Opportunities for Addressing Fundamental Issues Relevant to the US Compact Stellarator Program through International Collaboration

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Context: FESAC Goal 2.3

Determine the performance of large stellarators in confinement, stability, sustainment and divertor physics through international collaboration

International collaboration is an essential element of a strong US compact stellarator program

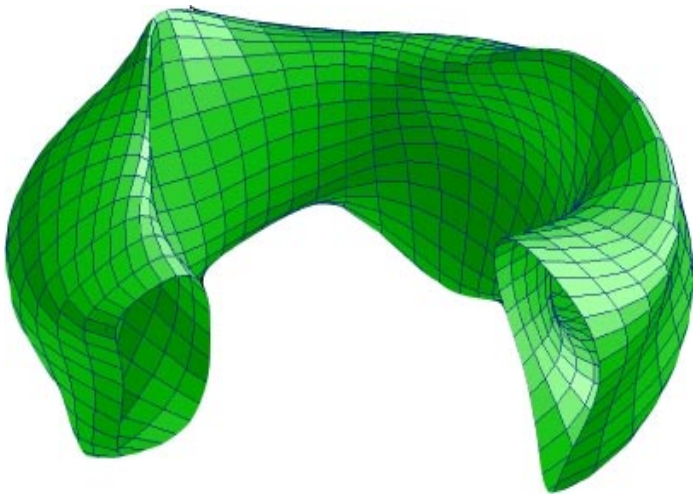
- Exciting time for stellarator research
  - dramatic progress demonstrated internationally
  - advanced large scale projects under construction and operational
  - rapid progress in the development of a CS program in the US adds to the excitement, broadens the program

- International community strongly contributed to the development of the US program
  - importation of codes and expertise
  - bilateral exchanges for refining and defining CS mission complementary to the world stellarator program
    (Aspect ratio, field periods,…)

Opportunity:

International collaboration across a range of configurations will be a key way we make discoveries in stellarator physics

US Compact Stellarator Program Addresses Key Questions in common with International Programs



International and national participation in design of NCSX:

Auburn U., Columbia U., LLNL, NYU, ORNL, PPPL, U. Texas, UCSD, U. Wisconsin Australia, Japan, Germany, Russia, Switzerland

- Can limiting instabilities and disruption be avoided or softened by external transform and 3D shaping?
  - Assess effect of internal current, low-A
- Can islands be detected and effectively controlled?
  - Role of neoclassical current, use of trim coils
- Can plasma performance be significantly improved by the reduction of neoclassical transport?
  - Role of symmetry in global confinement
- Can flow shear be effectively controlled in a CS?
  - Role in turbulence control, island formation
- How does 3D shaping (islands and stochasticity) affect power and particle handling?
- Can Alfvenic modes strongly affect fast ion transport?
  - Can Helicity induced gap modes be observed?

Background and Aims of PPPL International Collaborations

- Background:
  - Traditionally centered on the tokamak (JET, JT-60U)
  - Fills need for the US to address burning plasma physics issues on large scale facilities
- New stellarator thrust consistent with FESAC goal:
  - LHD, W7-AS (modest 2 FTE effort, < 20% per person)
- Guiding Principle:

  Develop integrated teams to take advantage of unique opportunities for advancing fusion science goals through mutually beneficial activities on international facilities.

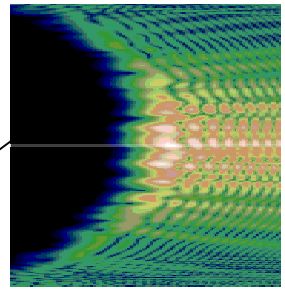
  Visibility and relevance are enhanced by integrated teams addressing key issues aligned with program goals

