INCREASED UNDERSTANDING OF THE DYNAMICS AND TRANSPORT IN ITB PLASMAS FROM MULTI-MACHINE COMPARISONS

by

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SUMMARY

- Our understanding of the physics of ITBs is being increased by analysis and comparisons of experimental data from many tokamaks worldwide.

- An international ITB database consisting of scalar and 2-D profile data on ITB plasmas has been developed
  - To determine the requirements for formation and sustainment of ITBs
  - To perform tests of theory-based transport models in an effort to improve their predictive capability

- Specific discharges from three major tokamaks (DIII–D, JET, JT-60U) were selected to better understand the influence of the q-profile on ITBs
  - Selected a low shear or monotonic q-profile discharge together with a high magnetic shear discharge from each machine

- Tests of several transport models (JETTO, Weiland model) using the 2-D profile data indicate there is only limited agreement between model predictions and experimental results for the selected discharges

- Gyrokinetic stability analysis of the selected discharges indicates that the ITG mode growth rates generally decrease with increased negative shear and that the E × B shear rate is comparable to the linear growth rates at the location of the ITB

PURPOSE OF THE ITPA GROUP ON TRANSPORT AND THE ITBDB WORKING GROUP

- Examination and compilation of experimental results on transport from many machines worldwide to better understand the physics of ITB formation and sustainment
- The development of an international database on ITB experimental results to determine the requirements for the formation and sustainment of ITBs
- Determining and performing comprehensive tests of theory based transport models and simulations using the international ITB database (ITBDB) – critical for model validation and improving predictive capability
- Identifying experiments to address and resolve critical issues in transport and ITB physics
- Facilitating inter-machine ITB experiments and comparisons

MOTIVATION FOR ITPA AND ITBDB WORKING GROUPS

- There is a wide variety of experimental results on plasma transport and ITB's from many machines worldwide
  - Need to assess large variety of results and improve our understanding of important transport issues
  - Define common definitions for ITBs
  - Assess reactor compatibility and develop reactor scenarios
- Provide a depository for ITB data for access by experimentalists and modelers
  - Development of international ITB database
  - Determine key trends from data, e.g., effect of q profile, momentum input, etc.
- Improve predictive capability of transport models
  - Need to test and validate models with experimental data
- Find solutions to critical issues such as impurity transport, electron transport, fueling, core-edge integration, profile control, etc.

MOTIVATION FOR THIS PAPER

- The formation and sustainment of ITBs is very dependent on behavior of the q-profile in many devices
  - Need to examine discharges with significant differences in q-profiles (e.g., positive shear to strong negative shear from many devices

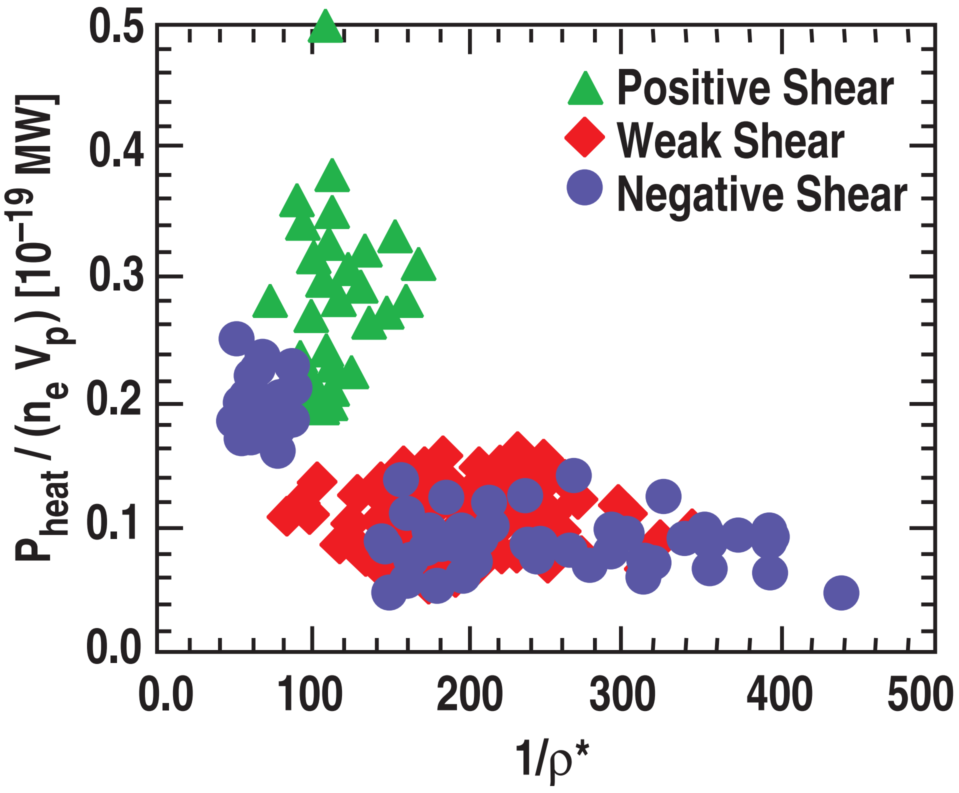
- Need to improve the predictive capability of transport models
  - Examine the level of agreement between model predictions and experimental results for selected discharges with significantly different q-profiles

