Stellarator Physics

Presented by A. Reiman

Review of PPPL Theory Group

Princeton, October 10, 2005

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

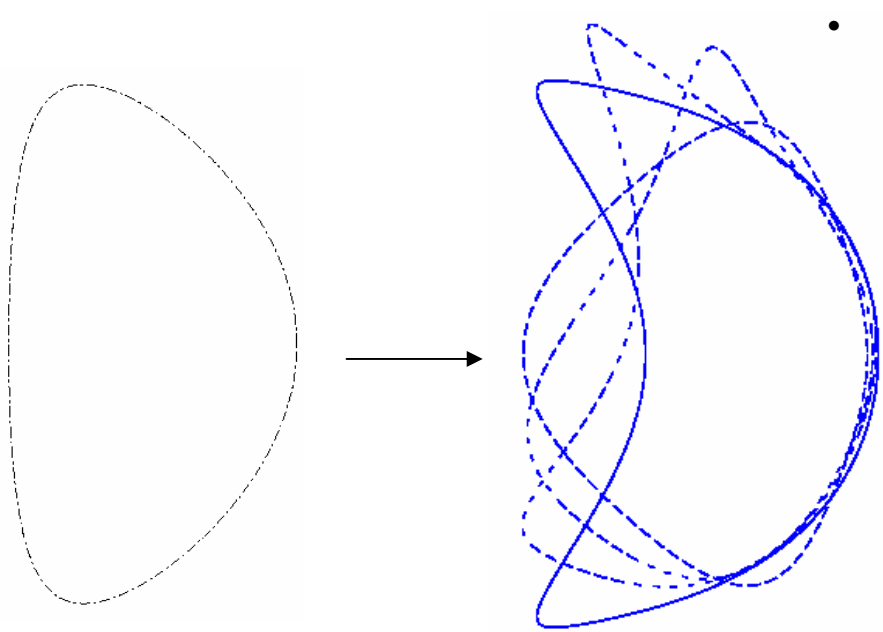
Outline

- Stellarator theory focused primarily on National Compact Stellarator Experiment (NCSX) design study through completion of coil design work (late '02).
- Subsequent work focused more broadly:
  - Some continued support of NCSX design;
  - Development of computational tools;
  - Key stellarator physics issues;
  - Collaborations with existing experiments.
- Preparing for major role in NCSX experimental campaigns. (Completion of experiment projected for summer of 2009.)
- Potential tokamak applications.

PPPL theory group played major role in guiding design of NCSX (late '96 – late '02).

G. Fu, S. Hudson, J. Lewandowski, Z. Lin, D. Monticello, H. Mynick, N. Pomphrey, A. Reiman, G. Rewoldt, R. White

- Physics design led by member of theory group for about three years.



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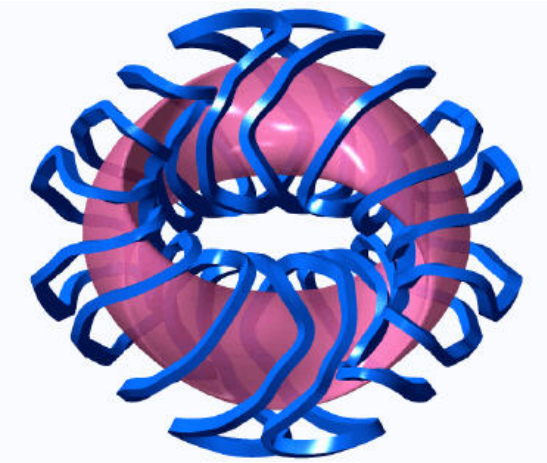
- Design strategy:
  - Use advanced tokamak equilibrium as starting point.
  - Numerical optimizer introduces 3D deformation while preserving quasi-axisymmetry and ballooning stability.
  - Target desired improvements in tokamak properties (e.g.: reduce or eliminate current drive; produce $dq/dr < 0$ for NTM stability)

Theory Calculations Guided Design of NCSX Configuration

- Ballooning stability:
  - Calculated β limits of previous quasi-symmetric designs < 2%.
  - Problem solved by development of innovative quasi-axisymmetric design with strong axisymmetric shaping.
- Kink stability:
  - Systematic studies of stabilization via externally generated shear;
  - Introduced stabilizing corrugation via Furth-Hartman coils, and later through optimizer.
- Adequacy of neoclassical confinement: PPPL codes GC3, GTC and Orbit (as well as ORNL codes) adapted and applied.
- Flux surfaces (PIES code):
  - Identification of fixed boundary configurations with intrinsically good surfaces;
  - Design of coils that preserve surfaces.

