Dynamic Modeling of Multi-channel Transport Bifurcations Resulting in Internal Transport Barriers in Tokamaks

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GENERAL ATOMICS

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Dynamic Modeling of Multi-channel Transport Bifurcations Resulting in Internal Transport Barriers in Tokamaks[1]

J.E. KINSEY, Lehigh University, R.E. WALTZ, G.M. STAEBLER, H.E. ST. JOHN, General Atomics — Internal transport barriers (ITBs) provide a means of minimizing turbulent transport giving access to fusion power plants at a reduced size. Rotational shear stabilization is believed to play a central role in the formation of ITBs. However, predicting bifurcations in particle, energy, and momentum confinement using comprehensive theoretical models remains an important issue. The GLF23 transport model has the distinguishing feature that it contains both heat flux and momentum bifurcation mechanisms. Recently, dynamic formation of an ITB resulting from an $E \times B$ shear driven bifurcation was successfully demonstrated using the GLF23 model for a DIII–D NCS discharge with an L–mode edge.[2] Here, the bifurcation dynamics and ITB formation in DIII–D NCS and JET OS discharges are compared and the synergistic coupling between the turbulent viscosity and thermal transport is assessed. The role of $T_{\rm i}/T_{\rm e}$ effects and the electron temperature gradient (ETG) mode on barrier formation is investigated.

[1]Supported by U.S. DOE Grants DE-FG03-95ER54309 and DE-FG03-92ER54141.

[2]J.E. Kinsey *et al.*, 26th EPS Meeting, Maastricht, Netherlands (1999).

☐ Prefer Oral Session
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Transport Barrier Simulations Using Predictive Models

Some theory based transport models have recently included ExB velocity shear and begun to look at internal transport barrier regimes.

- *ITG-TEM based models with ExB velocity shear using Waltz's rule:*
  - *GLF23 (R. E. Waltz, G. M. Staebler, W. Dorland, G. W. Hammett, M. Kotschenreuther and J. A. Konings, Phys. Plasmas 4 (1997) 2482)*
  - *IFS-PPPL (W. Dorland, M. Kotschenreuther, Q. P. Liu, M. A. Beer and G. W. Hammett, ISPP, Varenna 1996)*
  - *Multi-mode including ExB velocity shear (Bateman, et al, IAEA 1998; Kinsey, Nucl. Fusion, 1999).*
  - *CDBM based model including ExB velocity shear (Fukuyama, S-I Itoh, M. Yagi, K. Itoh, IAEA 1998)*

Dynamic Transport Bifurcation Modeling Using the GLF23 Model

- *Previous studies have focused on the dynamics of bifurcations using simple heuristic models and only for a single channel of transport. We are thus motivated to advance predictive capability by using the most comprehensive physics-based models.*
- *In this work, we consider the GLF23 gyro-fluid based transport model which contains both heat flux and momentum bifurcation mechanisms.*
- *Taking the density profile, sources, sinks, and equilibrium from a power balance analysis, time-dependent simulations are carried out where the thermal and toroidal transport are simultaneously evolved while self-consistently computing the effects of ExB shear stabilization.*
- *The profiles are initialized at pre-barrier levels and are followed through the bifurcation phase and resulting formation of an internal transport barrier*
- *Boundary conditions are enforced at $\rho = 0.9$ using experimental data.*

The GLF23 gyro-Landau-fluid Transport Model

- *The GLF23 model is a 1D dispersion type drift wave model with equations reduced from 3D GLF equations using a ballooning mode trial wave function along the field lines (Waltz, et al. Phys. Plasmas 1, 2229 (1994))*
- *The 1D dispersion equations are fitted to the approximate linear growth rates from a 3D gyro-kinetic stability (GKS) code and non-linear saturation levels are taken from 3D gyro-fluid (GLF) simulations*
- *Quasilinear theory is used to yield transport for 5 channels - electron and ion thermal, hydrogenic particles, impurities, momentum*
- *Model includes effects of Ti/Te, finite β, magnetic shear, Shafranov shift, and ExB shear*
- *Momentum driven rotational shear stabilization leads to transport bifurcations resulting in jumps to higher temperature gradient and/or toroidal rotation at fixed heating power and momentum input*

The GLF23 Model Has Been Parallelized Using MPI and Implemented in the XPTOR Transport Code

- *Previous bifurcation studies using the GLF23 model were very time consuming … wall clock times on the order of 3-4 hours.*
- *Using the MPI* library, the GLF23 transport model has been parallelized and incorporated into the XPTOR code which runs on the GA Luna Pentium II based Linux cluster. Here, the eigenvalue problem for the transport is solved for each perpendicular wavenumber (10 total) on separate processors.*
- *The performance of XPTOR running the GLF23 model using 10 CPU's was found to be more than a factor of 8 faster than the single processor runs.*
- *XPTOR evolved from the time-dependent transport solver PTOR which resides in the Cray Basis version of the MLT transport code used in ITER model testing studies.*

* *http://www-unix.mcs.anl.gov/mpi/index.html*

Bifurcation Mechanisms

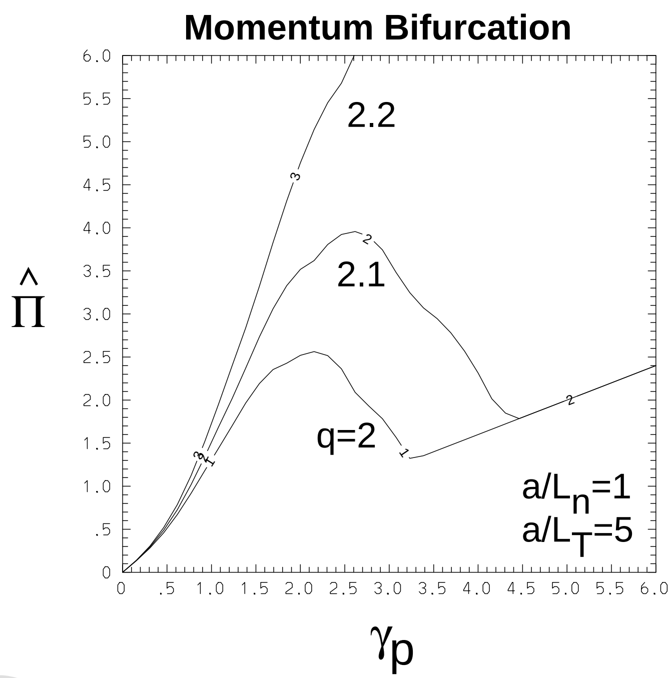
There are 3 known mechanisms for transport bifurcations in tokamaks:

