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The National Compact Stellarator Experiment Design - A Theory-Based Approach to the Optimization of a Non-Axisymmetric System

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These are preliminary lecture notes, intended only for distribution to participants.

The National Compact Stellarator Experiment Design – A Theory-Based Approach to the Optimization of a Non-Axisymmetric System

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and
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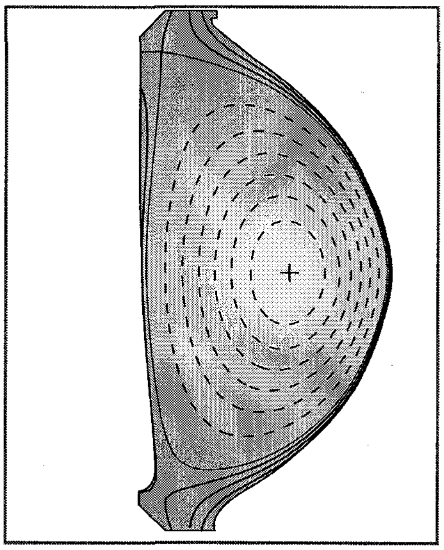
October 18, 2001

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Plasma Science Challenges

Plasma Science, NRC Plasma Science Committee

- Macroscopic Stability
  - Maximize plasma pressure
  - $\rightarrow$ Coronal mass ejections
- Wave-particle Interactions
  - Successful alpha heating
  - $\rightarrow$ Cosmic ray isotropy
- Microturbulence & Transport
  - Energy confinement
  - Suppression of turbulence
- Plasma-material Interactions
  - First wall survivability, exhaust
  - $\rightarrow$ Materials processing



$\therefore$ Configuration Sustainment
- Highly nonlinear high pressure equilibrium
- How much self-organization is stable?

Stellarators

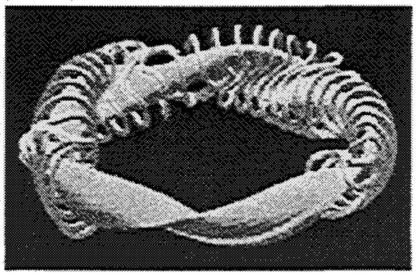
¥In toroidal magnetic confinement, need a poloidal component of B, so that particle orbits average out cross-field drifts

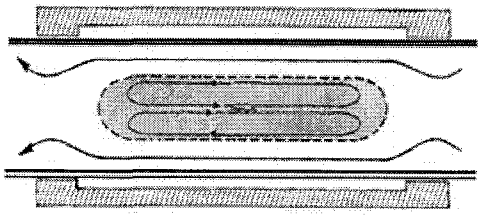
E.g. in tokamak $B \times \nabla B$ drift is vertical, would sweep plasma away without B_P

- Two methods for producing B_P or magnetic rotational transform
  $\iota = 1/q \propto B_P / B_T$
  - current, usually inductive
    Tokamaks, spheromaks, FRCs, RFPs... All axisymmetric
  - 3D helical fields, from external coils
    Stellarators
    $\Rightarrow$ intrinsically steady state; external control of configuration

Portfolio of MFE Configurations

Externally Controlled ⟷ **Self-Organized**

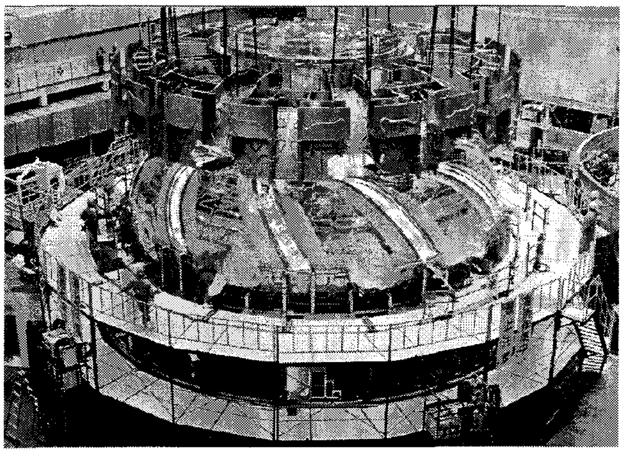




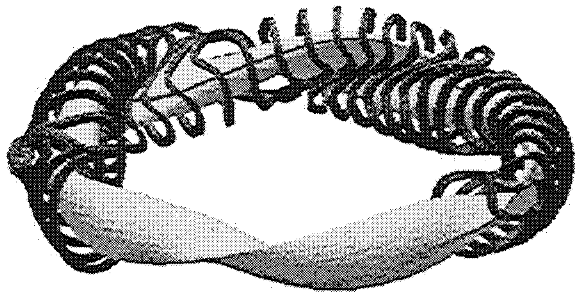
Example: Stellarator
Coils link plasma
Magnetic fields from external currents
Toroidal field >> poloidal field
Large R/a
More stable, better confinement

Example: FRC
Coils do not link plasma
B from internal currents
Poloidal B >> Toroidal B
R/a $\rightarrow$ 1.0
Higher power density

The World Stellarator Program is Substantial



Large Helical Device (Japan)
Enhanced confinement, high β;
A = 6-7, R=3.9 m, B=3$\rightarrow$4T



Wendelstein 7-X (Germany) (2006)
non-symmetric optimized design:
no current, A = 11, R=5.4 m, B=3T

- New large international experiments use superconducting coils for steady-state
- Medium-scale experiments (W7-AS, CHS), and
- Exploratory helical-axis experiments in Japan, Spain, Australia.

