Advances that Might Broaden the Usage of TRANSP*

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TRANSP for Predictive Integrated Simulations

- Although TRANSP was developed primarily as an Analysis Code it has always had some predictive capability as well
  - Predictive capability relies on introduction of reduced theory based models
    - Predictive studies involving ECH in PLT were carried out by a member of Lehigh group, in collaboration with D. McCune and other scientists at PPPL, in early 1980's, more than 30 years ago
    - A. H. Kritz *et al., Study of the Effect of Localized ECH on Transport and Stability in Plasmas*, AIP Conference Proceedings 129, 235 (1985)
  - Over the years, and particularly in the past 15 years, members of the Lehigh group have focused on extending the TRANSP predictive capability
- From 2007 to 2011 DOE, funded a national effort, the PTRANSP project, led by the Lehigh group, to advance the predictive capability of TRANSP
  - Focus on adding and extending the applicability of theory based models
  - Verification and validation of the code components was emphasized
  - Architectural modernizations improved the code modularity
- The improvements and addition of theory based models has led to a significant increase in the utilization of TRANSP
  - Results of numerous predictive studies carried out using the TRANSP code have appeared in many peer reviewed publications
- Essential that the reduced models, used in whole device modeling, continue to be improved in order that the reduced models accurately replicate the underlying basic plasma physics

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Motivation for the Development of Reduced Models

- Use of integrated predictive simulations over the entire discharge period both in planning and interpreting results of experiments will result in more effective use of limited experimental facilities
  - Avoid costly design mistakes and facilitates the optimization and control of experimental scenarios
- Ability to understand the physics involved in fusion plasmas requires whole device modeling
  - Where all the relevant interactive physics is included
- Integrated predictive modeling, for the duration of the existence of the plasma, need to be carried out for time periods ranging from seconds to thousands of seconds
  - Not possible to carry out the required integrated modeling simulations using first principal physics
  - For example, thousands of processors, running for many days, are required to carry out a few microsecond simulation of plasma turbulence
- Important to develop reduced theory based models that can be utilized in whole device physics modeling
  - Compare simulation results with experimental data
  - Determine what works and what aspects of the model requires further theoretical development

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Motivation for the Development of Microtearing Mode Model

- **Two modules (microtrearing mode and interchange mode modules) are being developed at Lehigh which, when installed in TRANSP will extend the applicability of the TRANSP code**
- **Dependence of energy confinement time (τ_E) on the plasma collisionality (ν*) is an important experimental discovery in the NSTX discharges**
  - **NSTX discharges show $\tau_E \propto 1/\nu^*$**
- **Preliminary studies of the collisionality effect on the anomalous thermal transport were carried out**
  - **Results for τ_E were found to be inconsistent with NSTX experimental results**
  - **Likelihood of missing electron thermal transport component**
  - **Parameter range for NSTX operation is such that microtearing modes (MTMs) can be unstable**
    - **MTMs are short wavelength ion scale electromagnetic instabilities driven by electron temperature gradient in a collisional plasma**
  - **Turbulent transport associated with unstable MTMs is currently not included in the Multi-mode transport model**

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Reduced Transport Model for MTMs

- Unified fluid/kinetic approach is used to derive NL dispersion relation
- Parallel current is calculated using nonlinear fluid equations of electron momentum, electron density, Maxwell equations, Ampere's law and quasi-neutrality condition
  - Iterative nonlinear approach is used to calculate perturbed distribution function, which in turn is used to calculate nonlinear parallel current and nonlinear dispersion relation
  - Influence of third order NL effects on a multi-wave system are considered
- Magnetic fluctuation strength and electron thermal diffusivity due to MTM are calculated
  - Saturated amplitude of the magnetic fluctuations are calculated utilizing numerically determined MTM eigenvalues in the nonlinear microtearing modes envelope equation
- Model developed for MTM electron thermal diffusivity includes
  - Collisionality, density and temperature gradient, magnetic curvature, electrostatic potential, and parallel dynamics
- Details of derivation of model:
  - T Rafiq, *et al*., *Microtearing Modes in Tokamak Discharges*, Phys. Plasmas 23, 062507 (2016)