Example of an Integrated Team Approach to International Collaboration on JT-60U

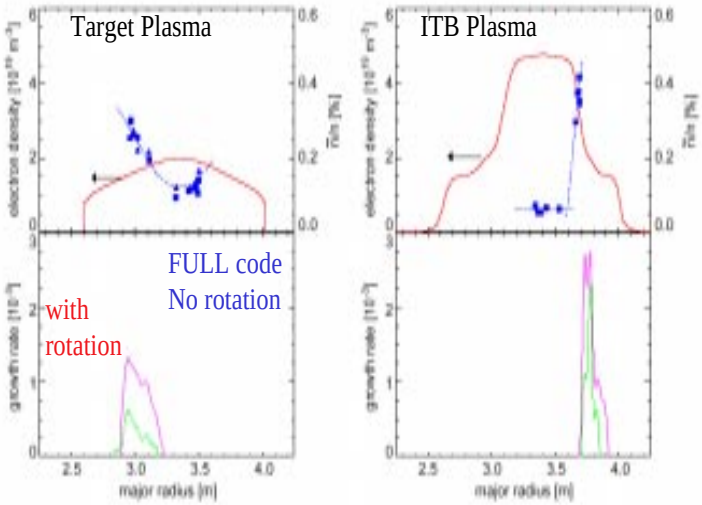
- Goal: Understand the role of turbulence decorrelation in ITB formation
- Opportunity: Strong reverse shear ITBs in JT-60U
- PPPL collaboration team:
  - Reflectometer
  - Wave modeling
  - Microstability

Hardware: Correlation reflectometer

Modeling: Reflectometer Analysis



Output: Profile of Fluctuations vs Growth rate in target and ITB plasmas



G. Rewoldt et al., Phys. Fluids **25**, 480 (1982) & **30**, 807 (1987)

$\lambda_y = 1$ cm $k_y = 2$ cm^{-1} target plasma $\lambda_y = 1$ cm $k_y = 2$ cm^{-1} ITB plasma

Goal: Understand Role of Neoclassical and Turbulent Transport and Fast Ion Confinement in Improved Performance Regimes on LHD

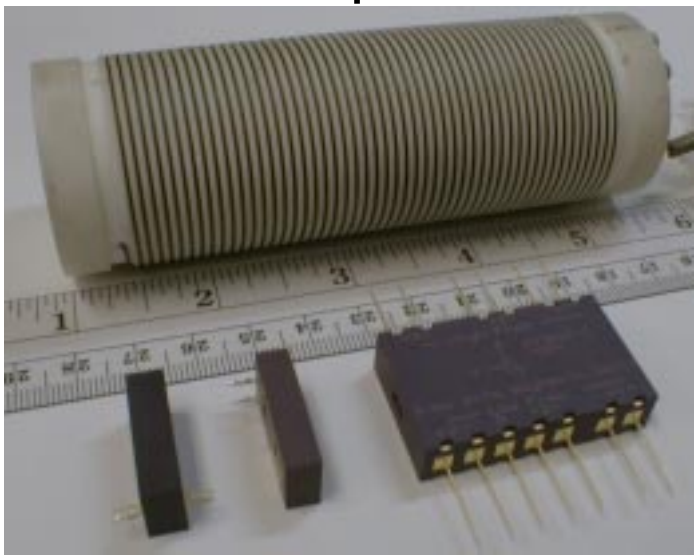
- Exciting Opportunity Inward shifted 3.6 m configuration in LHD demonstrates superior performance relative to standard configuration
  - beta exceeds low-n threshold
  - improved neoclassical transport
  - role of turbulence, flow shear ?
- Current PPPL participation in LHD
  - NPA installed for fast ion studies: S. Medley, D. Darrow
  - Detailed microstability analysis of 3.6, 3.75 m cases: Rewoldt
    Finds stability inside r/a=0.4 in both cases
  - Initiated neoclassical transport study: D. Mikkelsen

Future:

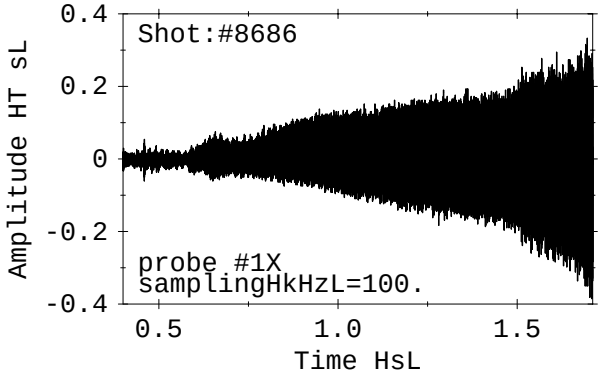
- 3-D Alfven instability analysis: F. Cheng, N. Gorelenkov
- Local microstability analysis with GS2: D. Mikkelsen
- Global simulation code GTC, hardware for turbulence measurements (D. Mikkelsen, G. Rewoldt, …)

