PPPL Stellarator Theory Update

Presented by A. Reiman

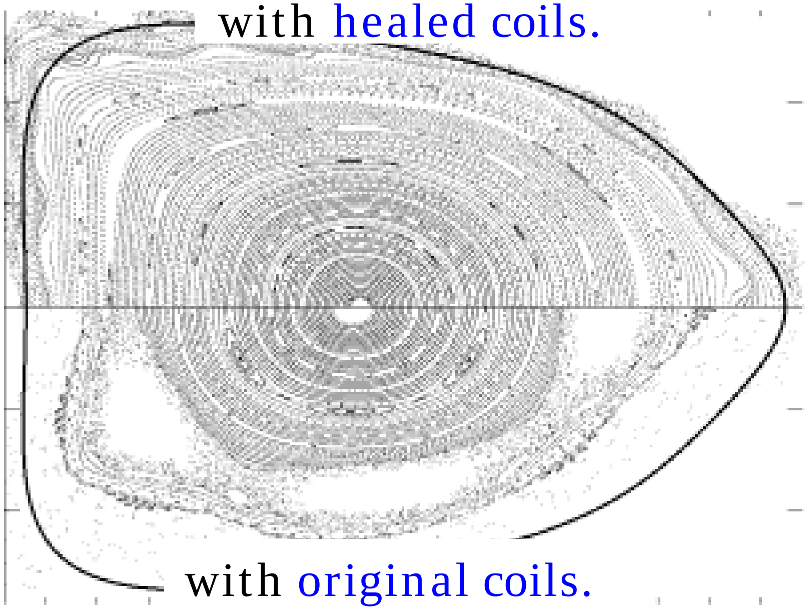
NCSX PAC Meeting #6

Princeton, Dec. 9, 2002

Outline

- Overview of what we've been doing over past year and our plans:
  - NCSX physics design issues for CDR and post-CDR, including PIES applications and plans;
  - New studies motivated by needs of NCSX program and ARIES stellarator reactor study;
  - Further adaptation and application of tokamak tools and expertise to stellarators.
- Collaborations.
- Participation in stellarator community discussions & planning.
- The PPPL stellarator theory team.

Have Continued to Address Key NCSX Physics Design Issues



- Flux surfaces. (Hudson, Monticello, et al)
  Optimization code built around PIES.
  Modifies coils to produce good flux surfaces, and desired physics and engineering properties.

  Applied to design of CDR coils (M45H), and to post-CDR coils.

- Assessment of flow shielding effects on magnetic islands. (Reiman et al)
- Verified flexibility and robustness of M45H coils. (Pomphrey)
- Stability. (Fu)
  - Convergence study verified kink & ballooning stability properties.
  - Finite n (≤45) ballooning study found ballooning $\beta_c \approx 6\%$.

PIES Plans

CDR report requests additional PIES studies:

- "Determine the physics impact of magnetic field error…"
- "Extend the use of the PIES code to additional flexibility studies."

PIES work to also turn in more fundamental directions:

- Application to international experiments: W7AS, LHD, Heliotron-J.
- Studies of island physics (with Wisconsin).
- Development of a fundamental tool:
  - Numerical improvements: improved grid in vacuum region for W7AS; improved meshing to avoid resonances; algorithm improvements to increase speed.
  - Add physics: neoclassical effects; estimate of flow shielding effects.
  - Long term: Couple to transport code to follow 1½ D (Grad-Hogan) evolution of plasma with islands. Target for NCSX first plasma?

An issue: availability of dedicated computational expert to aid in parallelization and modernization of code.

New Studies Motivated by Needs of NCSX Program and ARIES Study

- Reconstruction of equilibria from emissivity data. (Mynick, Pomphrey) Demonstrated that 3D equilibrium can be reconstructed given only shape of flux surfaces. Phys Plasmas paper.

Plan:

  - Study practical implementation on test problem to determine effects of experimental error, sparseness of data, etc.
  - If promising, apply to W7AS emissivity data.