- Determine the variation in the E × B shearing rate and the ITG/TEM mode growth rates for the selected discharges in order to evaluate the relative influence of the q-profiles

- The work described in this paper is expandable
  - By increasing the number of models to be tested
  - By examining more issues relevant for reactor scenarios

TARGET PLASMAS WITH WEAK OR NEGATIVE MAGNETIC SHEAR REQUIRE LOWER HEATING POWER FOR ITB FORMATION

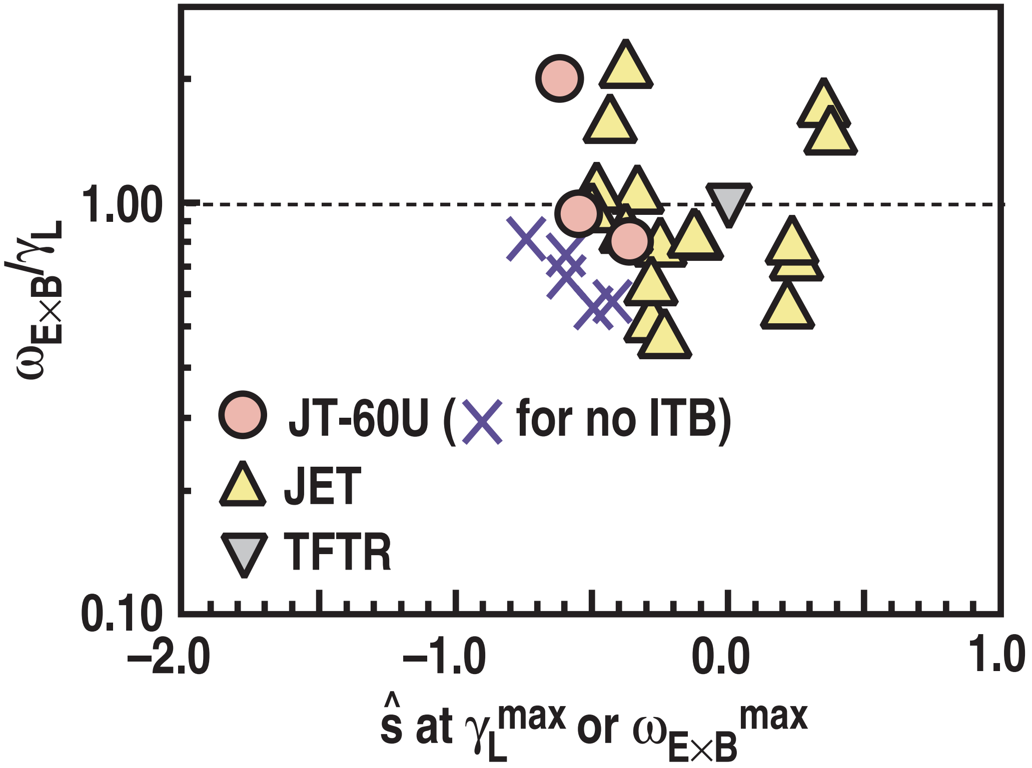
- Analysis of data from ITB database [1]
- Heating power per particle just prior to ion-ITB formation (for dominantly ion heated plasmas) (n_e = plasma density; V_p = plasma volume)
- Plasmas with weak or negative magnetic shear are more favorable for ITB formation