Goal: Address Stability Limits and MHD Phenomena in Inward Shifted LHD Configurations

Takahashi probes



Initial data



- 64 toroidal and poloidal coils installed: H. Takahashi
- MHD analysis Planned using probes
- Equilibrium analysis H. Takahashi, L-P. Ku
- Opportunity for National teaming (3-D EFIT: ORNL)
- Kinetic & nonlinear stability (Gorelenkov, Fu)

LHD stability

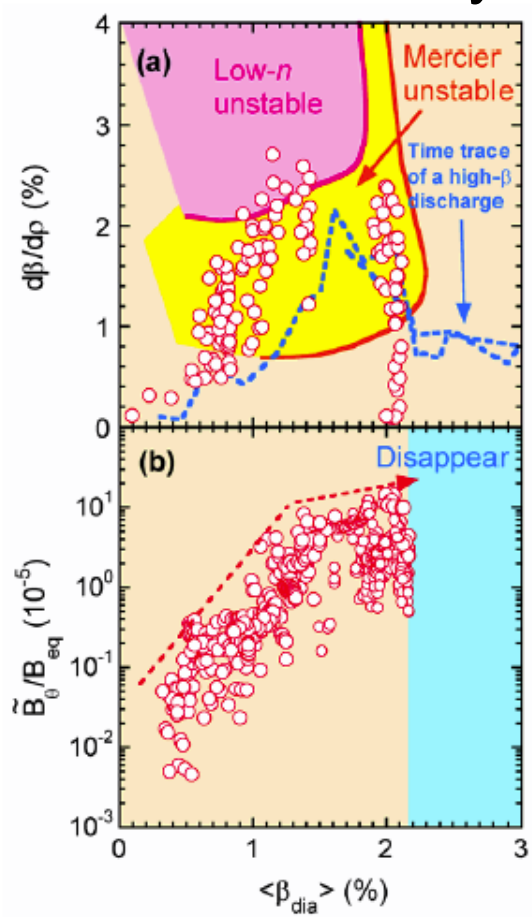


Fig. 2. Changes in (a) pressure gradient at ρ = 0.5 and (b) fluctuation amplitude of *m*/*n* = 2/1 mode as a function of ⟨β_{dia}⟩.

Goal: Understand stability of a current carrying stellarator

- Opportunity:

  - Participate in joint experiments on W7-AS aimed at understanding the physics of stability limits by varying OH current with well documented equilibria
  - Study occurrence of islands at finite beta and current
  - Planned for summer 2002

W7-AS

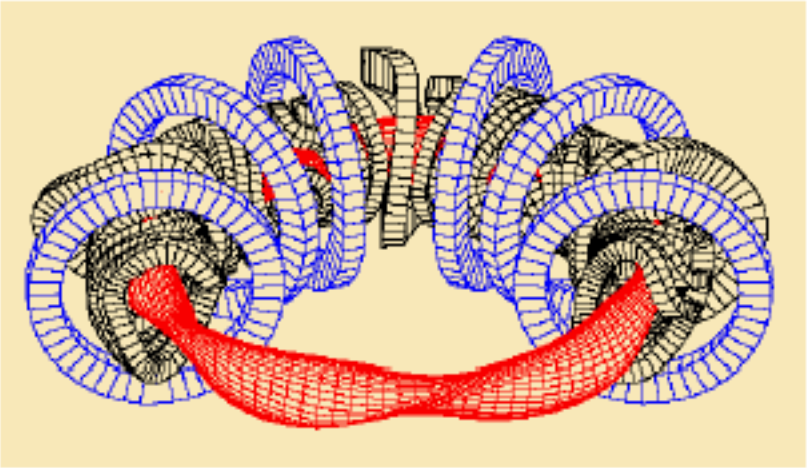


Fig. 3. Coil system and magnetic surface of Wendelstein 7-AS.