Large aspect ratios; physics-optimized designs without symmetry, no current.

Strong Connection Between Stellarators and Other 3D Plasma Physics Problems

- Many other plasma problems are three-dimensional
  - Magnetosphere; astrophysical plasmas
  - free-electron lasers; accelerators
  - perturbed axisymmetric laboratory configurations
- Development of 3D plasma physics is synergistic, with stellarator research often driving new 3D methods. Examples:
  - methods to reduce orbit chaos in accelerators based on stellarator methods [Chow & Carry, Phys. Rev. Lett. 72, 1196 (1994)]
  - chaotic orbits in the magnetotail analyzed using methods developed for transitioning orbits in stellarators [Chen, J. Geophys. Res. 97, 15011 (1992)]
  - astrophysical electron orbits using drift Hamiltonian techniques and magnetic coordinates developed for stellarators
  - tokamak and RFP resistive wall modes are 3D equilibrium issues
  - transport due to symmetry breaking was developed with stellarators
- We expect this connection to continue

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Motivation: Build Upon Recent Advances in Understanding

Stellarators:

- Design for orbit confinement, good flux surfaces
- Numerical design to obtain desired physics properties
- Accurate construction of experiments with good properties (including large superconducting systems)

Tokamaks:

- Confirmation of ideal MHD equilibrium & stability theory; neoclassical theory; neoclassical tearing theory
- Importance of shear-flow & zonal (self-generated) flows for turbulence stabilization

Meet Plasma Science Challenges:

- High pressure plasmas stability, with good confinement
- sustainment of non-linear equilibrium (e.g. AT: ~80% self-generated current)

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Combine Best Features of Both

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

  —Stellarators: *Externally-generated helical fields; steady-state compatible; generally disruption free.*

  —Advanced tokamaks: *Excellent confinement; low aspect ratio – affordable; self-generated bootstrap current and flows*

The compact stellarator opportunity

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Two strategies for Orbit Confinement in 3D

3D shape of standard stellarators ⇒ no conserved canonical momenta

orbits can have resonant perturbations, become stochastic ⇒ lost

B is bumpy every direction ⇒ rotation is strongly damped

- Non-symmetric drift-orbit omnigeneity; "linked mirror" configurations
  - reduce: $\nabla B \times B$ drift ⇒ orbit width, Pfirsch-Schluter & bootstrap currents
  - Principle of W-7X, new German superconducting experiment (A=11)

- 'quasi-symmetric'
  - Boozer (1983) Drift orbits & neoclassical transport depends on variation of $|B|$ within flux surface, not the vector components of B !
  - If $|B|$ is symmetric in "Boozer" coordinates, get confined orbits like tokamak

  ⇒ neoclassical transport very similar to tokamaks, undamped rotation

Boozer coord: straight field-line coordinates, Jacobian $\propto 1/B^2$

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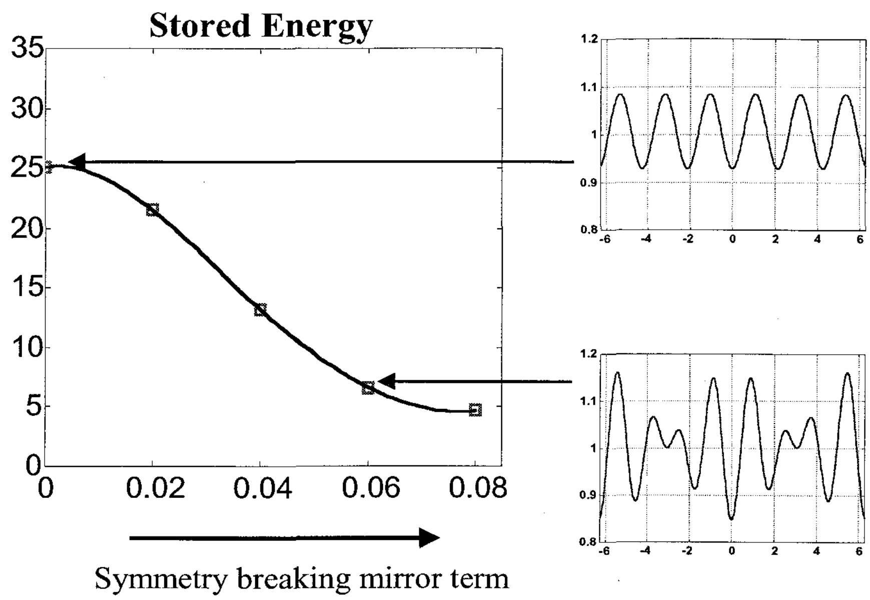
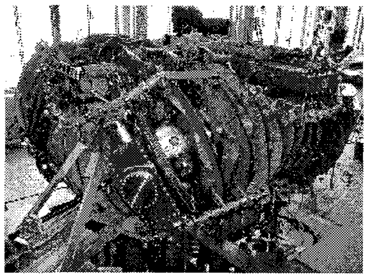
Initial Results from HSX: Symmetry Matters!