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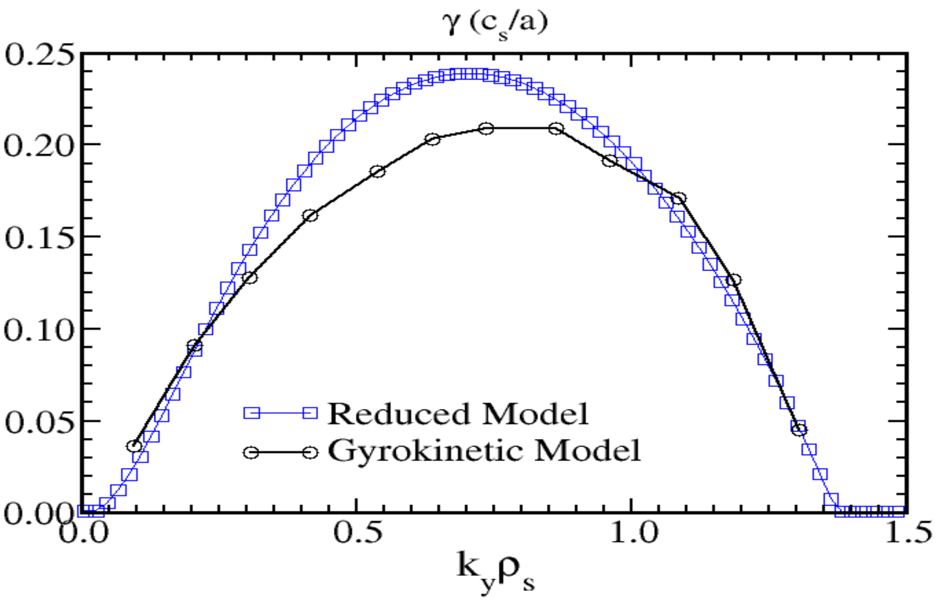
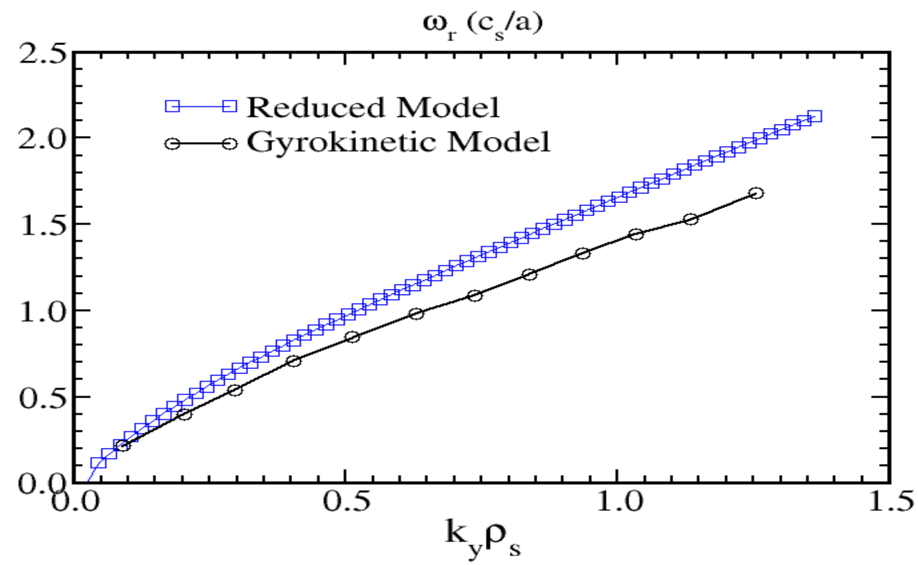
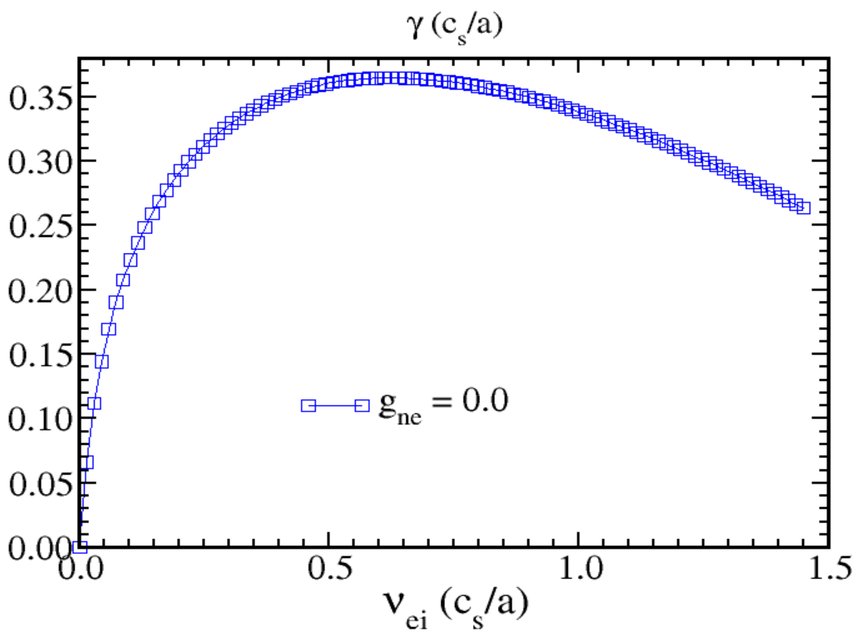
Comparison Between Reduced Model and Gyrokinetic MTM Linear Growthrate and Frequency