- Collaboration team:

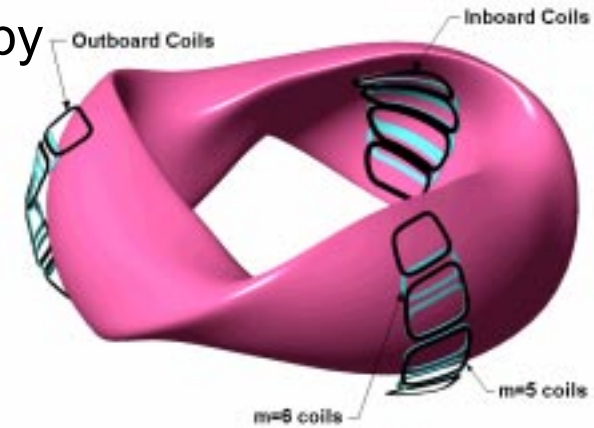
  - joint experiments and analysis: M. Zarnstorff, E.D. Fredrickson
  - 3-D linear stability analysis: M. Redi…

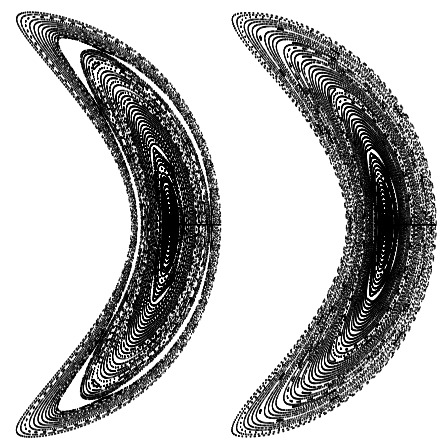
- Present status:

  - Starting discussions

Goal: Understanding of equilibrium magnetic Islands, detection, modeling and control

- NCSX physics basis for island control:
  - remove resonant fields by design
  - reverse magnetic shear for neoclassical healing
  - trim coils for low-order resonances

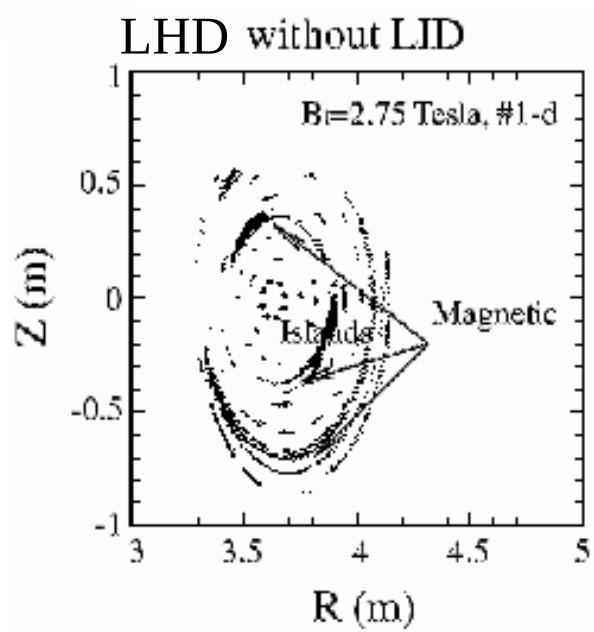




- Opportunity:
Participate in experiments on LHD where island healing by J_{BS} has been observed

- Existing effort:
PIES and HINT benchmarking on LHD equilibria:
A. Reiman, D. Monticello

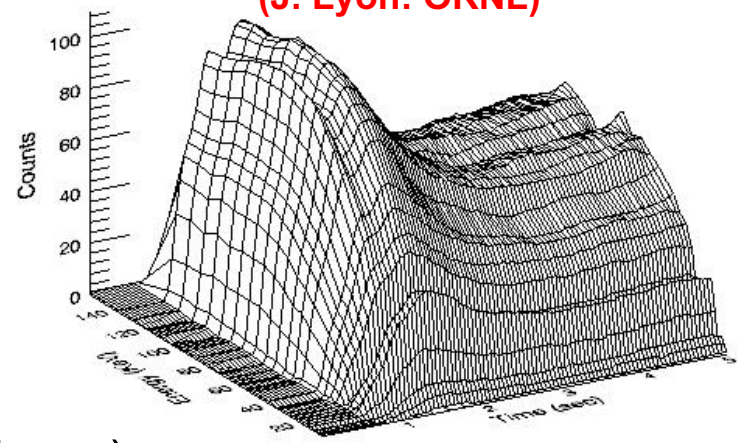
- Long term: National teaming with 3-D EFIT
PIES full torus calculations with neoclassical effects