[1] G.T. Hoang et al., Proc. 29th EPS Conference, Montreux, Switzerland (2002)

THE E × B SHEARING RATE IS CLOSE TO THE MAXIMUM LINEAR GROWTH RATE AT THE TIME OF ITB FORMATION

- Using data from ITB database [1]
- Data at time of ITB formation
- For ion-ITB with dominant ion heating
- Indicates strong influence of E × B flow shear in several devices



[1] T. Fukuda et al., Proc. 29th EPS Conference, Montreux, Switzerland (2002)

PREDICTIVE SIMULATIONS USING TRANSPORT MODELS: JETTO AND WEILAND MODEL

- Used 2-D profile data from ITBDB for DIII–D, JET and JT-60U
- Examined pairs of discharge from each device
  - With weak negative shear or monotonic q profile
  - Strong negative shear
- JETTO is based on an empirical mixed Bohm/gyroBohm transport model [1]

Bohm term:

$$\chi_{\mathrm{Bohm}} \propto \frac{|\nabla nT|}{nB} q^2 \frac{|\nabla Te|}{T} H \left(0.05 + s - C \frac{\omega_{E\times B}}{\gamma}\right)$$

GyroBohm term:

$$\chi_{\mathrm{gyroBohm}} \propto \frac{|\nabla Te|^{3/2}}{B^2} \frac{|s|}{1+|s|}$$

Where H (x) is a Heaviside step-function, s is magnetic shear, C is an adjustable factor, γ is the growth rate, $\omega_{E\times B}$ is the shearing rate

PREDICTIVE SIMULATIONS USING TRANSPORT MODELS: JETTO AND WEILAND MODEL (CONTINUED)

- Weiland model is an advanced fluid model [2] whereby

$$\chi \propto \sum_{k} \frac{\gamma_k - \omega_{E\times B}}{k_\perp^2} H\left(\gamma_k - \omega_{E\times B}\right)$$

Where H (x) is a Heaviside step-function, γ_k is the characteristic growth rate and k is the characteristic perpendicular wave-vector

[1] G. Cennachi and A. Tami, JET-IR (88), 03 (1988)

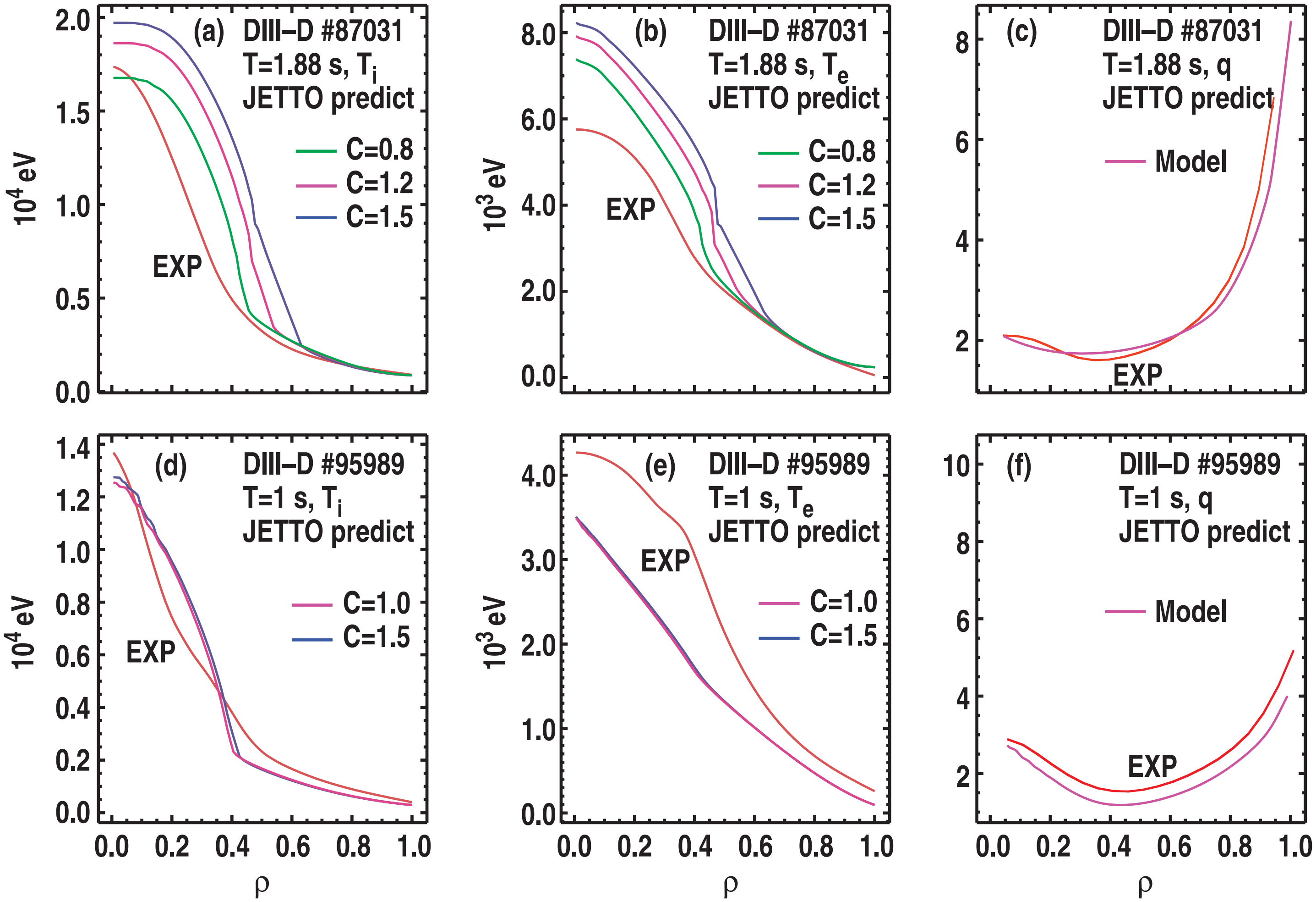
[2] J. Weiland "Collective Modes in Inhomogeneous Plasmas"
Institute of Physics Publishing, Bristol and Philadelphia (2000)