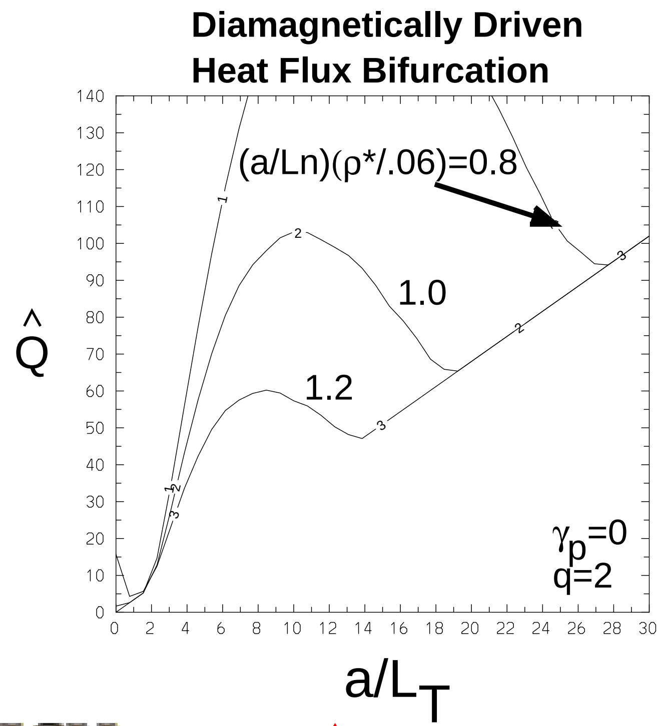
- ***ExB velocity shear***
  - ***S. I. Itoh, K. Itoh; K.C. Shaing, E.C. Crume; H. Biglari, P.H. Diamond, P. Terry; F.L. Hinton***
- ***Shafranov shift (α-stabilization)***
  - ***J.F. Drake, Y.T. Lau, P.N. Guzdar, et al.; M.A. Beer, G.W. Hammett***
- ***Density gradient driven***
  - ***G. Staebler***

In reality, bifurcations that lead to the formation of transport barriers are multi-channel (particle, energy, and momentum). The challenge is predict when and how transport barriers are formed in time-dependent codes with numerically robust and efficient algorithms.

Single-channel Rotational Bifurcations

- *Rotational bifurcations can allow the plasma to jump to higher temperature gradients (a/L_T) and toroidal rotation (γ_p) at a fixed heat flux $\hat{Q}$ and momentum flux $\hat{\Pi}$. Here, $\gamma_p = dv_{||}/dr/(c_s/a)$*
- *Momentum bifurcations are believed to be the principal cause of internal transport barriers in DIII-D NCS discharges*





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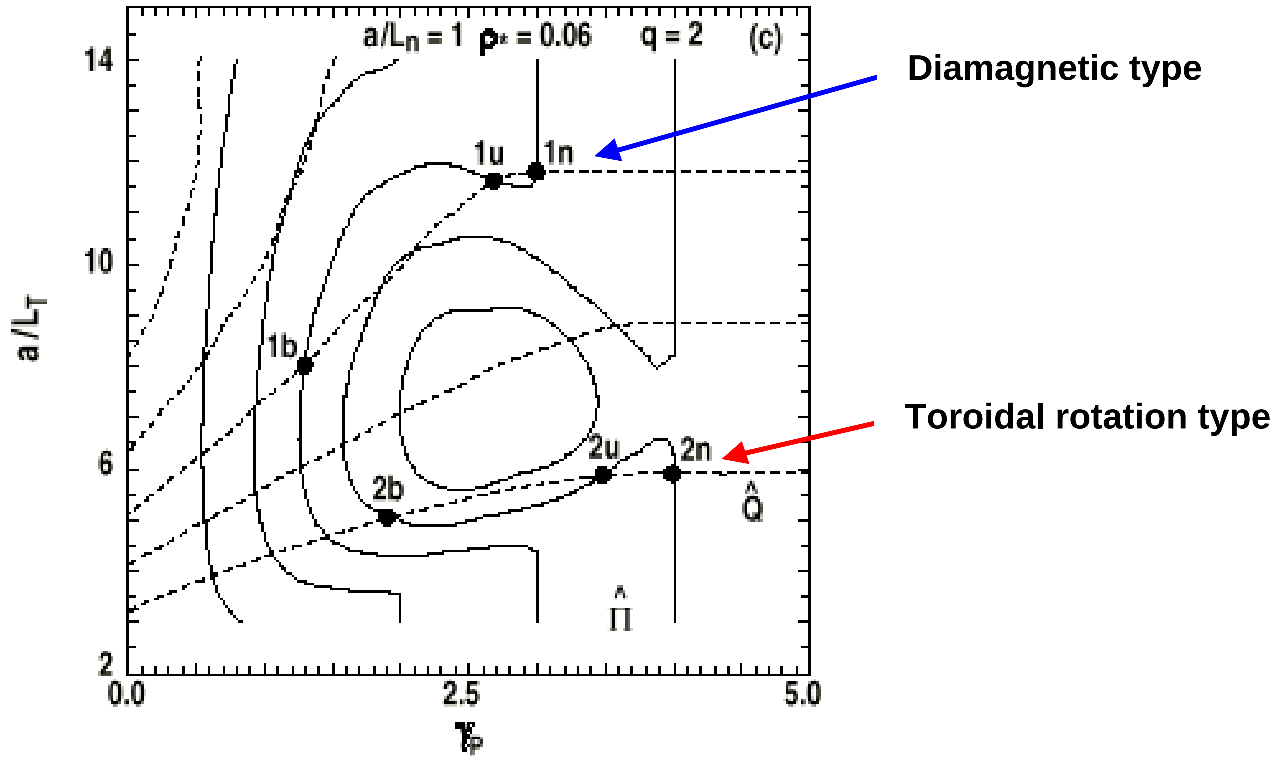
Multi-channel Rotational Bifurcations

- ***Rotational bifurcations can allow the plasma to jump to higher temperature gradients (a/L_T) and toroidal rotation (γ_p) at a fixed heat flux $\hat{Q}$ and momentum flux $\hat{\Pi}$***