Goal: Understand Dynamics of Fast Ion Transport, Alfven Instabilities and Implications for Long Pulse Operation

- Strong collaboration with LHD, CHS, W7-AS
  - scintillator probes: D. Darrow
  - NPA: S. Medley, J. Lyon (ORNL)

TFTR E||B NPA Is Being Used on LHD (J. Lyon: ORNL)

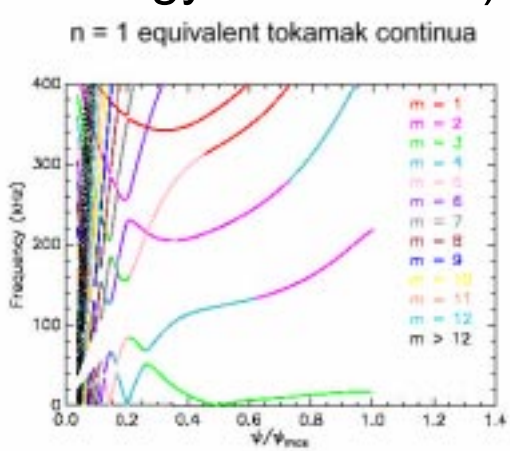


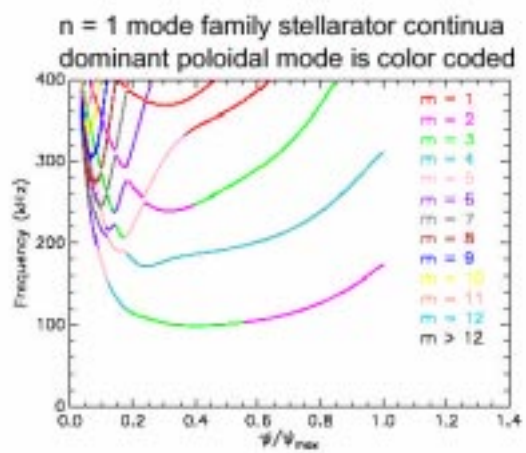
- Near term activity:

-Upgrade HINST to 3-D local analysis of kinetic ballooning modes:
N. Gorelenkov, Dr. Nakajima (NIFS)

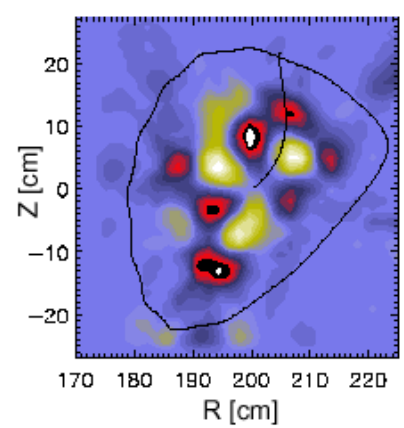
- Longer term: Fuly 3-D NOVA (Gorelenkov, Cheng)

Also, pursue opportunity for teaming with ORNL
(D. Spong: Full 3-D gyrofluid code)





W7-AS



Program Goal: Understand the role of Flow Shear in Turbulence Reduction in CS

- Opportunity:
  - Understand role of flow shear in existing high performance experiments
  - turbulence and flow under active investigation in current stellarators
- Initial PPPL Participation in LHD:
  - microwave interface for LHD: Bretz
  - microstability modeling: Rewoldt
- Longer term opportunities:
  - apply neoclassical and turbulent GTC analysis (D. Mikkelsen, G. Rewoldt)
  - reflectometry analysis and interpretation
  - participate in experiments which vary flow damping and assess turbulent transport