JETTO PREDICTIVE MODELING FOR DIII–D DATA

- DIII–D discharge 87031 – weak negative central shear
- DIII–D discharge 85989 – strong negative central shear (NCS)
- Only reasonable agreement with T_i profile for strong NCS case

Weak Shear →

High Negative Shear →



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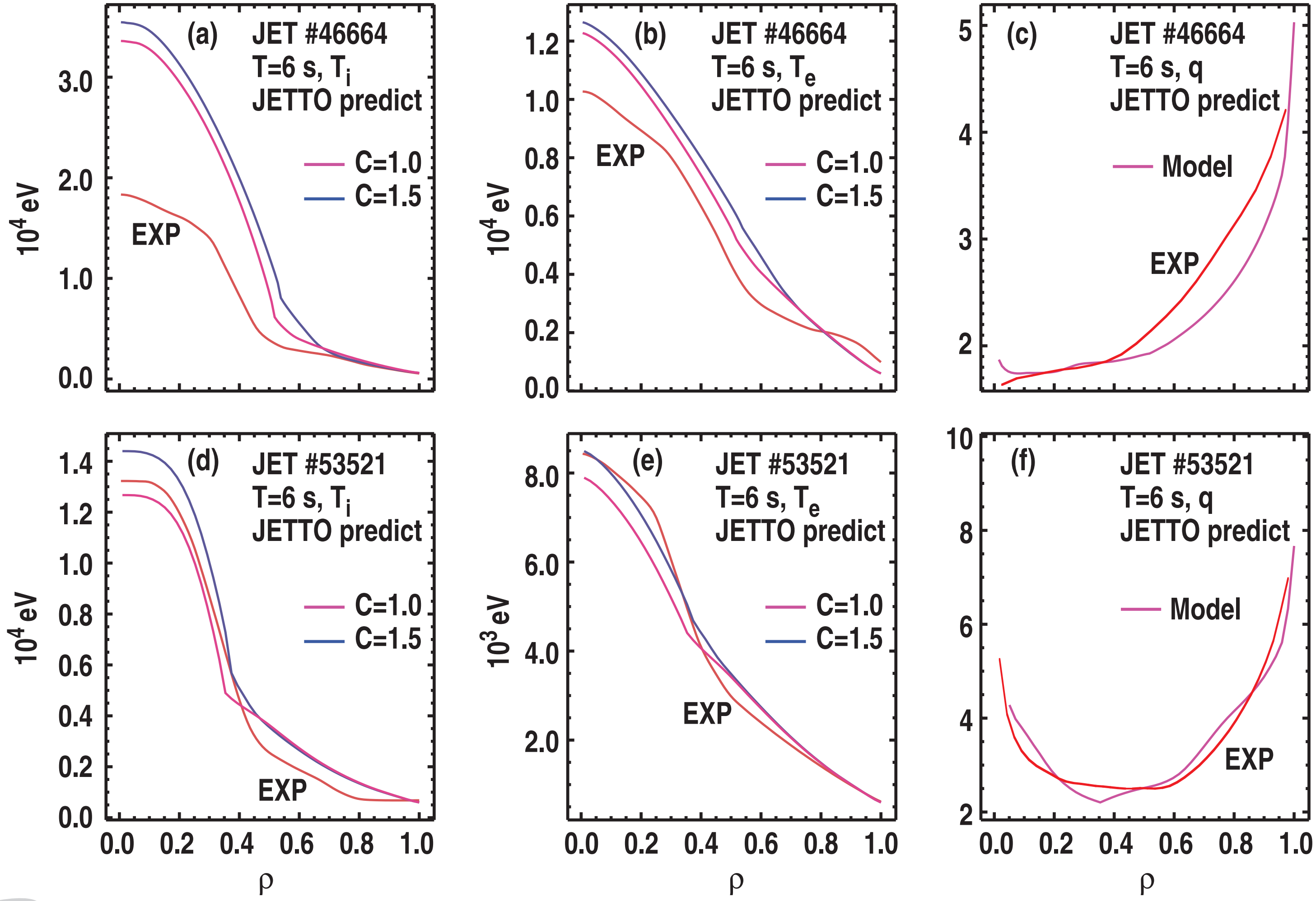
JETTO PREDICTIVE MODELING FOR JET DATA