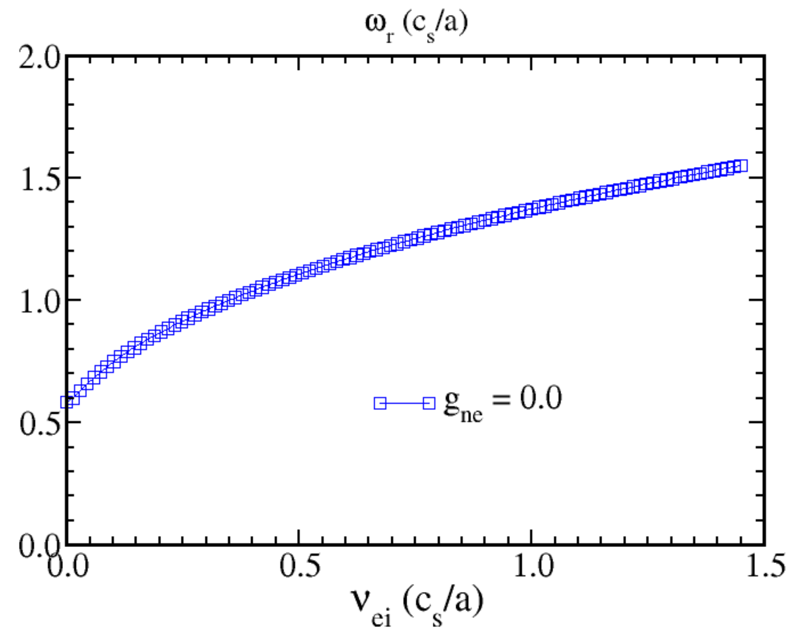




- **MTM linear growthrate and real frequency as function of $k_y\rho_s$ compared with gyrokinetic code GYRO MTM linear growthrate and real frequency**
  - **W. Guttenfelder et al. Phys Plasmas 19, 022506 (2012)**
- **The MTM model will be employed as a component of the Multi-Mode Transport model which has been used extensively in TRANSP predictive whole device integrated simulations**
  - **T. Rafiq *et al*., *Fusion Power Production in ITER Baseline H-mode Scenarios*, Phys of Plasmas, 22, 042511 (2015)**
  - **A.H. Kritz *et al., Integrated Modeling for Prediction of Optimized ITER Performance*, Nucl. Fusion 51, 123009 (2011)**