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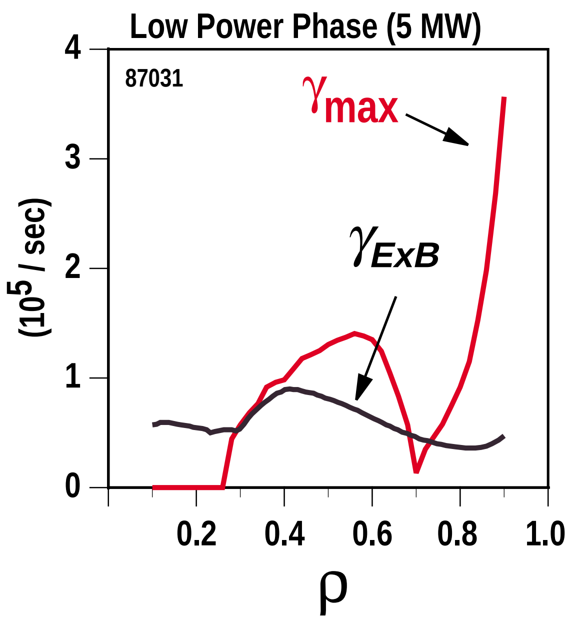
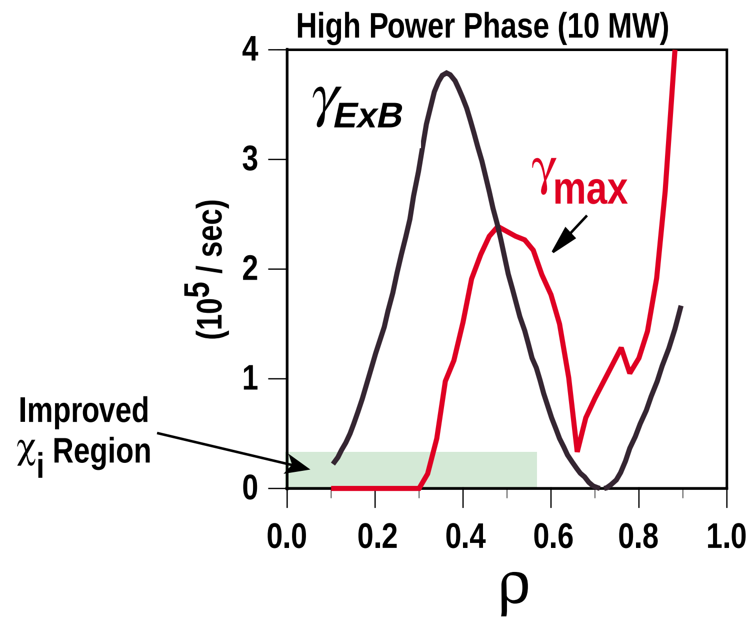
ExB Shear Flow Is A Leading Candidate To Explain Stabilization of Microturbulence

- *NCS plasmas with L-mode edges have internal transport barriers*
- *In the low power phase, $\gamma_{max} > \gamma_{ExB}$ over most of the plasma*
- *In the high power phase, $\gamma_{max} < \gamma_{ExB}$ inside $\rho = 0.5$*





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ExB Flow Shear and Turbulence

- *Effect of ExB flow shear can be quantified by comparing the shearing rate to the turbulence growth rates*
- *ExB shear rate can determined by Doppler shift shear rate (Waltz, et al., Phys. Plasmas 1, 2229 (1994))*

$$\gamma_{ExB} = \frac{r}{q}\frac{\partial}{\partial r}\left(\frac{qE_r}{rB_\phi}\right)$$

where the radial electric field E_r from force balance is

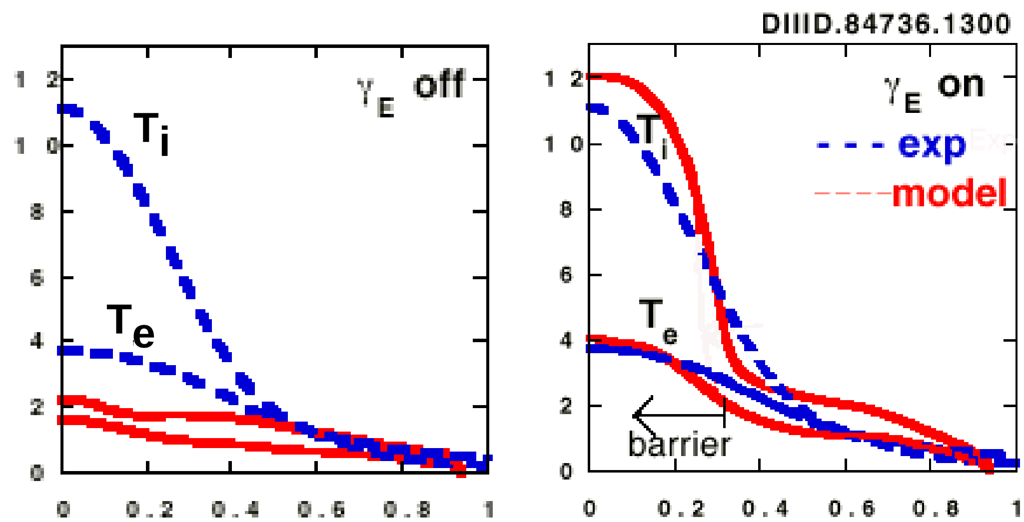
with $v_{\theta i}$ computed from neoclassical theory.

$$E_r = \frac{\nabla P_i}{Z_i e n_i} - \mathbf{v}_{\theta i} B_\phi + \mathbf{v}_{\phi i} B_\theta$$

- *It has been shown that turbulent transport is suppressed when $\omega_{ExB} > \gamma_{max}$ (Waltz, et al., Phys. Plasmas 1, 2229 (1994))*
  - *γ_{max} is the maximum linear growth rate calculated from your favorite stability code*

Toroidally Driven ExB Shear Stabilization Plays A Dominant Role in the Formation of Internal Transport Barriers in DIII-D NCS Discharges

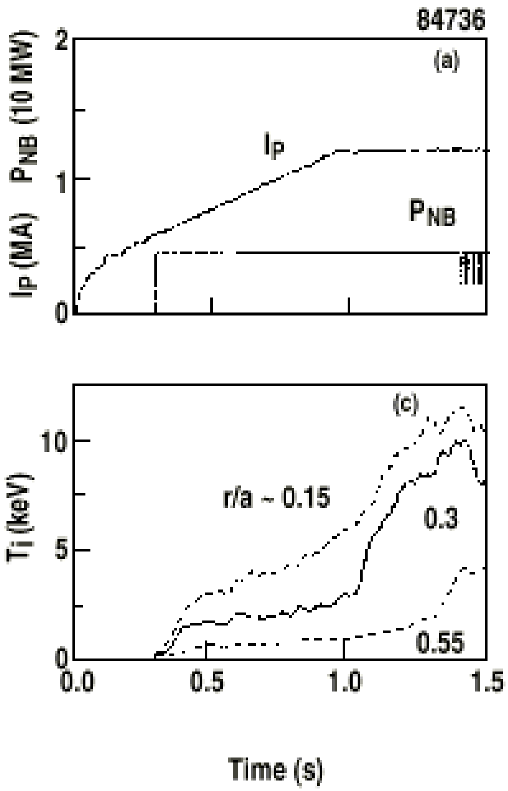
- ***Predicted temperature profiles using GLF23 model demonstrate that the thermal transport is signficantly reduced by ExB shear … primarily toroidal rotation driven***
- ***α-stabilization and T_i/T_e effects contribute but play less of a role***