The Theory Group Has Also Contributed to the Design of Domestic Stellarator Experiments other than NCSX

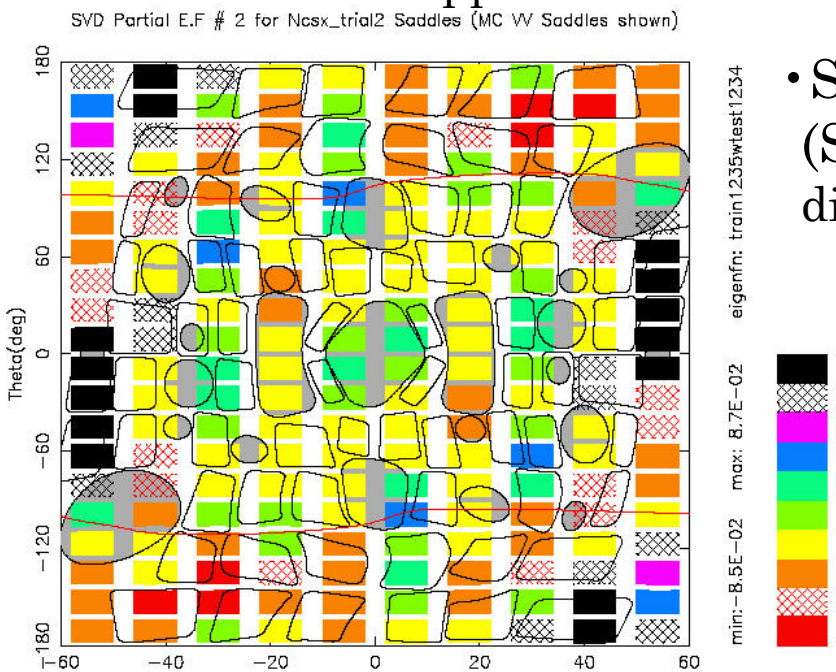


- QPS (ORNL).
  - MHD stability calculations.
  - PIES calculations.
  - Two members of theory group shared in ORNL Scientific Research by a Team Award.
- CTH (Auburn) – stability calculations.
- Columbia Nonneutral Torus (CNT) – contributions to optimization of coil design.

Theory group has continued to support NCSX design into the construction phase.

- PIES field error calculations.
- NCSX edge modeling studies using PIES. (with T. Kaiser, LLNL)
  - Required development of new routines for calculating field in exterior vacuum region (with M. Drevlak, Greifswald, Germany).

    Modified code also applied to W7X calculations.



- Singular value decomposition (SVD) methods for optimizing diagnostics design.
  - o To be extended to diagnostic systems other than saddle loops.
  - o SVD analysis of diagnostic data also being explored.