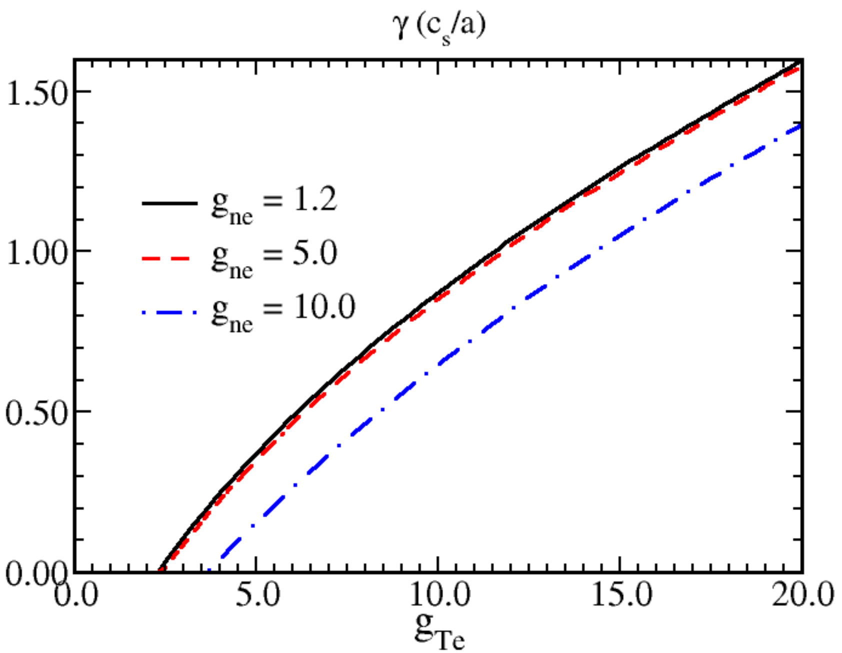
Collisionality Dependence of MTM

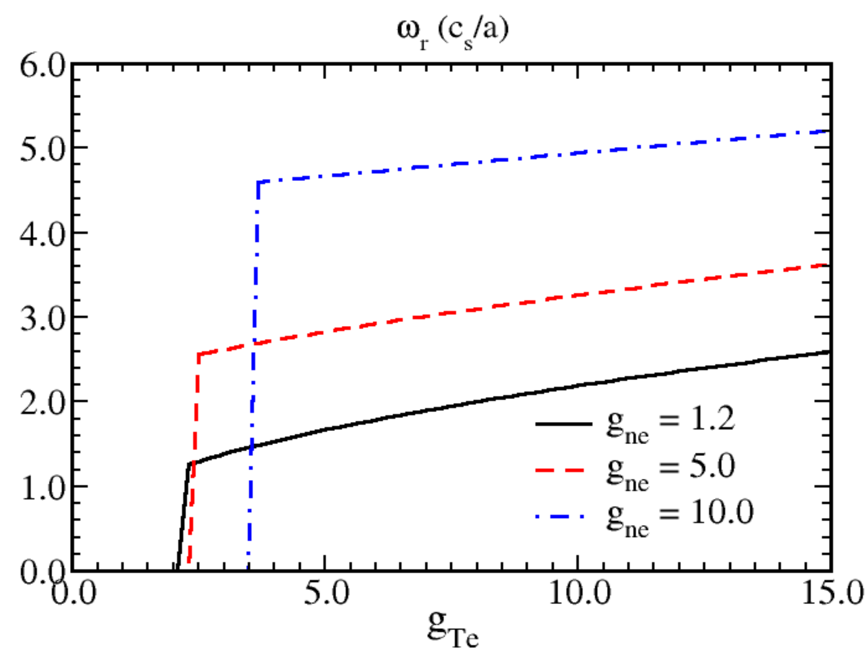




- **Maximum γ is found for moderate values of collision frequency**
- **Non monotonic dependence of γ on ν_{ei} is consistent with gyrokinetic simulations**
  - **γ decreases with decreasing ν_{ei} consistent with the dependence on collisionality ($\tau_E \propto \nu^{-(0.8\text{-}0.95)}$) is observed in the NSTX discharges**
  - **S. Kaye *et al*., Nucl. Fusion 47, 499 (2007)**
- **Real frequency of MTM increases with collision frequency**