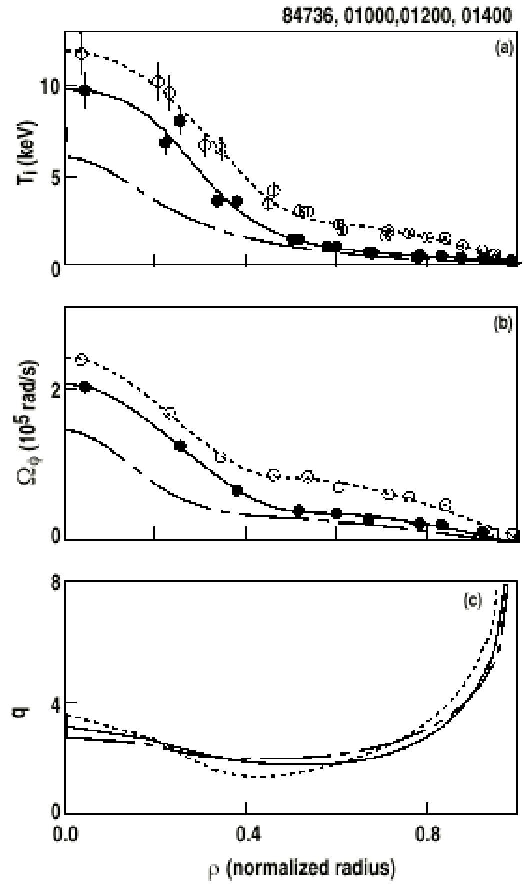


- ***Prior simulations have been successful, but did not compute ExB shear self-consistently and did not evolve the toroidal momentum***

Simulations Were Conducted Using DIII-D #84736 as the Reference NCS Discharge with an L-mode Edge

- ***B=2.1T, I=1.2MA, P=4.6MW, $\bar{n}_e$=2.0x10^{19}m^{-3}*** ***(Lao, et al., Phys. Plasmas 3, 1951 (1996)***
- ***Reference time of 1.30 secs after transport barrier formation was selected***





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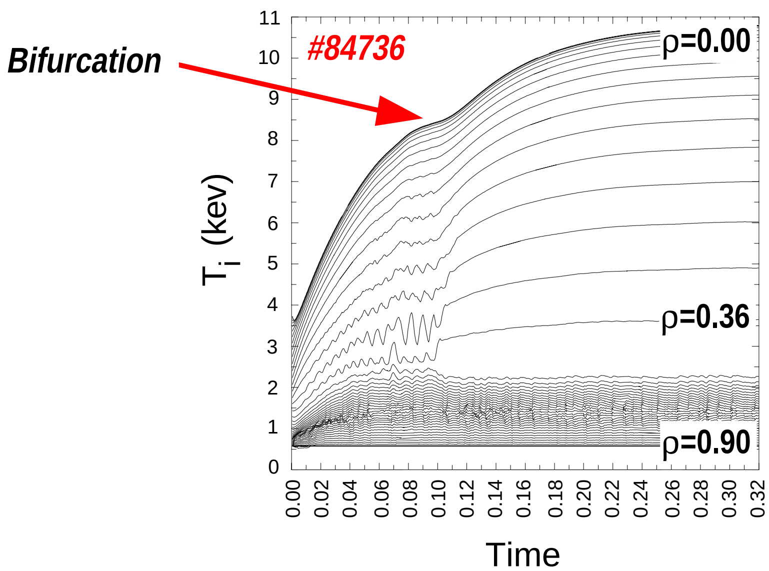
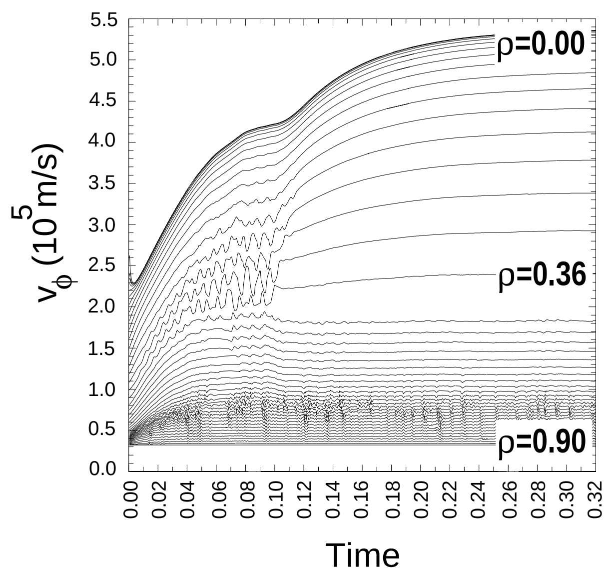
Dynamic Formation of an Internal Transport Barrier Resulting From an ExB Driven Bifurcation Has Been Demonstrated Using the GLF23 Model For a DIII-D NCS Discharge With an L-mode Edge

- ***The thermal and toroidal momentum transport were evolved while self-consistently computing ExB shear (toroidal rotation term only)***
- ***Using the PTOR time-dependent solver within the MLT code, the simulations were carried out taking the sources, sinks, equilibrium, and density profile from a power balance analysis with experimental boundary conditions enforced at $\hat{\rho}$ =0.9***