- JET discharge 46664 – weak positive shear
- JET discharge 53521 – strong negative shear
- Good agreement with T_i and T_e profiles only for strong negative shear case

Low Shear

High Negative Shear



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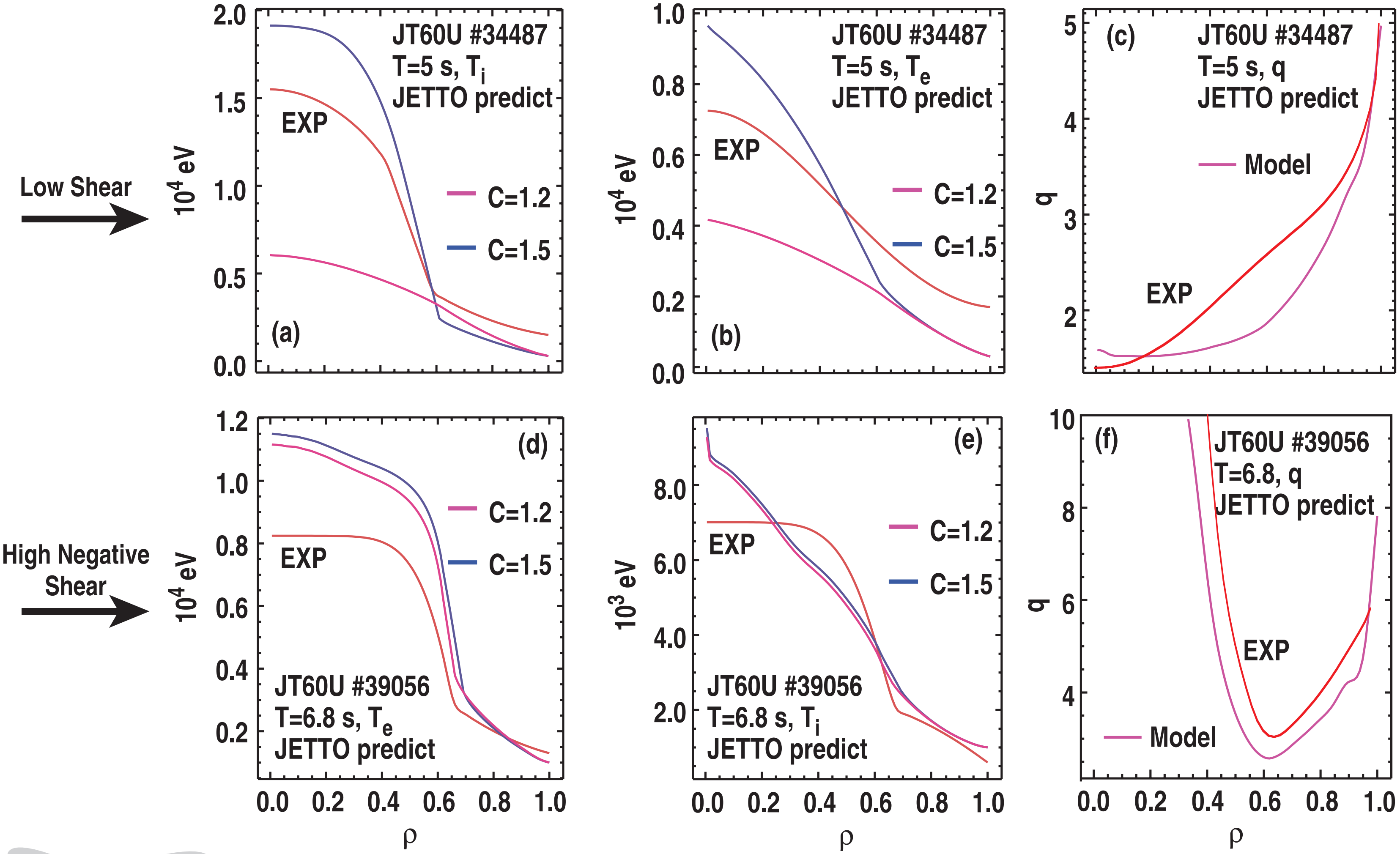