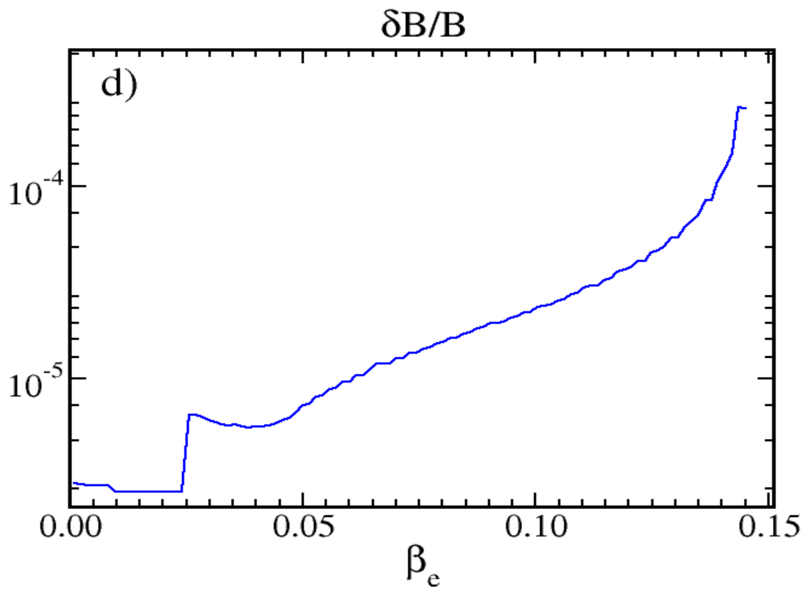
Temperature Gradient Dependence of MTM for Different Values of Density Gradients