First Test of Quasi-symmetry





- **~50 kW of 2nd harmonic ECH used to produce energetic deeply-trapped electrons (B = 0.5T, 28 GHz)**
- **Stored energy drops by a factor ~ 5 as mirror term is introduced**

- D. Anderson, U. Wisconsin

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Quasi-Axisymmetry Offers Innovative Solutions

Use 3D shaping to:

- Quasi-axisymmetry to close orbits, allow flow, get good confinement
  - Take advantage of tokamak advances on transport control
  - Use bootstrap to raise rotational transform
- Passively stabilize external kink, vertical, neo-tearing, ballooning modes
  - expand stable operating area to $\beta \geq 4\%$, without need for conducting walls or feedback systems
  - prevent disruptions? Understand their occurrences.
- Aspect ratio ~ 4 $\Rightarrow$ n=0 toroidal Fourier terms dominant
  $\Rightarrow$ compatible with quasi-axisymmetry
- Control of iota (q) and shear via coils, independent of plasma currents

$\longrightarrow$ **NCSX Design Goals + flexibility to study each of these.**

Using Advances in Theory and Numerical modeling; parallel computing (NERSC, ACL/LANL, Princeton/PPPL)

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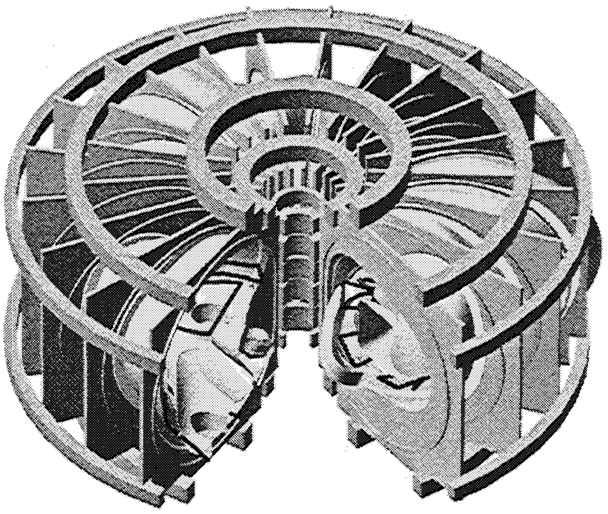
NCSX Mission: Address Key Issues of Fusion Energy Science



Macroscopic Stability:

- Disruptions - when, why, why not?
- High β, 3-D stability of kink, ballooning, neoclassical tearing, vertical displacement.

Microturbulence and Transport:

- Is quasi-symmetry effective at high T_i?
- Challenge E_r shear understanding via ripple control.
  $\Rightarrow$ High T_i, flexible coil system

Wave-particle Interactions:

- Do we understand 3-D fast ion resonant modes & Alfvenic modes in 3-D?
  $\Rightarrow$ Good fast ion confinement

Plasma-boundary interaction:

- Effects of edge magnetic stochasticity?
  $\Rightarrow$ High power, flexible coil system

Is our understanding of 3D plasma physics correct?

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The NCSX Design Team

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UCSD, Columbia, LLNL, NYU, ORNL, PPPL, SNL-A, U. Texas

in collaboration with

Auburn, Wisconsin

Australia, Austria, Germany, Japan , Russia, Spain, Switzerland

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NCSX Design Process Similar to W7-X, HSX

Fixed Boundary Equilibrium Optimization (for desired properties) → In depth analysis
¥Flux surface quality
¥Transport
¥Stability

Coil Design (to reproduced Fixed Bdry Equilibrium) → Engineering Analysis

Free Boundary Analysis
¥Robustness/Flexibility
¥Discharge Evolution
→ ¥Transport, stability, flux surface quality
¥Engineering
¥Edge analysis

¥Same general process as first developed for W7-X, used on HSX
— extended to address finite β, current, and low A

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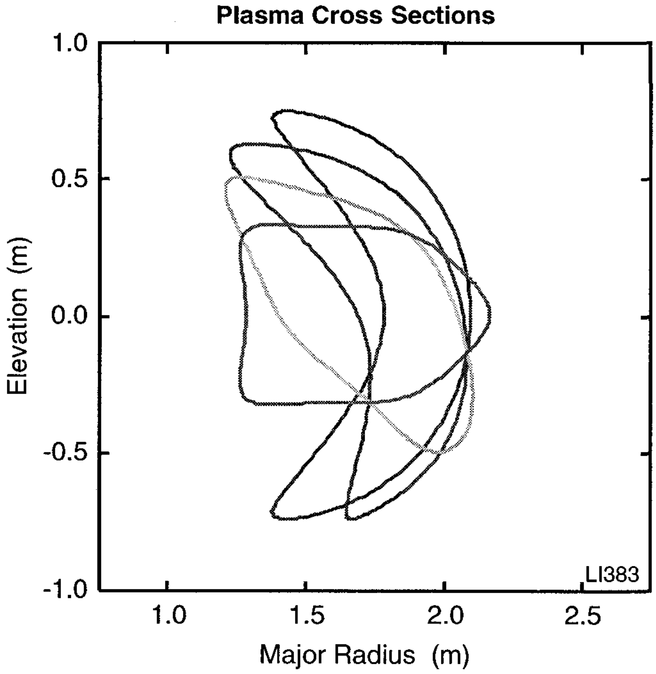
NCSX Plasma Configuration Has Attractive Physics

