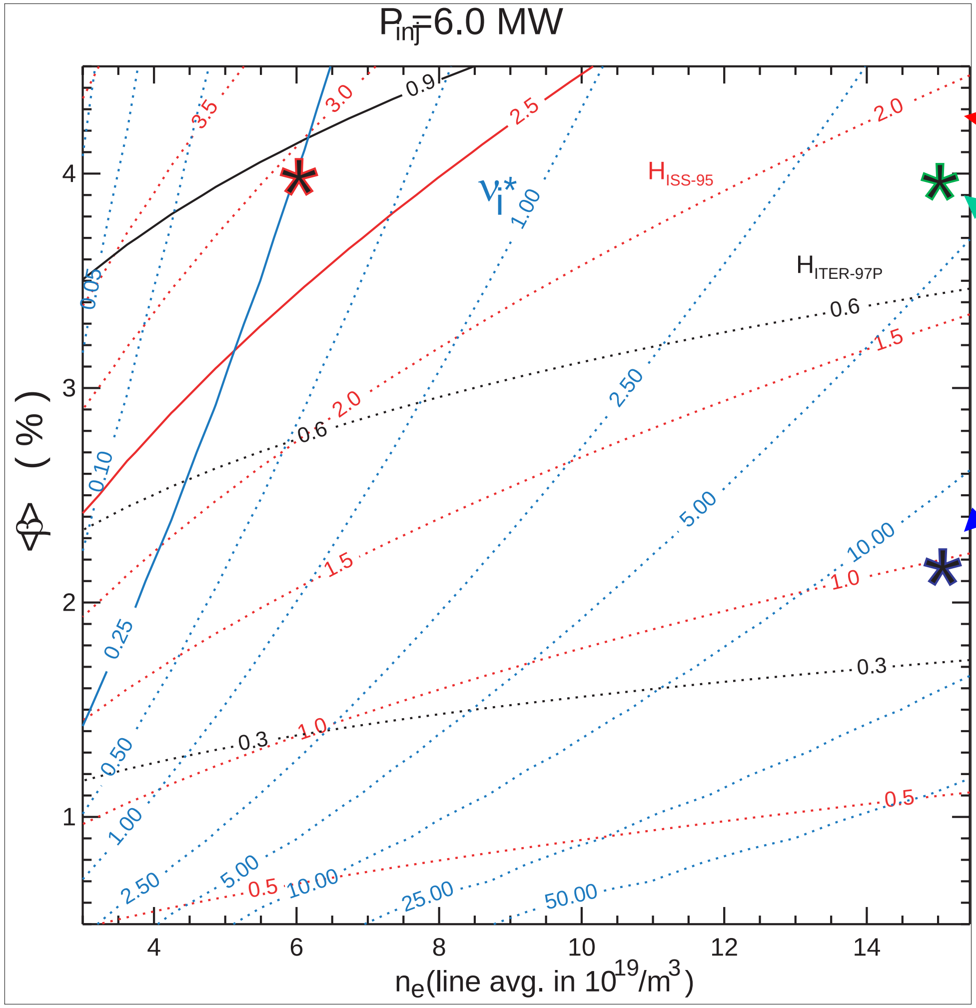
Low $\varepsilon_{h,eff}$ $\Rightarrow$ Low Ripple Transport



- β = 4%, ν^* ~ 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 B=1.7T gives access to ν^* ~ 0.1, $T_i(0)$~2.3 keV
- Uniform anomalous χ used. Similar results obtained with Lackner-Gottardi Anomalous transport adjusted to match global scaling.
- Core rotation undamped; edge damping will prevent edge-co-rotation