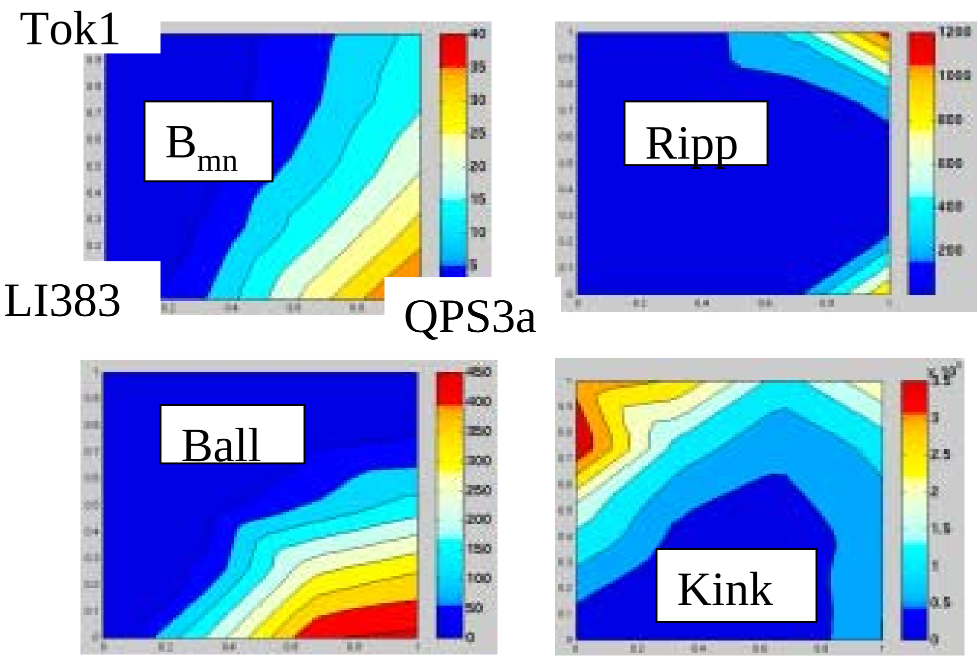
- Coil design. (Pomphrey, Reiersen) Optimization of configurations produced by coils having simple geometry. Applied to Pedersen experiment at Columbia.

Plan:

  - Investigate in context of ARIES reactor study.

- Physics of flows & transport: transport barriers, etc. (Mynick) A new study being planned.

New Studies Motivated by NCSX and ARIES Programs (continued)



• Global optimization: (Mynick, Pomphrey) Feasibility of "differential evolution" algorithm demonstrated. Potential applications to reactor design, NCSX experiments.

• Topography of global design space. (Mynick, Pomphrey)

Compare χ_i^2 of 3 quite different configurations: LI383, QPS3a, Tok1.

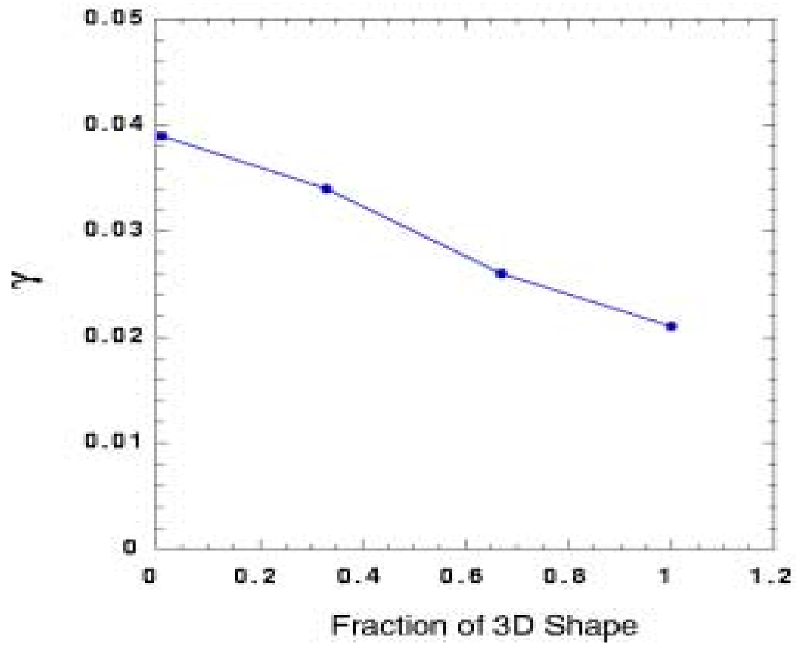
Plan:

o More extensive study of topography for optimized configurations.

o Include measure of turbulent transport in optimization.

o Develop understanding of barriers between basins.

Adaptation and Application of Tokamak Tools and Expertise



- Stellarator version of hybrid M3D code developed, and applied to fast ion driven Alfven modes in quasi-axisymmetric stellarators. (Fu and Park, with Strauss, NYU)

TAE growth rate for sequence of equilibria varied from equivalent tokamak to full stellarator geometry.

Plans: Calculation of nonlinear TAE and tearing modes for NCSX and international stellarator experiments.

Adaptation and Application of Tokamak Tools and Expertise (continued)

- Kinetic high-n stability code (HINST) interfaced to 3D numerical equilibrium. (N. Gorelenkov, with N. Nakajima, NIFS, Japan)

Plans:

  - Complete implementation and apply to kinetic ballooning
  - Incorporate helically trapped particles and apply to TAE modes.
  - Long term: Development of 3D version of Nova-K. (Cheng)

- Continued application of nonaxisymmetric FULL code to calculate electrostatic drift modes for LHD. Nucl. Fusion paper on effects of magnetic axis position and pellet injection. (Rewoldt with LHD group)

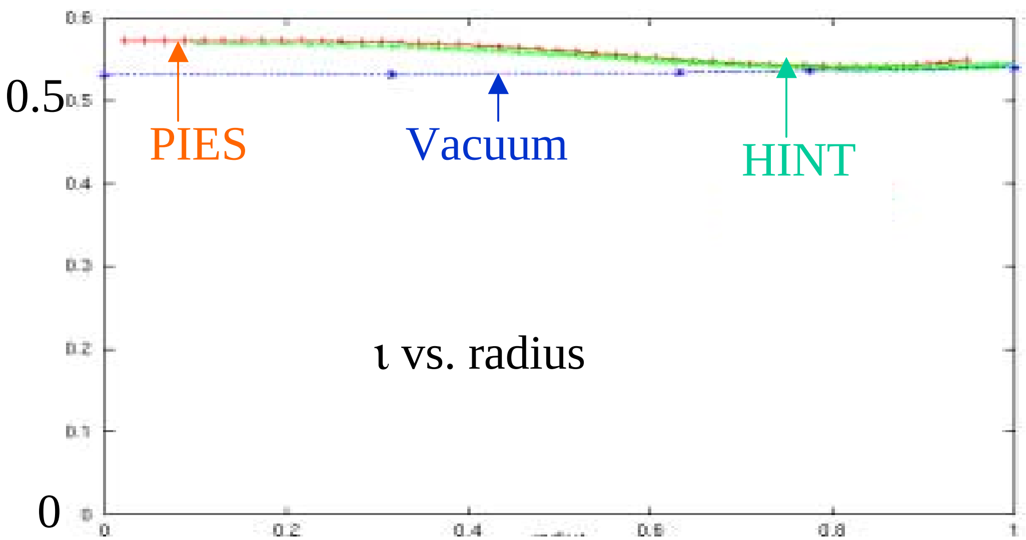
Plans:

  - Continue LHD studies.
  - Long term: Develop stellarator version of GTC gyrokinetic code (W. Wang) and apply to international experiments.