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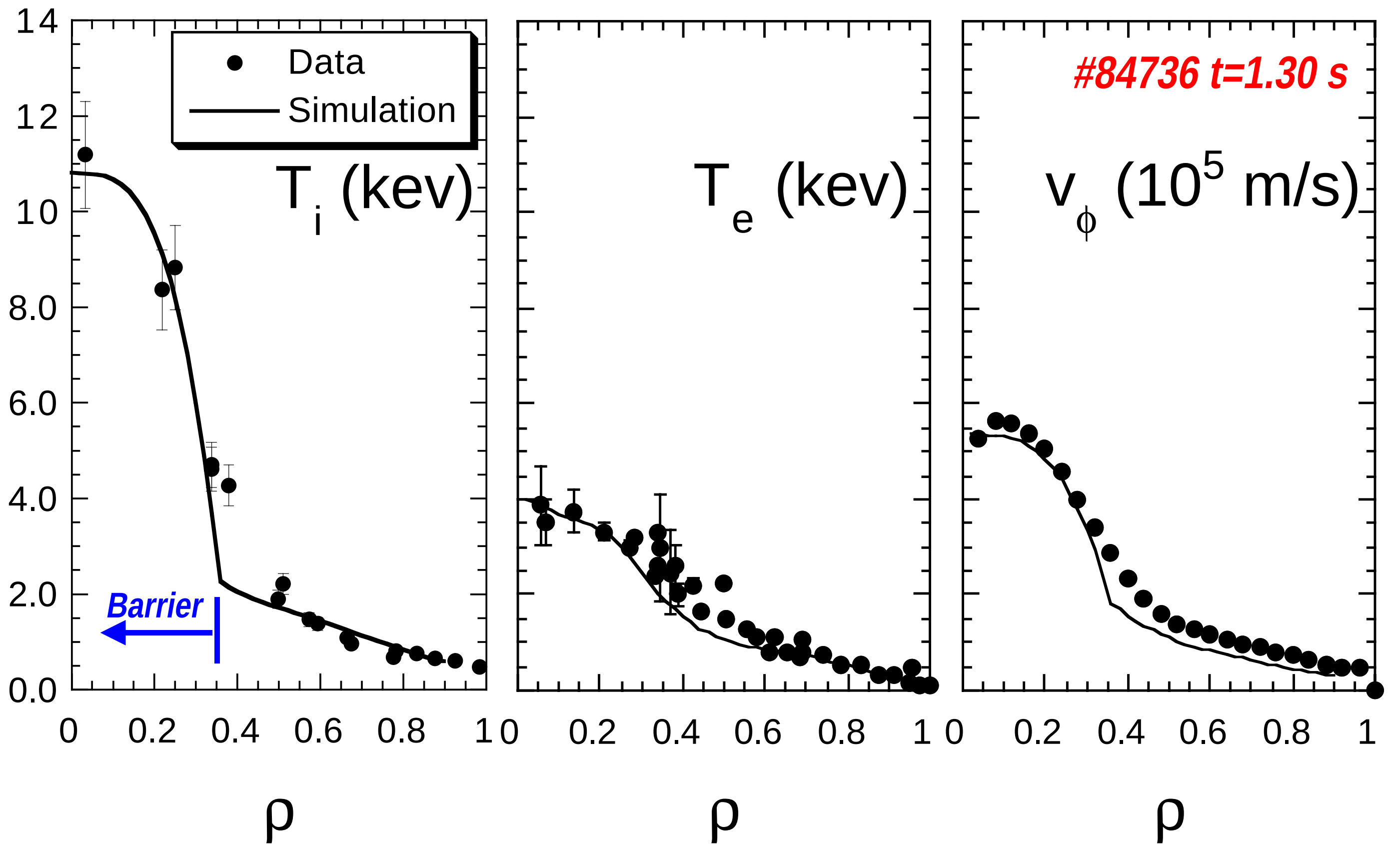
Predicted Steady-state Temperature and Toroidal Velocity Profiles Show Agreement with Experimental Data



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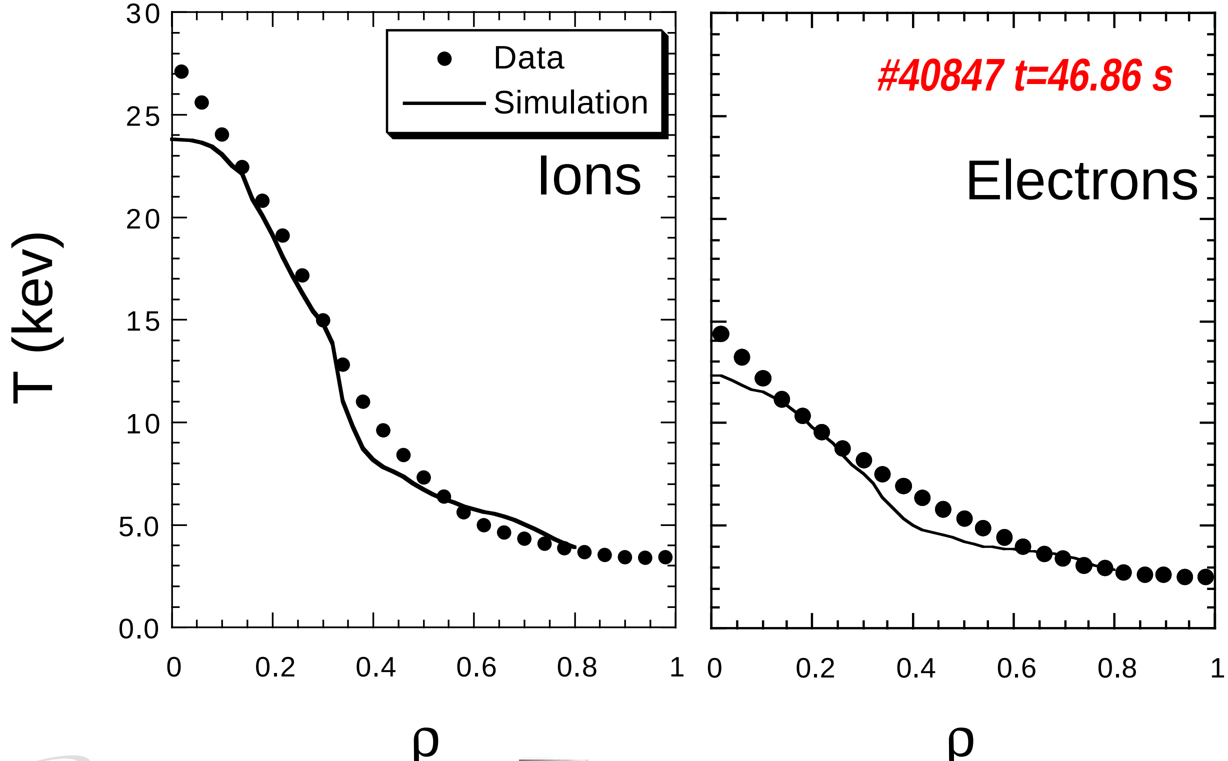
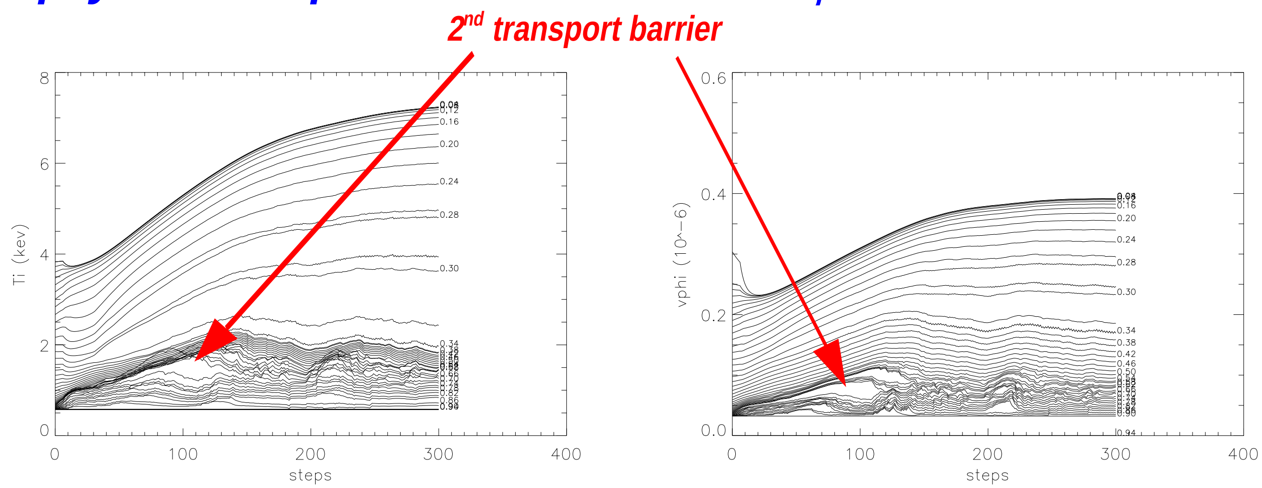
For the JET Optimised Shear Discharges, the Level of ExB Shear Stabilization Needs to be Significantly Increased to Yield Agreement With Experimental Profiles Using GLF23 Model