Wide Range of Plasmas Accessible

Contours of H_{ISS95}, $H_{ITER\text{-}97P}$, and min ν_{*i}



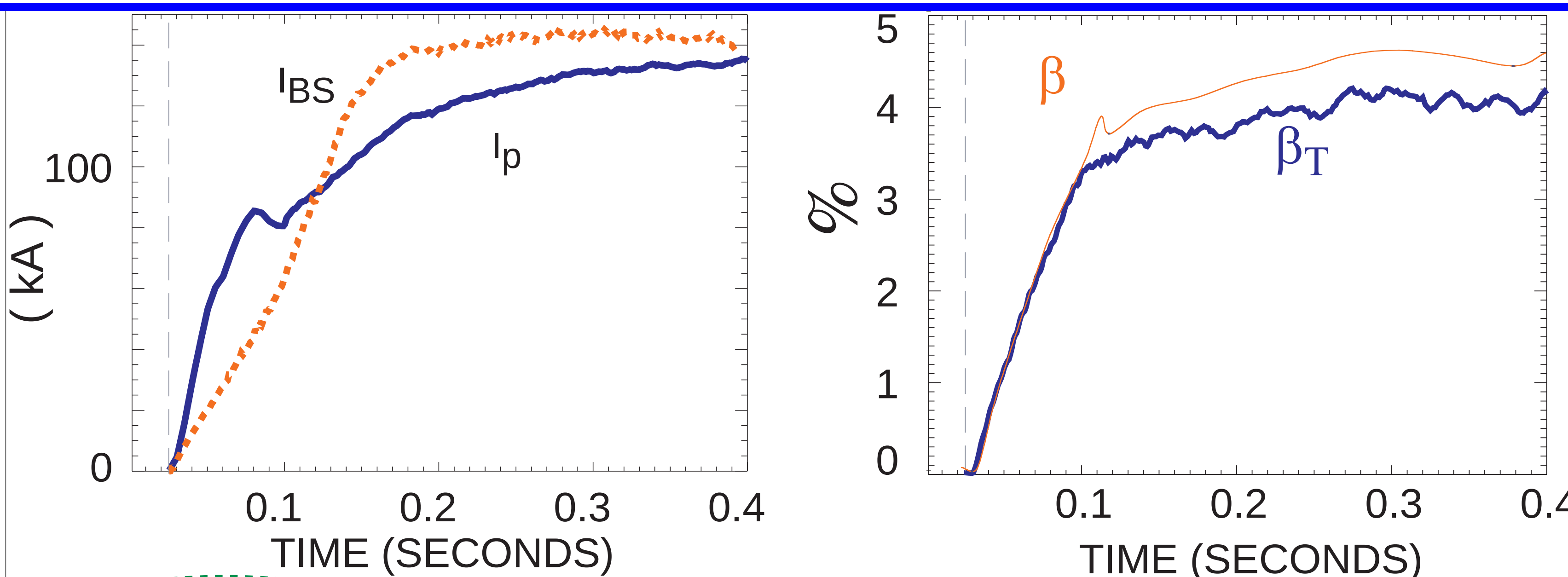
B = 1.2 T

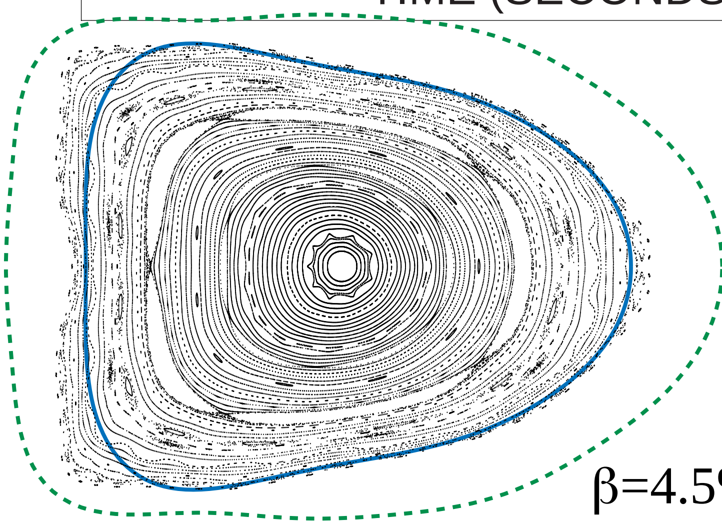
- * β=4%, ν_{*I} =0.25 requires H_{ISS95}=2.9, $H_{ITER\text{-}97P}$=0.9
- * β=4% at Sudo 'density-limit' requires H_{ISS95}=1.8
- * H_{ISS95}=1.0 gives β=2.2% sufficient to test stability theory

- 3MW gives β=2.7%, ν_{*I} =0.25 with H_{ISS95}=2.9;
  β=1.4% with H_{ISS95}=1.0
  sufficient to test stability theory

LHD and W7-AS have achieved H_{ISS95} ~ 2.5
PBX-M obtained β = 6.8% with $H_{ITER\text{-}97P}$ = 1.7 and H_{ISS95} ~ 3.9

Modeling of Discharge Evolution Shows Stable Access





β=4.5%
2.5% effective surface loss

- Profiles modeled using predictive transport model, self-consistent bootstrap current
- Calculated: stable evolution
- Calculations indicate acceptable flux surfaces, including neoclassical effects

Motivation: Combine Best Features of Stellarators and Tokamaks

Use flexibility of 3D shaping to combine best features of stellarators and tokamaks, synergistically, to advance both

—Stellarators: *Externally-generated helical fields;*
no need for external current drive;
generally disruption free.

—Advanced tokamaks: *Excellent confinement;*
low aspect ratio – affordable, high power density;
self-generated bootstrap current

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Understand…

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- 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 3D Alfvenic-mode stability in reversed shear compact stellarator

Demonstrate…

- Conditions for high-beta, disruption-free operation

NCSX Research will Proceed in Phases

Currently envisioned as:

I. Initial operation - shake down systems
II. Field Line Mapping
III. Ohmic - plasma control
IV. Auxiliary Heating - (3MW NBI, PFC liner)
V. Confinement and High Beta - (~6 MW, 3rd gen. PFCs)
VI. Long Pulse – (pumped divertor)

- Further discussion in Breakout #2.
- Diagnostic upgrades throughout to match research goals
- Phases IV – VI may last multiple years.

(equipment included in project cost-TEC)

PVR Design Issues are Resolved

Documented in "Summary of NCSX Response to Recommendations from PVR…"

A number of the issues have been discussed already.

In addition:

- Design size: analysis indicates machine size adequate for mission.
- Objectives ↔ Diagnostics: see Breakout Session #2.
- Heating Choices: NBI for initial heating; MC-IBW as upgrade, as recommended.
- Beam Losses: Beam re-aiming impractical. Low-B losses are not unusual. Reduced losses available at higher-B.

See Breakout Session #5 for details on Evolution modeling, Flux-surface quality, Neutral penetration, Flexibility, Flow-Damping

NCSX Design Provides Required Capabilities

- Low-ripple, stable plasma shapes with good flux-surfaces
- Flexible coil-set
- Ability to generate design plasma shapes and control 3D shape during pulse
- B : 1.2 – 2.T, higher if possible. I_P up to ±350kA.
- Ability to accommodate (as upgrade):
  - Comprehensive diagnostic set
  - Up to 12MW of heating, including RF heating
  - Pulse-lengths ≥ 1.2 sec.
  - Pellet injection
  - Full PFC coverage; Divertor designs and upgrades
  - 350°-bake for any Carbon in-vessel components

Documented in GRD