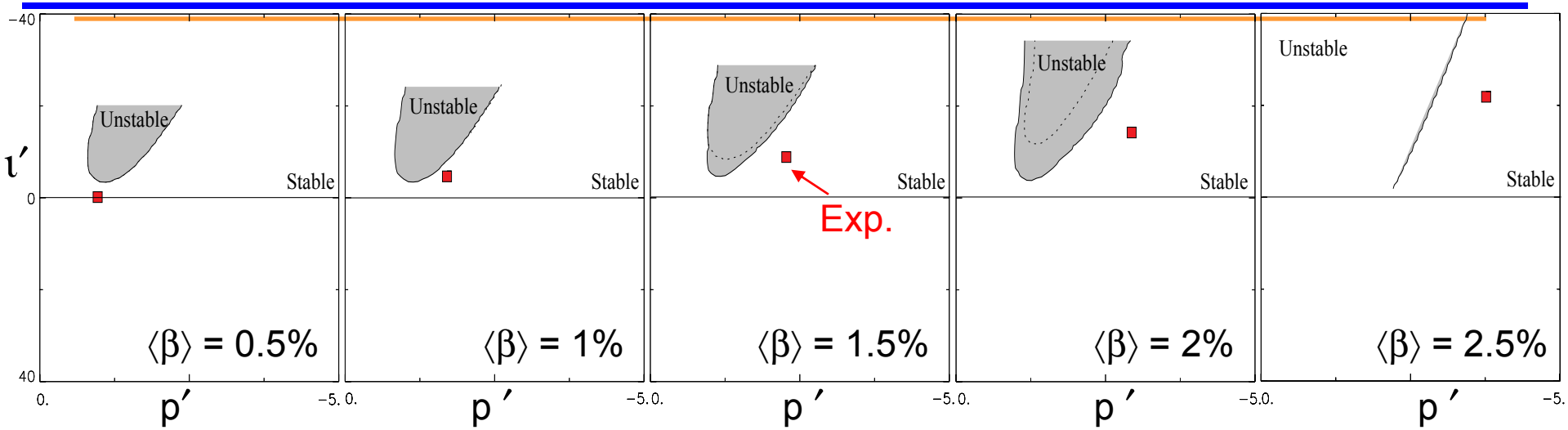
Pomphrey, Lazarus, Zarnstorff

Code Development: Key tokamak codes converted for stellarator calculations, and are being further improved.

Detailed development plans discussed in other talks.

- Full: Linear, electrostatic microstability code.
- GS2: Flux tube, gyrokinetic code. (Belli, Hammett, Dorland)
- GTC global gyrokinetic code:
  - Improved neoclassical stellarator version (FY07);
  - 3D turbulent transport in stellarators (FY08).
- M3D extended MHD:
  - Coupling to PIES initiated. (H. Strauss, NYU) Will allow calculation of stability for equilibria with islands.
  - Nonlinear energetic particle modes. (FY09-FY10)
- HINST high *n* stability code.
  - Kinetic effects on stellarator ballooning modes (FY06 – FY08);
  - Fast ion drive in stellarators (FY07 – FY08).

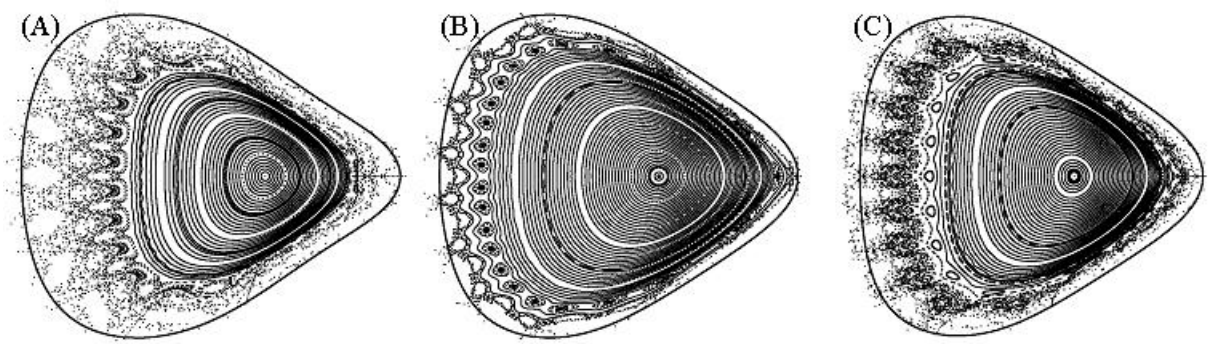
Code Development: New ballooning code developed for studies of second stability in stellarators.



- New code (with C. Hegna, Univ. Wisconsin) calculates marginal stability s-α diagrams for stellarators.
- Applied to second stability properties for a range of configurations.
- Connecting to global finite-n solutions:
  - Improved methods for ray tracing being studied.
  - Longer term: Global solution with finite gyroradius effects (community collaboration).