- ***With toroidal velocity taken from experiment, $\gamma_{ExB} = 2.65\, \gamma_E^{nominal}$***
- ***While the mode growth rates are comparable to DIII-D NCS discharges, the nominal predicted ExB shear rate is lower***



The GLF23 Model Has Been Extended to Real Geometry

- ***With the circular model, including ∇P term causes ExB shear rate to exceed the maximum linear growth rate where it is at a local minimum. The ion transport and momentum viscosity are reduced to neoclassical levels and an unphysical transport barrier is formed near $\rho = 0.74$.***

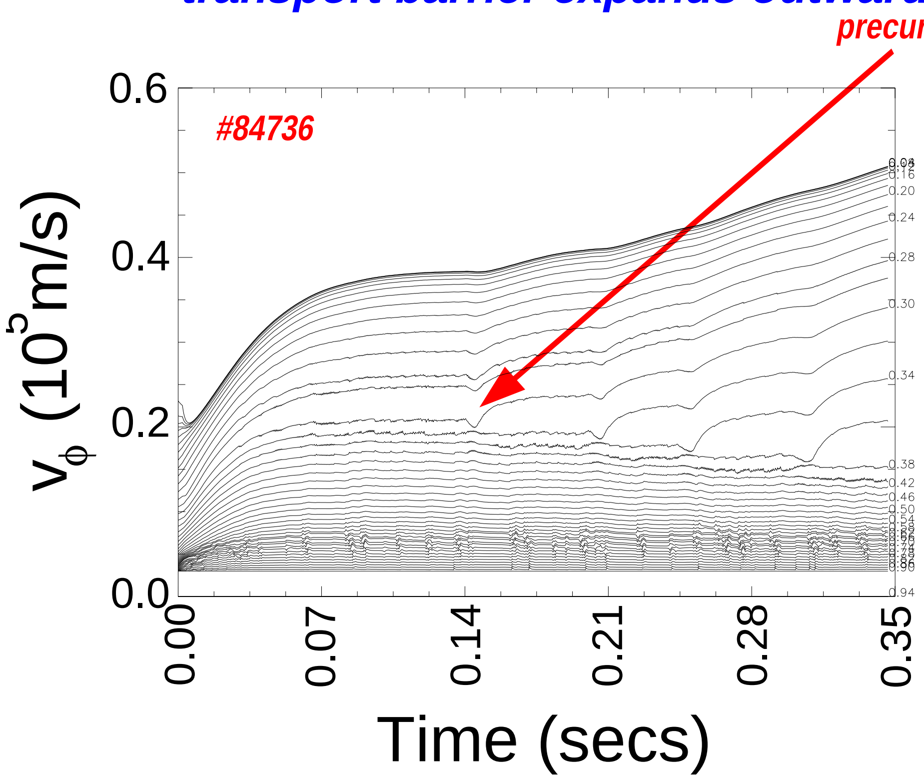


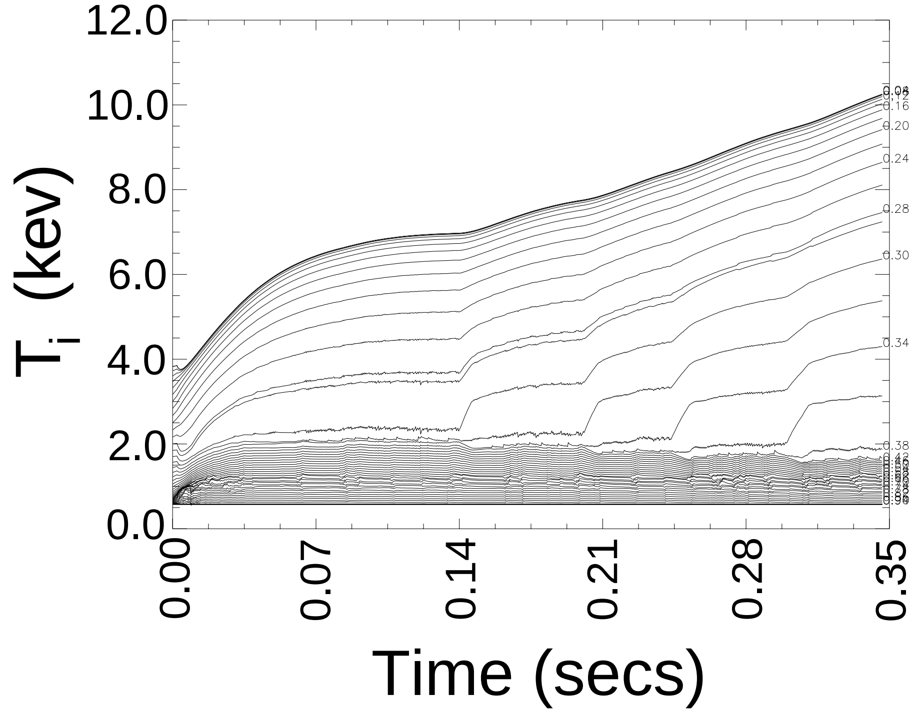
- ***In DIII-D NCS discharges, diamagnetic (∇P) term is significant in the region outside the leading edge of the transport barrier.***
- ***Both the transport model and the ExB shear formula were derived for circular geometry. To convert the models to real geometry, the toroidal magnetic field is replaced by an effective field***