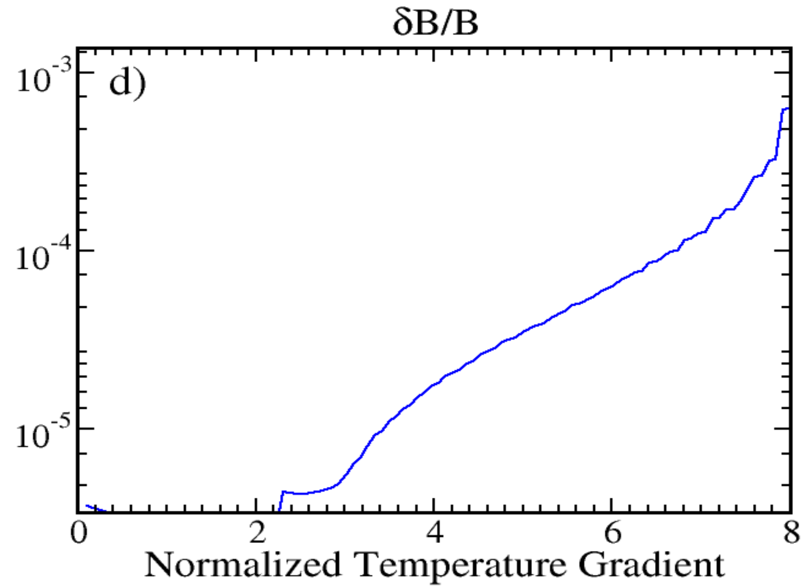


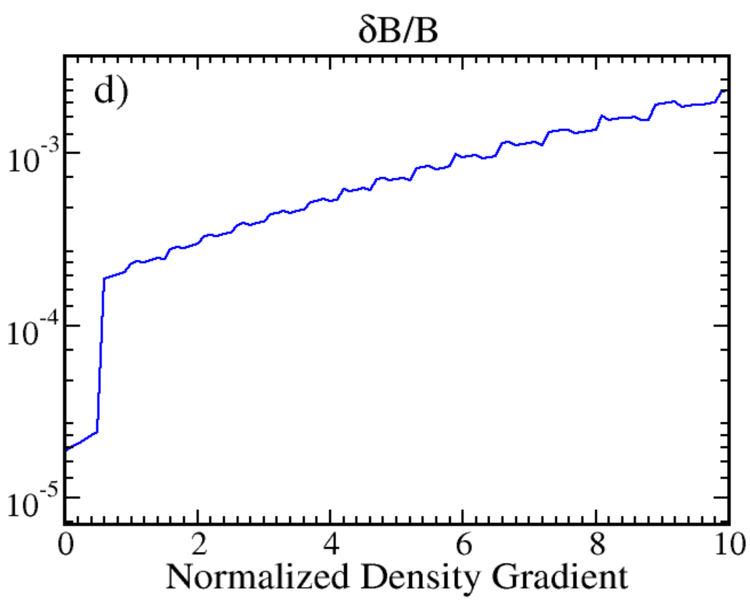


- Destabilizing effect of increasing temperature gradient, g_{Te} is illustrated
  - MTM instability threshold in g_{Te} is found to be dependent on density gradient
    - Threshold is found to be increasing and growthrate is found to be decreasing with increasing density gradient, g_{ne}
- Experimental g_{Te} is 2x larger than the inferred linear threshold in g_{Te}
- MTM growthrate increases rapidly above the g_{Te} threshold for small g_{ne}
- MTM real frequency increases with g_{Te} and with g_{ne}

Magnetic Fluctuation Dependence on β_e, Temperature Gradient and Density Gradient







- **Saturated magnetic fluctuation, $\delta B/B$, clearly depends on β_e and on temperature and density gradients**
  - **Mixing length estimate $\frac{\delta B}{B} \approx \rho_e/L_{\mathrm{Te}}$ used in previous MTM related publications is not capable of capturing these dependencies**

Reduced Transport Model for Interchange Modes

- Interchange instability is similar to the Rayleigh-Taylor instability
  - Driving force for these modes is the pressure gradient
  - Exists when the Mercier criterion is violated as a consequence of pressure gradient across flux surfaces that have, an average, unfavorable curvature
- Interchange modes are unstable in high beta tokamak discharges
  - Consequently, as tokamaks operate in increasingly high beta regimes, it is important to include transport associated with interchange modes in simulations of the evolution of plasma discharges
- Currently, in TRANSP simulations employing the TGLF transport model, the TGLF model is turned off in plasma regions where the interchange instability criterion is violated and interchange modes are present
  - In the region where the TGLF transport model is turned off, anomalous transport is replaced by neoclassical transport with an arbitrarily multiplier
- For self-consistent predictive simulations, it is very important to develop a model for interchange modes, which can explain the enhancement of electron thermal transport in regions of the plasma where interchange modes are present
  - Research program at Lehigh includes plans to develop a module for describing transport associated with Interchange Modes

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Anomalous Poloidal Momentum Transport Model

- **JET experimental results show larger poloidal momentum transport than predicted using existing transport models**
  - Experimental results contradict the assumption that the poloidal momentum transport is primarily neoclassical
  - In the region of internal transport barriers, the measured poloidal rotation velocity is approximately an order of magnitude larger than the neoclassical poloidal rotation velocity
- **In plasmas with low toroidal rotation, the poloidal rotation will yield an important contribution to the radial electric field**
  - The gradient of the radial electric field provides flow shear, which can suppress turbulence and result in larger plasma temperature
- **Particularly important to understand poloidal momentum transport in plasmas which are expected to have low toroidal rotation such as ITER**
  - Currently, turbulence driven poloidal momentum is not advanced in predictive simulations carried out using the TRANSP code
- **Model for turbulence driven poloidal momentum transport will help understand the basis for the reduced levels of anomalous ion thermal transport observed in tokamaks**

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Dynamic Model for H-Mode Pedestal Growth and ELM Cycles

- The NTCC PEDESTAL module has been implemented in TRANSP
  - Used to compute height and width of temperature pedestal at edge of H-mode discharges
- PEDESTAL module provides a predictive boundary condition for temperature profiles in TRANSP
  - Empirically based scaling model for H-mode pedestal currently used
    - T. Onjun, G. Bateman, A. Kritz, and G. Hammett, *Models for Pedestal Temperature at the Edge of High Mode Plasmas in Tokamaks*, Phys. of Plasmas, 9, 5018 (2002)
- It is important to have a predictive model for the pedestal
  - Since global confinement and core profiles depend on pedestal height
- Implementation of EPED code for boundary
- ELITE stability code to be installed in TRANSP
  - ELITE is particularly well suited for computing the onset and width of the MHD instabilities that trigger ELM crashes
- Install EPED (for boundary), ELITE (for stability), and ELM models

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Model for Neoclassical Tearing Modes