Collaborations: W7X and W7AS

• Drevlak (Nuehrenberg group): Application of PIES to edge modeling for W7X. Module developed to calculate field in vacuum region outside PIES grid. (with Monticello, Reiman)

• PIES calculations of W7AS equilibria in progress. (Reiman and Monticello, with Weller, Geiger and Zarnstorff.) Requires improved grid in vacuum region.



• Comparison with HINT runs done by Geiger for some W7AS cases. (Monticello, Reiman)

1st benchmark of HINT vs PIES.
$\beta \approx 0.5\%$.
Good agreement also of flux surface shapes.

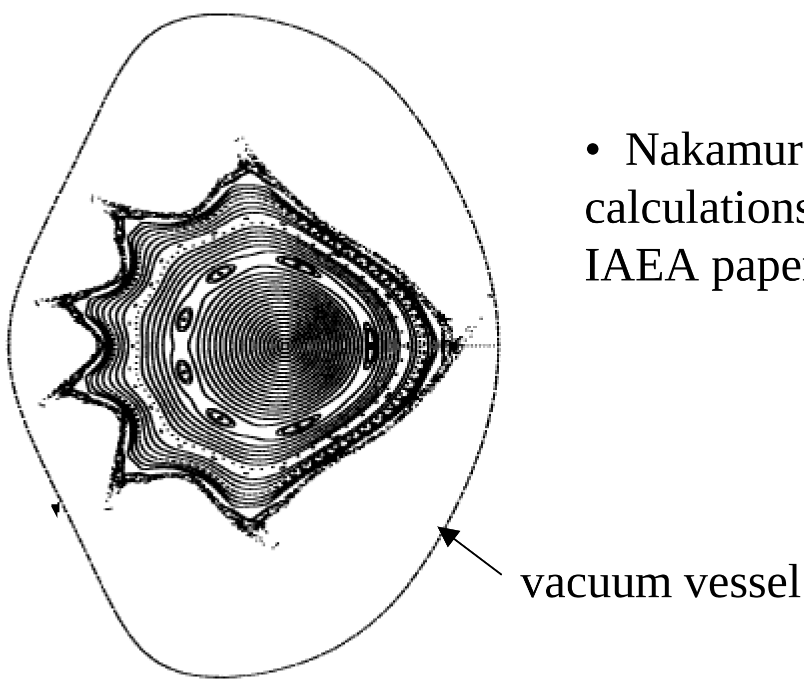
• Also planned: reconstruction from emissivity profile; Terpsichore stability calculations; M3D calculations of nonlinear instabilities.

Collaborations with Japan

• Full code microinstability studies on LHD. (Rewoldt)

• Kinetic high n HINST code adaptation to 3D. (Gorelenkov and Nakajima)

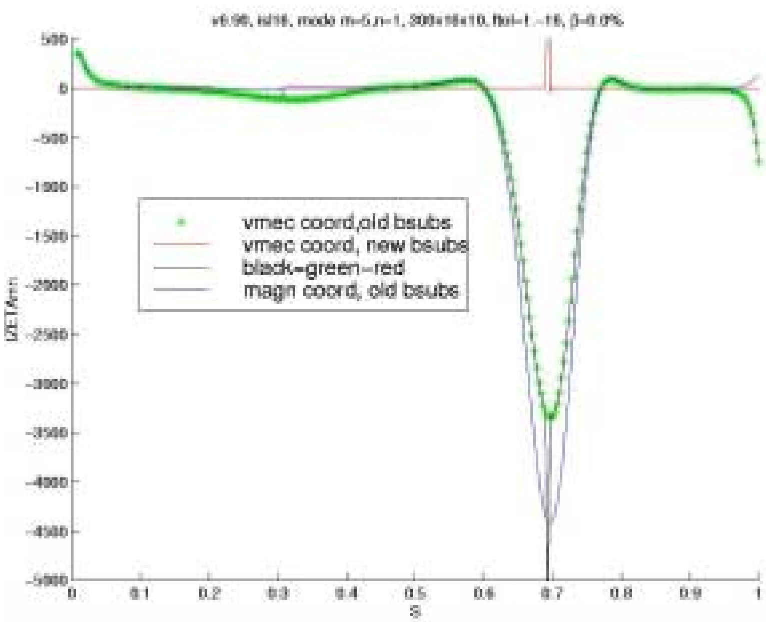
• 3-way collaboration with NIFS (Nakajima, Kanno) and Kyoto Univ. (Nakamura) on PIES LHD calculations and benchmarking against HINT. (Monticello and Reiman)