$$B_\phi \Rightarrow B_\phi^{eff} = B_\phi \frac{\rho}{r}\frac{d\rho}{dr}$$

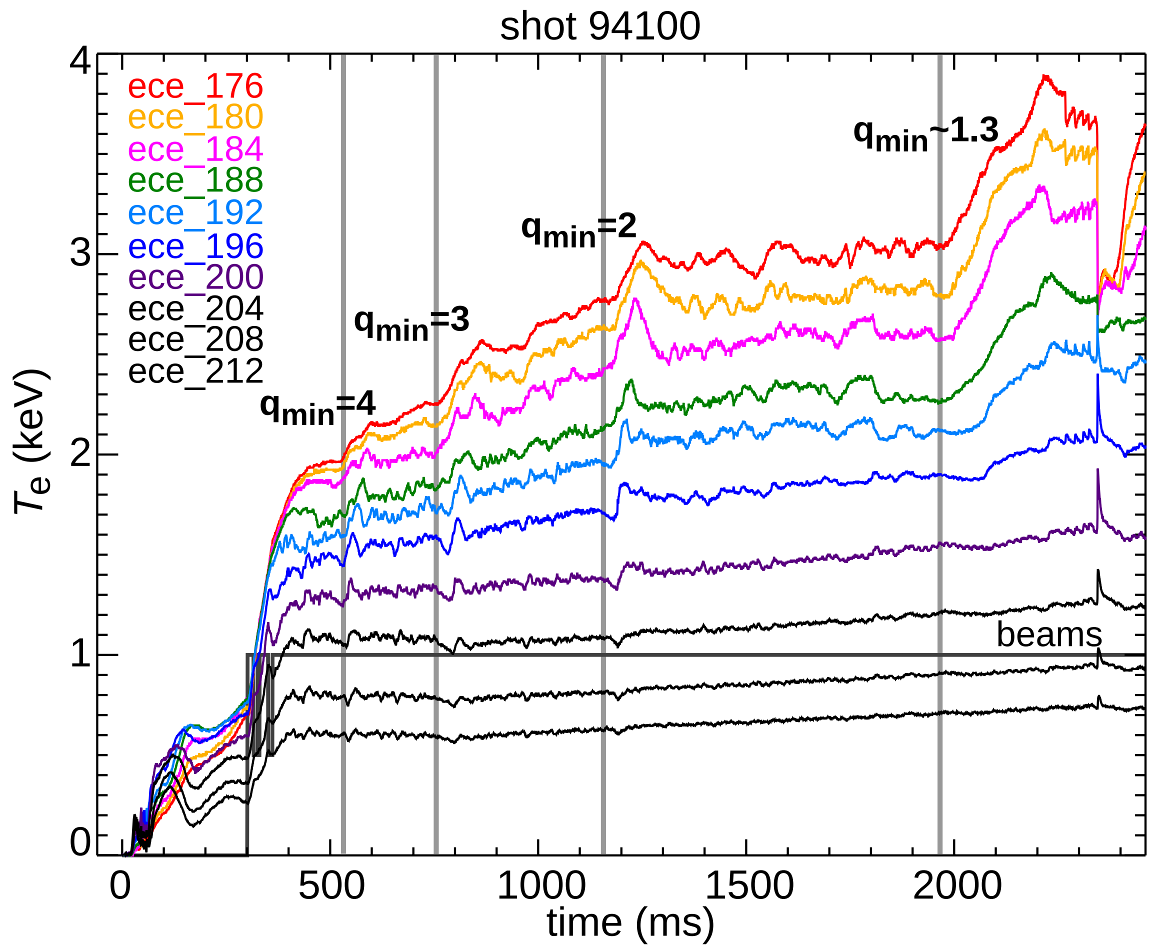
With Real Geometry Correction, ExB Shear Reduced in Outer Plasma and Unphysical Barrier Formation Avoided

- ***With all terms included in ExB shear, dithering at bifurcation point is not seen unlike case with purely toroidal rotation driven ExB shear***
- ***Multiple step-wise momentum bifurcations (and resulting heat flux bifurcations) observed as profiles evolve and leading edge of the transport barrier expands outward … precursor is evident***





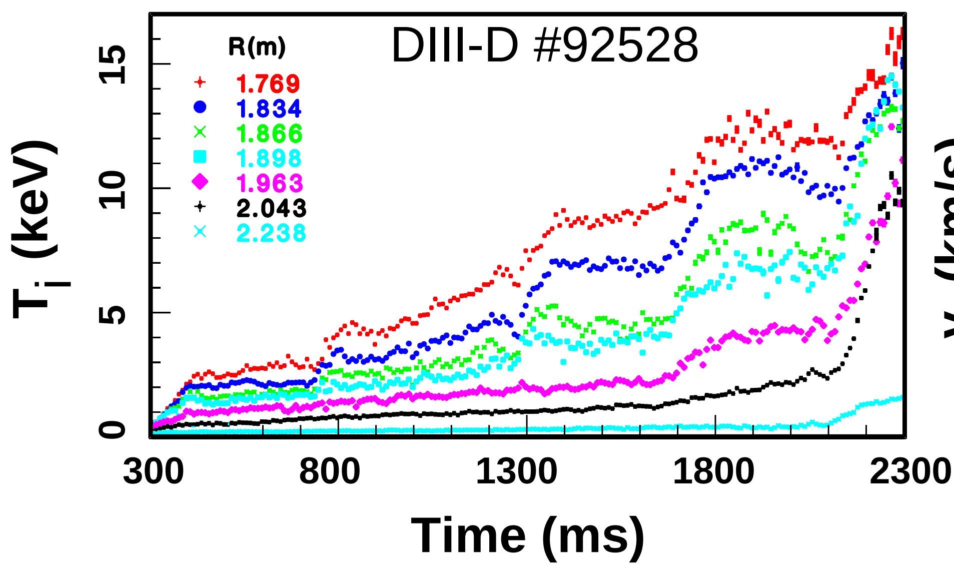
Multiple Step-wise Barrier Formations Are Observed in DIII-D Experiments