ITB in CHS

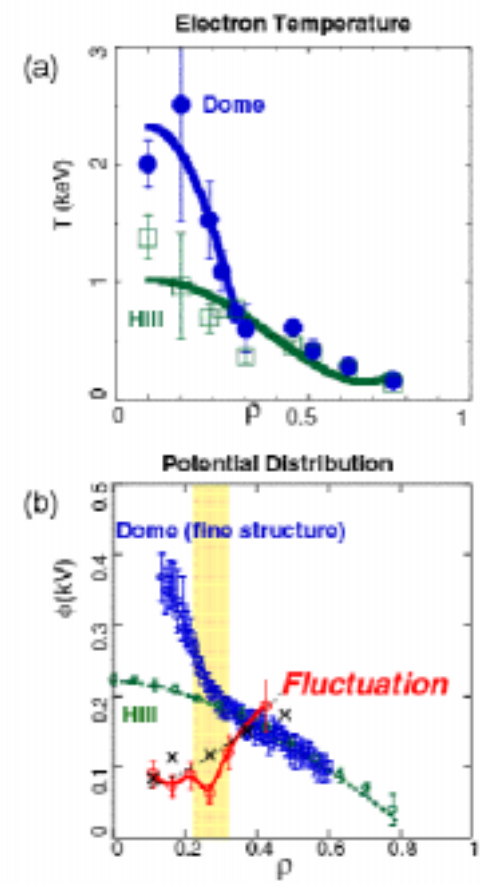


Fig. 2. (a) Electron temperature profiles of the dome and hill states. (b) Potential profiles of the dome and hill states, with total fluctuation power of the density. Density fluctuation is reduced where the E_r shear is maximum.

Goal: Understand Role of Islands and Stochasticity in Particle and Power Exhaust and Control

- Opportunity for National collaboration on W7-AS and LHD

- Strong modeling effort at IPP in this area

- Plan PIES calculations for edge modeling

- Opportunity for national collaboration:
  - Livermore group has interest to pursue divertor physics collaboratior
  - National teaming and coordination may be effective

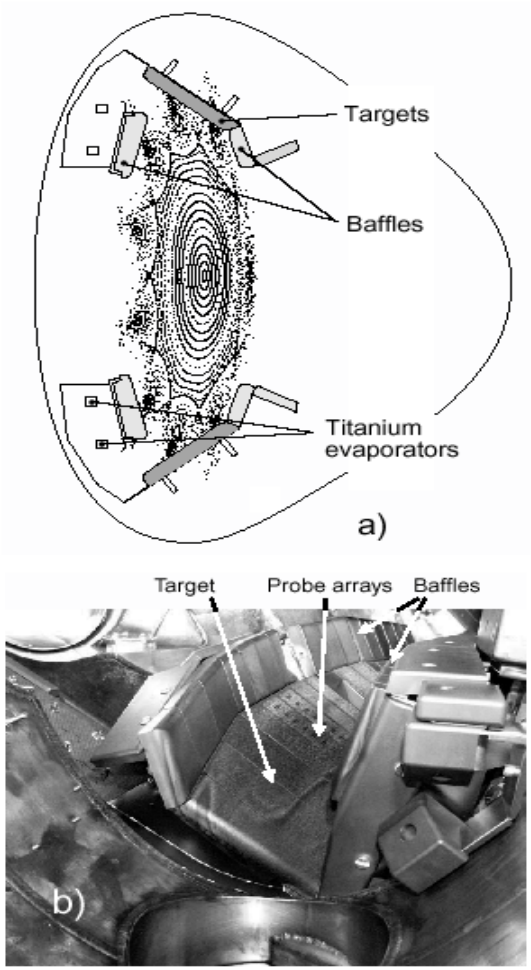


Fig. 1. (a) Elliptical plasma cross section with island divertor modules. Such modules are installed at the top and bottom of each of the five elliptical planes. The toroidal length of each module is 0.7 m. (b) Photograph of a bottom divertor module.

International Collaboration Provides a Unique Opportunity for the US to Advance Stellarator Program Goals

- Exciting developments internationally has motivated a strong stellarator program in the US
  - US compact stellarator program complementary to world effort

- Collaborations on international facilities is an effective way of addressing FESAC goals of understanding stellarator physics at high performance parameters

- PPPLs goal is to create integrated teams of experts to address key issues through hardware development , modeling effort and experimental participation
  - strong start in this direction in MHD, transport, fast ion physics

- Questions to the PAC:
  - Are we addressing the right issues on the right facilities?
  - Is there an advantage to further US coordination?
  - How can we best contribute to international programs?