• Nakamura free-boundary PIES calculations for Heliotron-J. IAEA paper.

Domestic Collaborations: ORNL

• QPS flux surface calculations with PIES. (Monticello with QPS group)



• Study of currents at rational surfaces in VMEC. Monticello with Hirshman and Isaev (Kurchatov). Motivated by interest in island diagnostic and desire to improve VMEC interface to PIES.

VMEC current vs normalized flux for vacuum case. 300x16x10 resolution.

• Joint project proposed on coupling DKES to PIES for 1½ D (Grad-Hogan) time-dependent transport calculations. Incremental funds requested in '02 FWP's.

• Planning teleconferences and gatherings at APS, Sherwood to maintain communication between groups.

Domestic Collaborations (continued)

• NYU: M3D collaboration with H. Strauss (G. Fu and W. Park)

• Wisconsin

  o Stellarator ballooning calculations (Hegna, Torasso, Hudson)

  o Planned study of island physics (Hegna, Hudson, Monticello, Reiman)

• Columbia

  o Coil design on Pedersen experiment. (Pomphrey, Reiersen, Dahlgren, Monticello, with Pedersen, Kremer, Boozer)

  o Boozer involvement in coil healing and other NCSX studies.

• ARIES group

  o Coils (Pomphrey)

  o Planned work on target for transport optimization (Mynick)

  o Global optimization (Mynick and Pomphrey)

We Have Participated Strongly in Stellarator Theory Community Discussions & Planning.

- Strong participation in Workshop on Future Directions in the Theory of 3D Magnetic Confinement Systems (January, Oak Ridge)
  - presentations by D. Monticello, A. Reiman, G. Fu, H. Mynick and N. Pomphrey
  - Mynick, Pomphrey and Reiman session leaders or co-leaders
  - Reiman on organizing committee for meeting
- DOE visit by Reiman with Neilson, Batchelor and Hill (September)
- Participation in community planning for simulation initiative:
  - Joint letter by Hirshman and Reiman, discussing needs for stellarator simulation, posted on project web site.
  - Participation and presentation by Reiman at Fusion Simulation Project Workshop.
- US/Japan theory workshop organized by Monticello with Nakajima (NIFS). Held at Princeton (Nov. 18-20).

Certain issues came up repeatedly as critical and having impact across a variety of topic areas, but with insufficient level of effort

Batchelor's summary

- **MHD equilibrium**
  - **Equilibrium calculations are fundamental starting points for virtually every type of stellarator theory – the critical codes for the US (and world) program are VMEC and PIES**
  - **Accurate and reliable calculation of island formation, including self-consistent bootstrap current and non-ideal effects is an urgent need**
  - **Speedup and improved convergence of codes both codes are needed, particularly for low A studies**
  - **Plasma performance depends sensitively on the plasma shape and ι profile $\Rightarrow$ diagnosing equilibrium is a critical need for experiments**
- **Accurate calculation of ambipolar potential is critical to understanding:**
  - **Neoclassical transport – ambipolarity sets level of neoclassical transport, can vary on a surface**
  - **Micro-stability and turbulence**
  - **Core and edge plasma flows $\rightarrow$ transport barriers**
- **Extending theories and codes to low collisionality is needed to treat modern experiments**
  - **Radial drifts**
  - **Coupling to turbulence**
  - **Momentum conservation essential for quasi-symmetric configurations**
- **Modeling and diagnostics**
  - **Presently there is no 3D predictive or interpretive transport code in the U.S. Needed for stellarators, tokamaks with islands, edge**
  - **Need 3D equilibrium reconstruction**
  - **Need full transport matrix fluid transport model – NCLASS for stellarators**
- **Edge Modeling**
  - **The plasma edge is a microcosm of plasma physics (equilibrium, stability, collisional and turbulent transport, neutrals) but with properties different from the core**
  - **Inherently 3D – progress in stellarators transfers directly to tokamaks**