- 3 periods, R/⟨a⟩=4.4, ⟨κ⟩~1.8
  <indented>
- Good magnetic surfaces.
- Quasi-axisymmetric: low helical ripple transport.
- Stable at β=4.1% to kink, ballooning, kink, vertical, Mercier, neoclassical-tearing modes
- ~75% of the magnetic transform (B_P) is from external coils at β=4%. Remainder from boostrap current
- Proposed device has R = 1.4 m, B ranging from 1.2 - 1.7T at full iota > 2 T at reduced iota



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3D Shaping Predicted to Stabilize Kink in Several Ways

- Via global shear, similar effect to shear variation in tokamak
  -- but now independent of current, due to external transform
- Large local shear on low-field side increases field-line bending energy
- Depth of magnetic well
- Edge current density is not de-stabilizing (!)
  [Mikhailov & Shafranov, NF **30** (1990) 413.]

→ Need to experimentally test whether these theoretical predictions are correct

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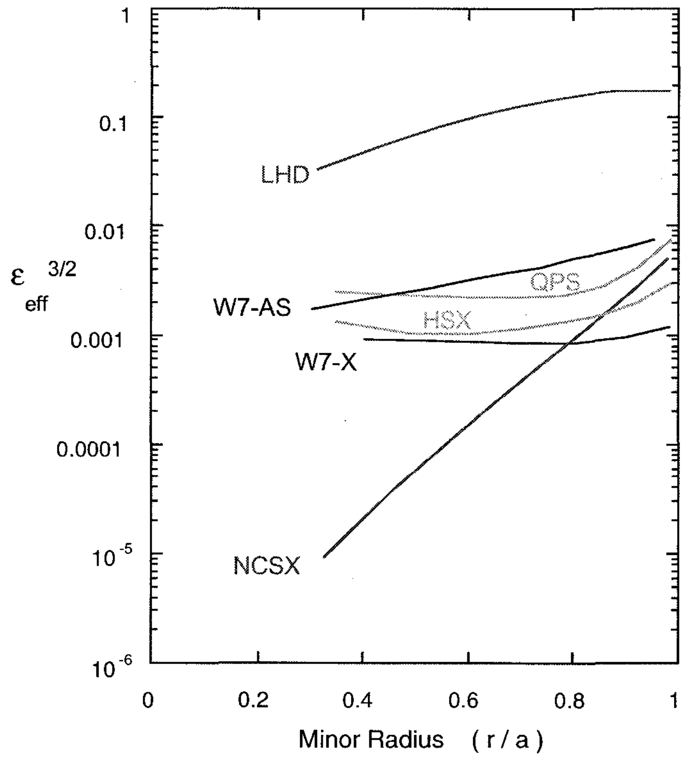
Quasi-Axisymmetric: Very Low effective ripple

- ε_{eff} from NEO code by Nemov-Kernbichler
- In 1/ν regime, neoclassical transport scales as $\varepsilon_{eff}^{3/2}$
- Edge ε_{eff} ~ 3.4%, < 0.1% in core
- Allows balanced-NBI
  24% loss at 1.2T, drops as B↑
- Should give low flow-damping
  - manipulation of flows for flow-shear stabilization
  - zonal flows like tokamaks
- Linear microstability similar to tokamaks [Rewoldt; Jost et al.]



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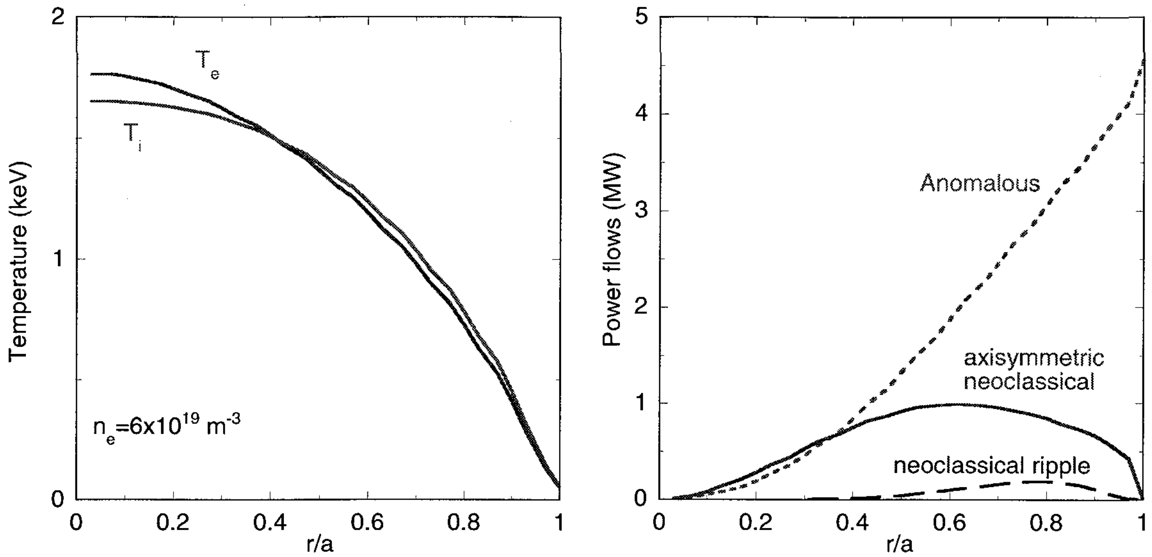
Low $\varepsilon_{h,eff}$ $\Rightarrow$ Low Ripple Transport