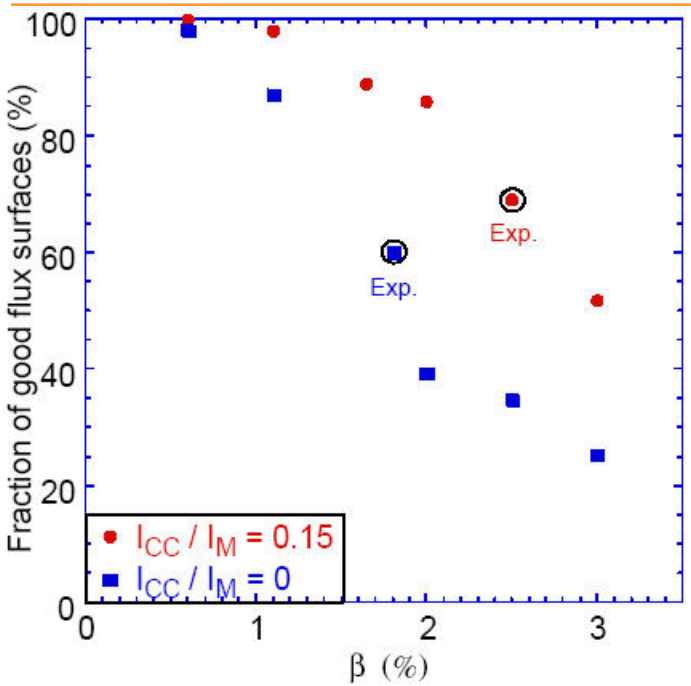
The PIES code calculates loss of flux surfaces in 3D equilibria.

- Developed at Princeton in mid-1980's for stellarator applications.
- Long-term, strong collaboration with W7X group on development and applications of PIES. (W7X is $1 billion class stellarator under construction in Germany.)
- Extensive verification and validation of code described in theory review document ("Theory Five-Year Plan").



PIES calculated Poincare plots for W7-AS for differing values of β and control coil current. In each case the dark line is the VMEC calculated plasma boundary.

PIES calculations of flux surface degradation in W7AS consistent with observations suggesting soft β limit.



Fraction of good flux surfaces vs. β as predicted by PIES for two values of control coil current in W7AS. (Reiman, Zarnstorff, Monticello)

- W7AS and LHD have now reached β's high enough to probe predicted equilibrium β limit due to flux surface degradation.
- PIES calculations for W7AS consistent with observed dependence on divertor control coil current.
- More detailed comparison will evaluate stochastic diffusion, quantities measured by edge diagnostics.(FY06)
- Develop self-consistent predictive calculation of equilibrium β limit via coupling to transport model.(FY07)

PIES plans include further benchmarking, incorporation of additional physics, and continued improvement of code.

- Comparison with quasi-analytic calculations for simplified geometry, and with NIMROD and M3D. (with C. Hegna and others) (FY06 – FY07)
- Incorporate additional physics into PIES code:
  - Neoclassical effects on islands, including coupling of pressure and current profiles to transport models (FY06 – FY07);
  - Subgrid model for shielding of rational surfaces by flow (FY08 – FY09). (Simplified model of flow shielding in NCSX presented at 2004 IAEA.)

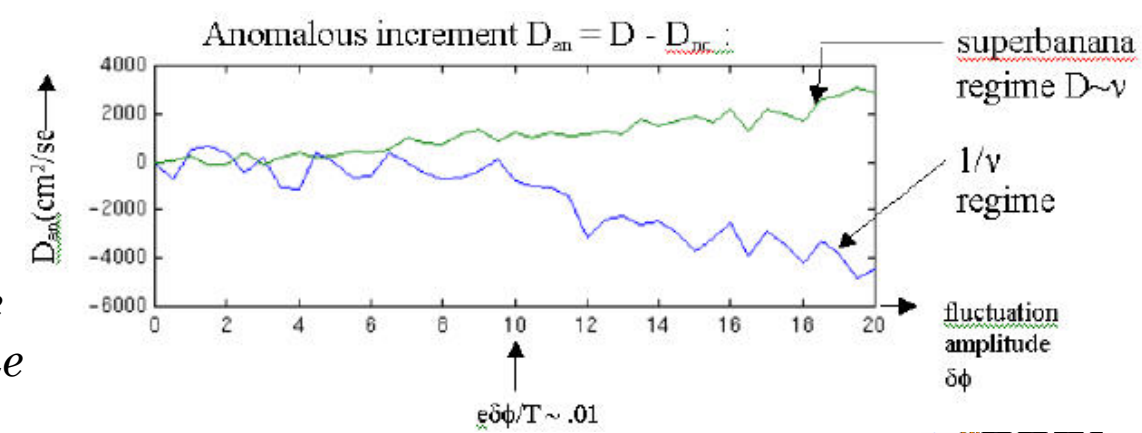
    Penetration of resonant field errors of interest for ITER.
- Continued modification to improve speed and robustness of code, including algorithmic improvements and parallelization. (FY06 – FY10)
- Development of time-dependent transport code that can handle islands. (Generalization of 1½D codes used for tokamaks.) (FY08 – FY09)