Status of PAC-5 Issues

- Recommended increased emphasis on “first principles understanding of the science behind 3D systems”.
  - We are moving in that direction.
- Recommended “strong presence” at 3D ORNL workshop, with PPPL presenting its vision and coordinating its work with that of the community.
  - We had strong presence at workshop, presenting our ideas and vision and listening to other views.
  - Has influenced our plans (e.g. looking at effects of flows on islands).
  - Workshop has been followed up by continued bilateral contacts and collaborations, and by US/Japan workshop at Princeton.
- Recommended exploiting connections with tokamaks.
  - We are adapting and applying tokamak tools and expertise to stellarators.
- Recommended application of stellarator codes to tokamak.
  - We are planning to apply PIES to tokamak field error and tearing mode issues.

Request for info: total no. FTEs in PPPL vs. national stellarator theory.

- about 5 FTE in theory group
- <1 FTE outside theory group (Ku, Mikkelsen, Zarnstorff)
- About 12 – 13 FTE total US stellarator theory (Goldston & Batchelor surveys)

The PPPL Stellarator Theory Team

Core Group (> ½ time) has expertise in range of key areas.

Harry Mynick

- 3D transport expert; work with Boozer and Chu in early 80's demonstrated possibility of stellarator transport optimization.

Neil Pomphrey

- Plasma control expert; coil designer for CIT, BPX, TPX, KSTAR, NCSX

Don Monticello

- MHD expert; with Rosenbluth, White, and Strauss, developer of early nonlinear, 3D time-dependent MHD codes in mid 70's.
- Main person maintaining and developing PIES since early 90's.

Allan Reiman

- With H. Greenside, wrote earliest version of PIES in mid 80's.
- Headed NCSX plasma configuration design work from '97 through '00.

Guoyong Fu

- Energetic particle driven modes via M3D.
- A developer of Terpsichore stellarator stability code as postdoc at Lausanne.

Stuart Hudson

- to PPPL in 2000, from ANU by way of Japan and Wisconsin.
  Brings Hamiltonian techniques for diagnosing fields from Dewar group.
- Lead role in healing NCSX islands.

Missing: expert in parallelization & other cutting edge computational issues.

The PPPL Stellarator Theory Team

Theorists developing and applying tools primarily for tokamaks, secondarily for stellarators, take advantage of tokamak investment:

Greg Rewoldt – FULL microstability code

Roscoe White – ORBIT guiding center code

Nikolai Gorelenkov – HINST high n kinetic stability code

Weixing Wang – GTC global gyrokinetic code

Daren Stotler – Degas code modeling neutrals

Frank Cheng – NOVA code calculating stability of global energetic particle driven modes

Conclusions

- Theory group has continued to make key contributions to NCSX NCSX physics design issues.
- Focus turning increasingly to more fundamental issues, and to new to new studies motivated by needs of NCSX program.
- Continuing to exploit tokamak tools and expertise.
- Collaborating broadly with major international experiments and with and with groups within the US.
- Have participated strongly in US stellarator theory community community planning, presenting our vision and listening to other other views, at ORNL workshop, at Fusion Simulation Workshop, at Workshop, at US/Japan theory workshop (organized by Princeton), Princeton), and in bilateral contacts.