- Helical transport is negligible with self-consistent E_r
- 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 $H_{ITER-97P}$=0.9 B=1.7T gives access to ν^* ~ 0.1, $T_i(0)$~2.3 keV
- Shaing-Houlberg for helical transport, benchmarked with Monte-Carlo.
- Uniform turbulent χ used. Similar results obtained with Lackner-Gottardi

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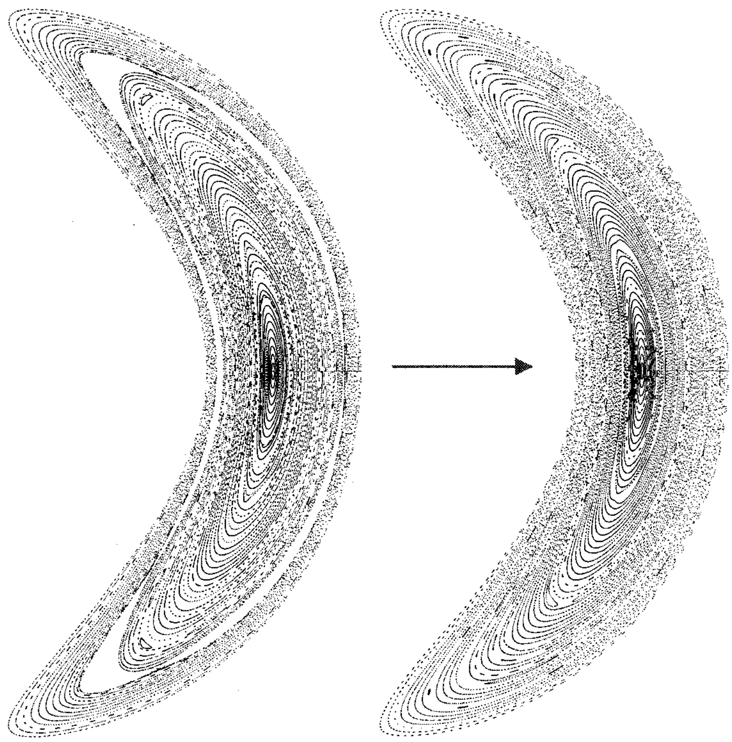
Island Removal Method



- Calculate coupling between plasma boundary shape and island widths by perturbation, using PIES
- Invert coupling matrix to find (small) shape modification to remove islands
- Modification had no effect on calculated stability or transport
- In experiment, neoclassical effects should heal islands

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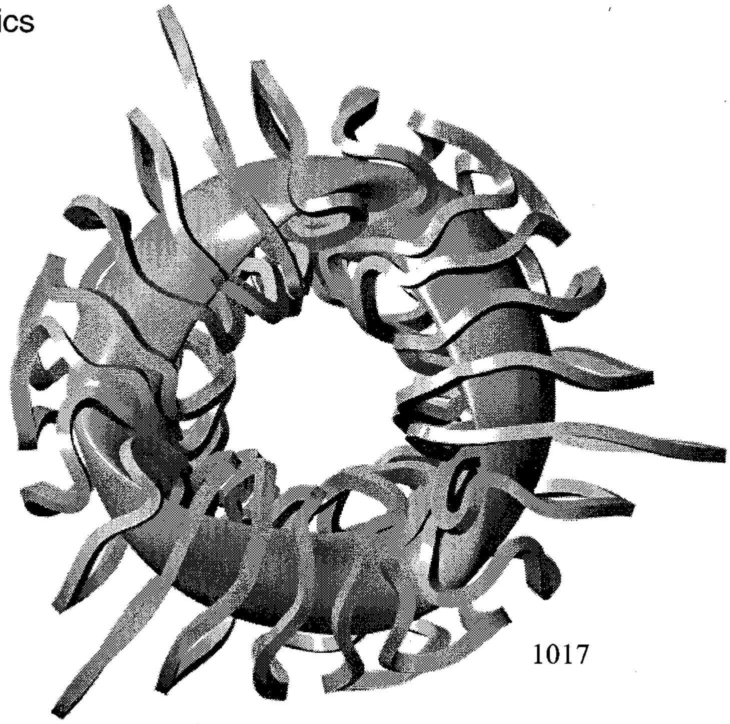
NCSX Modular Coils Provide Good Physics Capability

- Modular coils best preserve physics properties of reference plasma:
  - stable at reference β (4%).
  - Good magnetic surfaces.
  - A=4.1, modest increase in ripple.
- Outer coil-leg displaced for tangential NBI and diagnostics
- Also include Poloidal Field coils and weak Toroidal Field, for flexibility
- Stable to $\beta > 6.5\%$ with some increase in ripple