Studies of Interaction Between Stellarator Neoclassical Transport Effects and Turbulent Transport

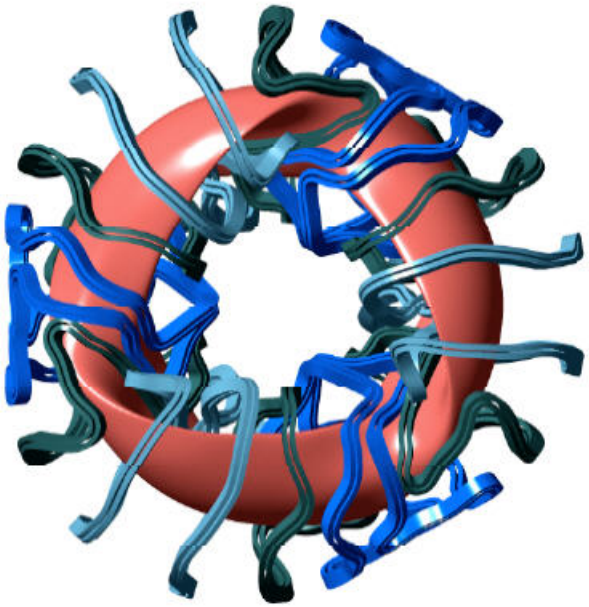
- For initial studies, Monte Carlo transport code modified to include a spectrum of electrostatic perturbations modeling effects of turbulence.
- Turbulence can sometimes reduce transport losses in stellarators. (Usual assumption takes effects to be additive.)
- Future studies will use improved model of turbulence spectrum. (FY06- 07)
- Will use GTC when modified to handle stellarator turbulent transport. (FY08)
- Apply theory to optimization of transport in NCSX. (FY09)

Plot of anomalous increment to neoclassical diffusion coefficient vs. amplitude of fluctuations applied, in a conventional stellarator, showing that in some regimes of collisionality, the fluctuations can decrease the total radial transport.

Mynick and Boozer



Looking Forward to Testing Theoretical Models Against NCSX Experiments



NCSX plasma and modular coils.

- Consequences of violating predicted MHD instability thresholds.
- Conditions for avoiding disruptions.
- Transport for various levels of quasi-axisymmetry, and effects on flow. Transport barriers.
- Magnetic islands, including neoclassical effects and shielding effects of plasma flow.

Some Potential Long-Term Applications of Stellarator Tools and Expertise to Tokamaks

- Modeling experiments: calculation of tokamak 3D equilibria with islands and stochastic regions.
  - PIES calculations of 3D effects on DIII-D edge, stochastic field near separatrix. (with Zarnstorff, Evans, etc.) (FY06 – FY07)
  - Field error effects. (An issue for ITER.)
- 3D transport effects in islands (K. Shaing) and RWMs.
- 3D time evolution of tokamak on transport time scale: islands, RWMs.
- Modeling of NCSX experiments will provide new perspective on some key tokamak physics issues: neoclassical tearing modes, penetration of resonant field errors, etc.
- Improved understanding of key physics issues that arise in introducing 3D shaping to improve tokamak: loss of flux surfaces, disruptions, etc.

Stellarator research done in context of extensive domestic collaborations.