- Magnetic islands driven by saturated neoclassical tearing modes(NTM) can produce increased radial transport and result in disruptive instabilities in tokamaks
- The ISLAND module or other module to compute NTM magnetic island widths is needed to be installed in TRANSP
  - NTCC ISLAND module computes multiple island widths in tokamaks with arbitrary cross section and beta
- Transport is enhanced across each island for self-consistency
  - Tested in BALDUR code but BALDUR no longer supported
    - C. Nguyen, G. Bateman and A.H. Kritz, *Simulation of Saturated Tearing Modes in Tokamaks,* Phys. Plasmas, 11, 3460 (2004)
    - F.D. Halpern, G. Bateman, A.H. Kritz and A.Y. Pankin, *The ISLAND Module for Computing Magnetic Island Widths in Tokamaks*, J. Plasma Physics 72, 1153-1157 (2006)
- Electron Cyclotron Current Drive needs to be implemented to model feedback stabilization of NTMs

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TRANSP Verification and Validation

- Standardized collection of plasma state datasets should be used for cross code verification and TRANSP regression tests
  - Facilitate the connection between TRANSP and data made available by experimental groups
  - Time dependent plasma state datasets will facilitate reproducible simulations by different integrated modeling codes
- Detailed comparisons should be made with wide range of scans of tokamak experimental data
  - For H-mode and dynamic advanced tokamak scenario discharges
  - To test TGLF and Multi-Mode anomalous transport models
  - To test other components as well as transport in the context of self-consistent predictive integrated simulations
- Documentation of archived TRANSP runs made available to community of TRANSP users

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TRANSP Closed-loop Simulations

- Predictive simulation capability is critical for controls
  - Validation of control-oriented models used for control design
  - Controller test in closed-loop simulations before implementation
  - Iterative design process (model improvement + control redesign)
- TRANSP currently runs in open loop
  - Controllable inputs are preset before the simulated run
- To perform control simulations the loop must be closed
  - The controllable inputs must be updated by the feedback controller based on the state evolution of the simulated run
- Control needs
  - Magnetic Control (Shape, Position, Total Current, …)
    - Free boundary simulation capability
  - Kinetic control (Current, Temperature, Pressure, Burn, Rotation, …)
    - Transport simulation capability
  - MHD Instability Control (NTMs, RWMs, ELMs, Sawteeth, Alfven, …)
    - MHD simulation capability

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Improve User Interface

- An Interface to the TRANSP code which facilitates the use of the code should have controls which avoids misuse of the code
  - Use of unphysical or incorrect variables results in meaningless output
- TRANSP Help Document is out of date and needs major revision
  - Unclear what are the limitations and use of many of the variables
  - Clearly indicate what modules: for example, heating, particle and current drive sources, anomalous and neoclassical transport models, stability packages, equilibrium packages, L-H transition, sawteeth, atomic physics
- Modern Plotting package based on python is needed for portability
- Support of the Code at NERSC
  - Cannot take advantage of parallelization that has been introduced
  - PT-Solver developed primarily for TGLF but TGLF can be run more efficiently at NERSC
- Choice of NCLASS, NEO, certain E×B shear models should be available for MMM when running PT-Solver
- Improve robustness of density evolution
- Complete testing of GENRAY/CQL3D

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Summary

- Install interchange mode, microtearing mode, poloidal momentum transport , intrinsic rotation and pellet Injection modules
  - Need equations for evolution of poloidal momentum and impurity transport to be installed
  - Sometimes a newly installed module yields unexpected and incorrect results
    - Defensive programming techniques are required
  - Important to review, verify and validate all features in the code that relate to the module being implemented
    - Standards should be established by the community that must be satisfied both with regard to the reliability of the module as well as documentation before a new module is advertised as being available in the TRANSP code
- Dynamic model for H-mode pedestal growth and ELM cycles
  - Install or establish connection to MHD codes
  - Install EPED (for boundary), ELITE (for stability), and ELM models
- Improvements to simulation control
  - Options for automated feedback modification of source powers
- Standardized test problems to facilitate TRANSP regression testing
  - Simpler interface for use of each module and code
- TRANSP workshops at PPPL and other locations (perhaps APS or EPS meetings) as well as TRANSP User Group meetings

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