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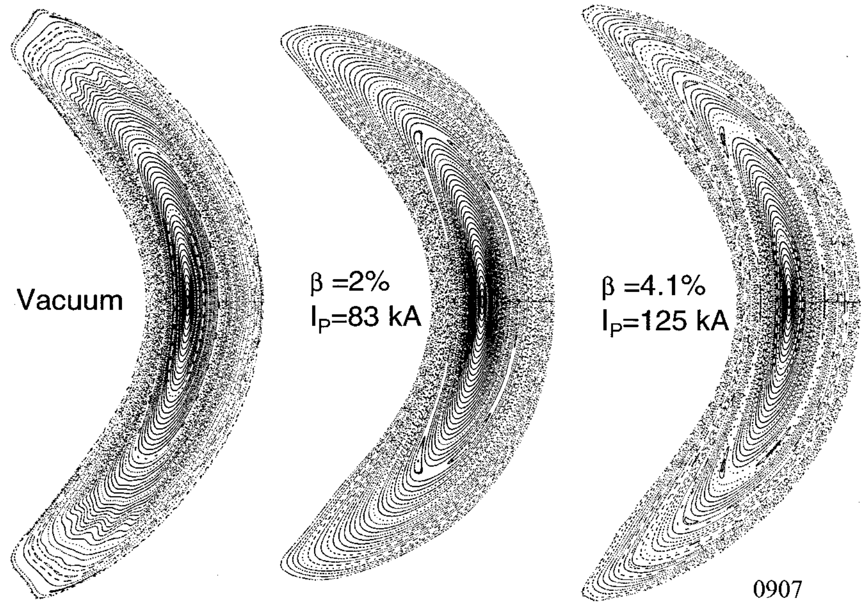
Coils Produce Good Flux Surfaces



- Free-boundary equilibria (PIES)
- I_P values for B_T=1.2 T
- Coils designed to produce good surfaces at full current. Island in middle case can be eliminated with trim coils.

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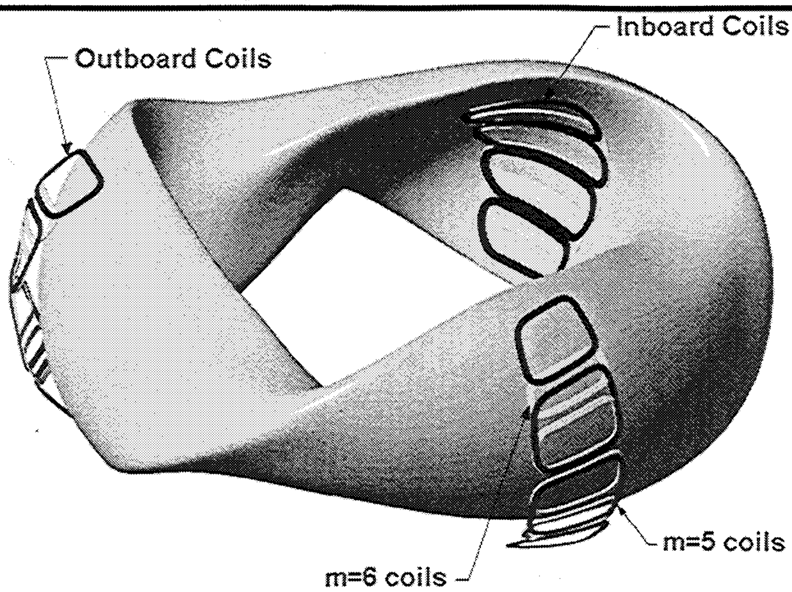
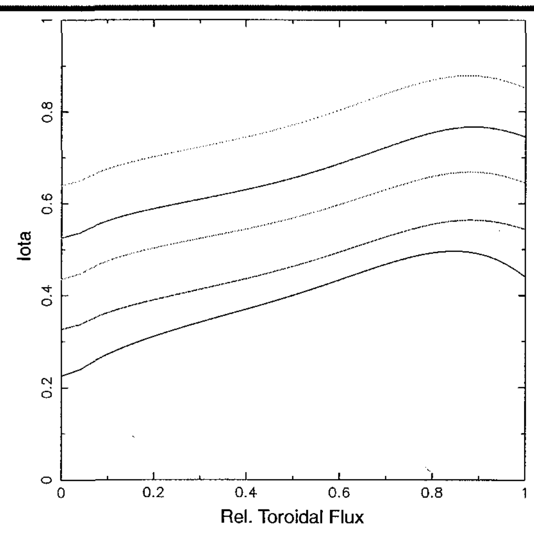
Trim Coil Array Controls Equilibrium Islands



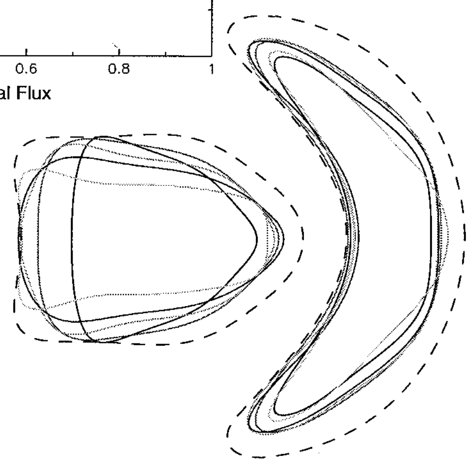
- For suppression of equilibrium islands over wide range of iota and shear profiles
- For controlled generation of islands to test neoclassical tearing theory
- Tested on vacuum and finite β configurations.