- *National Stellarator Theory Teleconference.* ~ monthly.
- *Oak Ridge National Laboratory (ORNL):* NCSX design; QPS flux surfaces and stability. Two Princeton theorists shared in ORNL Scientific Research by a Team Award.
- *Columbia University.* Contributions to optimization of coil design for CNT device. With A. Boozer: interaction between turbulent transport and stellarator neoclassical transport; transport in CNT.
- *NYU and MIT.* With H. Strauss (NYU) and L. Sugiyama (MIT): M3D code development and applications for stellarators.
- *University of Wisconsin.* With C. Hegna et al: stellarator ballooning stability; recently initiated study to benchmark PIES calculations against quasi-analytic island solutions for simple models.
- *Livermore MFE Group:* Edge modeling studies for NCSX using PIES.
- *Livermore, Center for Applied Scientific Computing (CASC).* With Chandrika Kamath, AI method for automated classification of magnetic field lines of 3D toroidal systems.
- *DIII-D*: Initiating project on PIES calculations of 3D effects near edge.

Extensive International Collaborations

- *US/Japan Workshops.* US organizer: Princeton FY02, Japan FY05.
- *W7-AS Stellarator group (Germany)* : calculations using PIES, ballooning code, Terpsichore linear MHD code.
- *W7X Group (Germany):* Long-term collaboration on development and applications of PIES. Most recently, with M. Drevlak: implementation of method for calculating magnetic field in vacuum region outside PIES grid; application to W7X; benchmarking against MFBE code.
- *TJ-II Stellarator Group (Spain):* Intermittent collaboration since mid 80's on development and application of PIES code. Most recently, PIES study of TJ-II stellarator configurations with net toroidal current.
- *LHD and Heliotron-J groups (Japan):* Full code microinstability studies; PIES calculations for LHD and Heliotron-J, including benchmarking against HINT; ballooning calculations for LHD; with Nakajima, modification of HINST code for calculating kinetic effects on high n instabilities in stellarators, including drive due to energetic-particles.
- *Australia National University (ANU):* Collaboration with Dewar's group on a new 3D equilibrium code they are proposing.

Strong contributions to the Priorities Panel's Topical Questions:

T1.How does magnetic structure impact confinement? What is the effect of 3D shaping on confinement? Shear? Is quasi-axisymmetry effective? How does it differ from axisymmetry?

T2.What limits maximum pressure? Can 3D shaping increase the β limit? Is reversed shear beneficial? What are the limiting mechanisms with 3D fields and how can they be controlled?

T3.External control and self organization How does 3D shaping affect self-organization of profiles? How high a bootstrap fraction is controllable? Under what conditions are disruptions eliminated?

T4.Turbulent transport How is turbulent transport affected by 3D shaping? Does reversed shear help stabilize turbulence in 3D? How does electron transport depend on local shear and curvature?

T5 Electromagnetic fields and mass flow generation How does flow damping affect zonal flows and turbulence stabilization? Can transport barriers be accessed with quasi-symmetry?

T6.Magnetic field rearrange and dissipate How do shear, pressure, seed perturbations, and ion kinetics affect NTM onset and saturation,in detail?

T9.How to interface to room temperature surroundings? How is the SOL and interface affected by stochasticity and 3D shaping? Can the interface and exhaust be improved using 3D effects?

T11.Electromagnetic waves interacting with plasma How do RF waves interact with plasma in 3D?

T12.High-energy particles interacting with plasma How does 3D shaping affect energetic-ion instabilities? Can they be stabilized? Can orbit losses of energetic ions be controlled in 3D?

T15.How to heat, fuel, confine steady-state or pulsed plasmas? How can we control and fuel a 3D plasma? How much control is required? How can we diagnose the plasma state in 3D?

Conclusions

- Theory group played crucial role in NCSX design effort, helping to guide physics configuration design, solving critical problems, and defining key features of the configuration.
  - A team effort that brought to bear the tools and expertise of ten members of theory group working closely with each other and with a group of associated experimentalists and engineers.
- Stellarator theory effort now more broadly focused:
  - Tokamak codes being converted and improved for stellarator applications;
  - Stellarator codes (PIES and ballooning) being improved and applied to contemporary experiments;
  - Key physics issues being addressed: stellarator equilibrium β limit, interaction between turbulent and stellarator neoclassical transport, etc.
  - Beginning to pursue tokamak applications.
- NCSX experiments will challenge and drive further theoretical understanding of 3D physics.