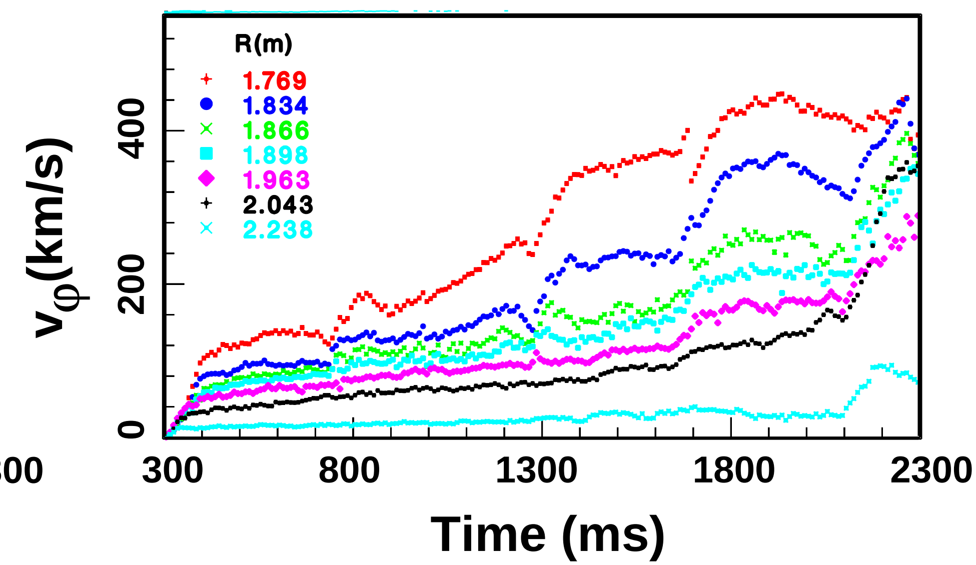


- ***Data courtesy of M. Austin***

Multiple Step-wise Barrier Formations Are Observed in DIII-D Experiments

- ***Simultaneous jumps in both T_i and v_φ observed during I_p ramp at constant heating power***

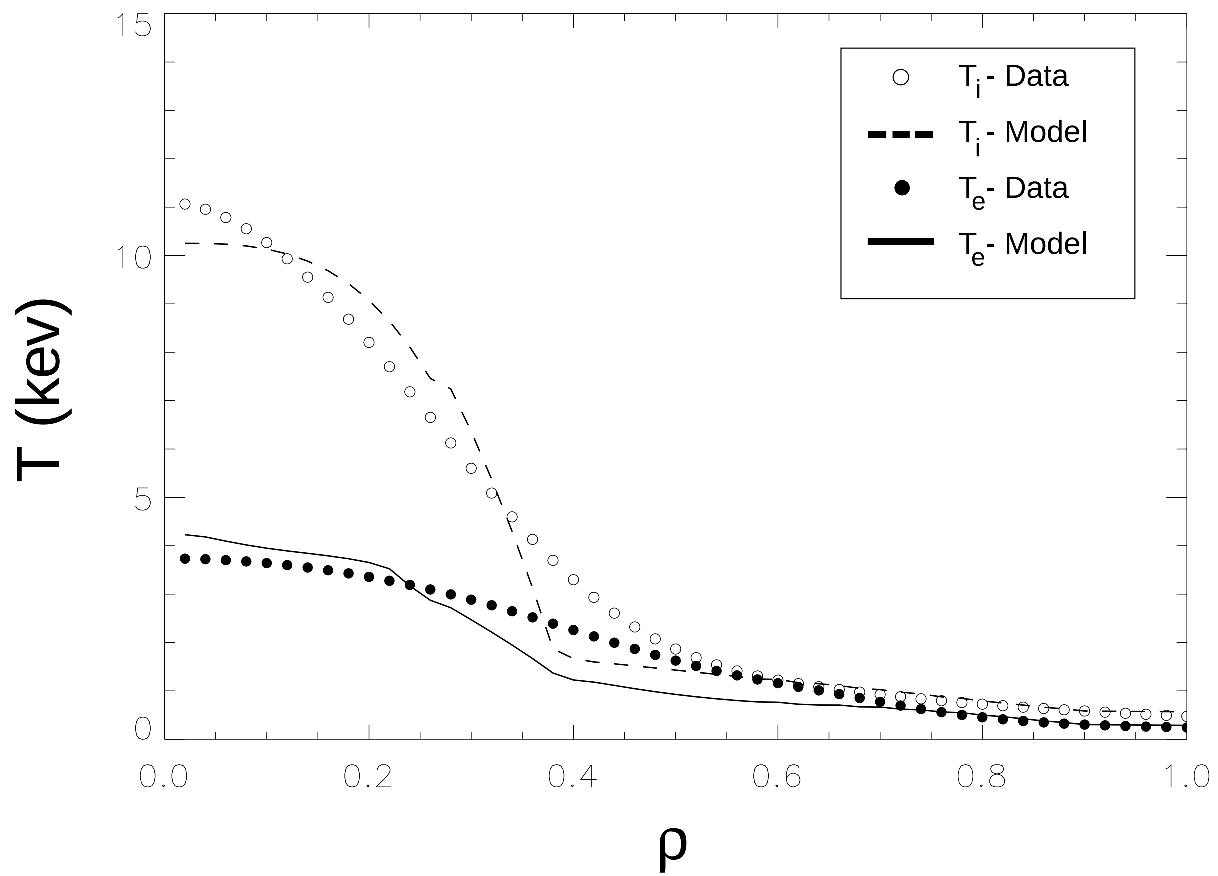




K. Burrell, 1997 H-mode workshop

Predicted Temperature Profiles With Real Geometry Correction Show Agreement with Experimental Data

- ***Results are comparable to case with purely toroidal rotation driven ExB shear but now including v_θ and ∇ P terms in E_r***



Conclusions

- ***The dynamic formation of an internal transport barrier resulting from a ExB shear driven bifurcation has been demonstrated in a simulation of a DIII-D NCS discharge having an L-mode edge***
  - ***The GLF23 model has been successfully used to follow the simultaneous evolution of thermal and toroidal momentum transport while self-consistently computing the effects of rotational shear and alpha stabilization***
- ***The level of ExB shear stabilization needed to be enhanced by a factor of 2.65 for JET optimised shear discharges***
  - ***Growth rates are comparable to DIII-D NCS discharge but predicted ExB shear rate is significantly lower***
  - ***∇P term needs to be investigated for JET OS discharges***
- ***For the case with purely toroidal rotation driven ExB shear, oscillations in the temperature and toroidal velocity profiles at the leading edge of the transport barrier are observed as the model approaches a bifurcated state***

Conclusions (cont.)

- When including all terms in γ_{ExB} , circular form of GLF23 model predicts the formation of unphysical transport barrier in outer half of the plasma where γ_{max} is at a local minimum
- Adding real geometry correction to the GLF23 model and to the formula for γ_{ExB} reduces stabilization by a factor of 2-3 outside of ρ=0.5 and 2^{nd} barrier is avoided.
  - The level of ExB shear stabilization needs to be reduced by a factor of 1/3 (from 1 -> 0.6) to be consistent with experimental profiles for the DIII-D NCS discharge considered
  - With real geometry correction, dithering about bifurcation point is not observed and internal barrier expands with multiple step-wise bifurcations
- The ETG mode is predicted to be unstable and keeps the electron transport at anomalous levels in the interior region where the ion transport is suppressed.