Modular Coils are Flexibile

- 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 stabley accommodate wide range of p,j profiles
- Can use to test stability, island effects

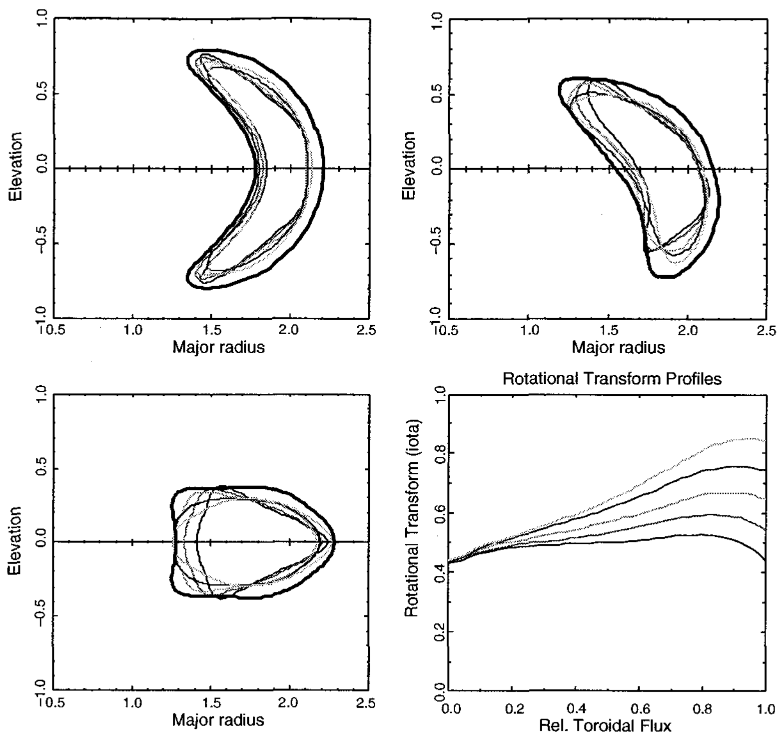


β=0, full current



Modular Coils give External Shear Control

- Coil-generated rotational transform decouples shear from plasma current profile
- Can control magnetic shear at fixed plasma current and profiles
- Allows controlled study of shear effects , e.g., kink-stabilization physics; turbulent transport.



β=0, full current

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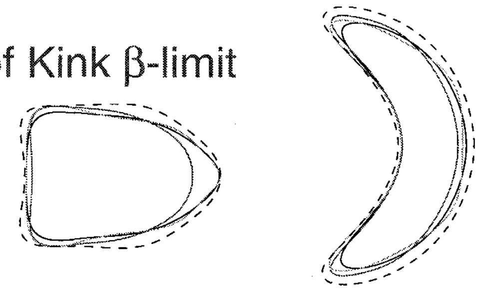
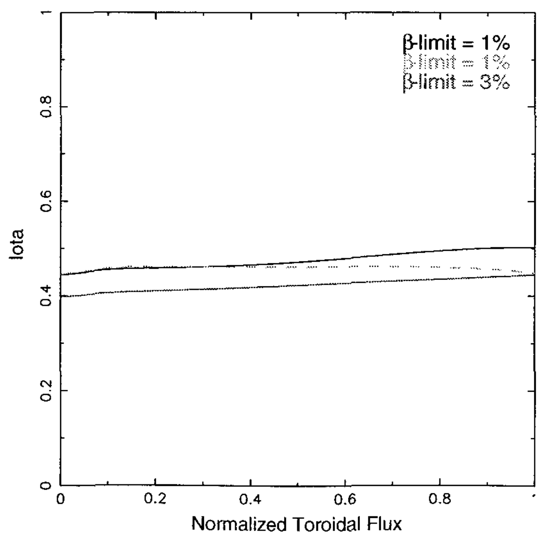
Coil Flexibility Gives Control of Kink β-limit



- External-kink marginally stable β changed from 3% to 1% by modifying plasma shape
  - either at fixed shear or fixed edge-iota !
- Free-boundary equilibria, fixed pressure and current profiles
- Useful for testing understanding of 3D effects in theory & determining role of iota-profile

- Similarly, can find stable equilibria with effective ripple varying by factor ~ 5. For testing transport optimization & flow damping



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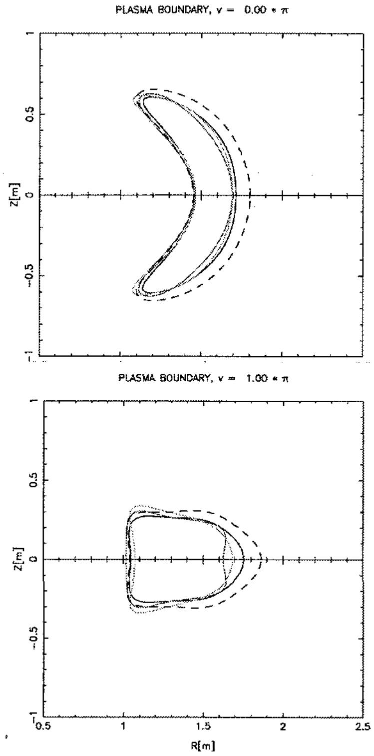
Equilibrium Maintained even with Loss of I_P or β

- Total loss of I_P or β only causes a small shift in equilibrium (few cm), for fixed coil currents.
- For comparable tokamak, loss of $\beta \Rightarrow$ radial shift of ~ 30cm. Similar shift for ~ 20% drop in I_P.
- NCSX disruptions will not lose radial equilibrium, should give unique insight into disruption dynamics.



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NCSX Research Advances Fusion Science in Unique Ways

- Can limiting instabilities, such as external kinks and neoclassical tearing modes, be stabilized by external transform and 3D shaping? How are the non-linear dynamics and disruptions affected? How much external transform is enough?
- Can the collisionless orbit losses from 3D fields be reduced by designing the magnetic field to be quasi-axisymmetric? Is flow damping reduced?
- Do anomalous transport reduction mechanisms that work in tokamaks transfer to quasi-axisymmetric stellarators? Are zonal flows effective? How much effective-ripple is too much?
- How do stellarator characteristics such as 3D shape, islands and stochasticity affect the boundary plasma and plasma-material interactions?

NCSX provides unique knobs to understand toroidal confinement fundamentals: rotational transform, 3D shaping, magnetic symmetry.

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Energy Vision: a More Attractive Reactor

Vision: A steady-state toroidal reactor with

- No disruptions
- No near-plasma conducting structures or active feedback control of instabilities
- No current drive (⇒ minimal recirculating power)
- High power density (~3 MW/m^2)

Likely configuration features (based on present knowledge)

- Rotational transform from a combination of bootstrap and externally-generated (how much of each?)
- 3D plasma shaping to stabilize limiting instabilities (how strong?)
- Quasi-axisymmetric to reduce helical ripple transport, alpha losses, flow damping (how low must ripple be?)
- Power and particle exhaust via a divertor (what topology?)
- $R/\langle a \rangle \sim 4$ (how low?) and $\beta \sim 4\%$ (how high?)

Design involves tradeoffs.

Need experimental data to quantify mix, assess attractiveness.

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FESAC Approved NCSX for PoP Status

"The NCSX program offers an exciting opportunity in fusion research for several reasons. First, a plausible case has been made (for example, at the NCSX Physics Validation Review) that a fusion power system based on a compact stellarator may resolve two significant issues for fusion power systems: *reduction or elimination of plasma disruptions, and provision for steady-state operation.* ***These gains earn for the compact stellarator an important place in the portfolio of confinement concepts being pursued by the US Fusion Energy Sciences program. Second, the NCSX would*** *complement research now underway on the advanced tokamak,* ***which addresses closely related issues by different methods. It also*** *complements stellarator research outside the US,* ***which has emphasized different geometries and plasma regimes. Finally, understanding the behavior of magnetized plasmas in*** *three-dimensional configurations is an important scientific frontier* ***area, which the NCSX program would advance and strengthen."***

- DOE Physics Validation Review (March 2001) was very positive, confirmed approach and design choices; recommended proceeding.

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Plans for Proceeding

- **Proposed milestones:**
  - Conceptual design review (CDR), April, 2002.
  - Start Title I design, October, 2002.
  - Start fabrication, October, 2003.
  - First plasma, September, 2006

Bottoms-up cost and schedule will be developed for CDR.

- **NCSX Is Using a Proven Project Management Approach**
  - similar to NSTX and TFTR D&D; both ahead of schedule and on budget.
  - Follows DOE project management guidelines and orders

- **NCSX will continue national team approach through all phases**
  - Combines the best talents and experience of DOE Labs and Universities
  - Integrated team led by PPPL and ORNL, with numerous collaborators; similar to NSTX.

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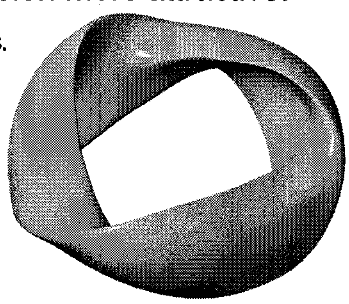
Conclusions

- NCSX is an exciting opportunity for unique fusion science.
  - Stabilize high-β instabilities with 3D shaping; understand 3D effects
  - Transport in low-collisionality quasi-axisymmetric system.
- Strong linkages with all of magnetic fusion science, complementing other toroidal confinement research programs.
- Physics basis for NCSX is sound, attractive configuration identified
  - passive stability to kink, ballooning, vertical, Mercier, neoclassical tearing with $\beta > 4\%$
  - very good quasi-axisymmetry
  - ability to study disruptive processes in 3D
  - flexible coil system
- NCSX provides innovative solutions to make magnetic fusion more attractive.
  - Combine best characteristics of stellarators and tokamaks.
  - Possibly eliminate disruptions; intrinsically steady state
- Good plans are in place for going forward.

We look forward to earning your support.



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