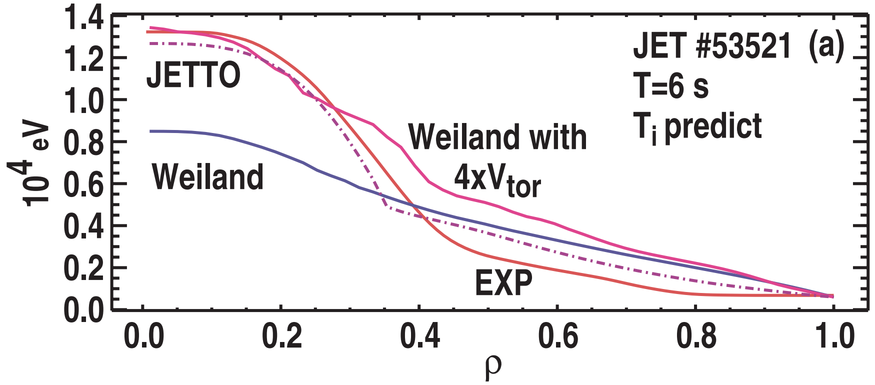
JETTO PREDICTIVE SIMULATIONS FOR JT-6OU DATA

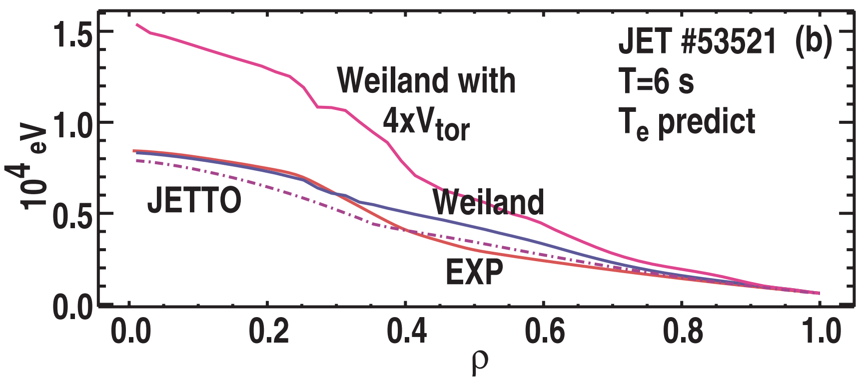
- JT-6OU discharge 34487 – weak positive shear
- JT-6OU discharge 39056 – strong negative shear
- Poor agreement for all cases



COMPARISON BETWEEN JETTO AND WEILAND MODELS USING EXPERIMENTAL DATA FROM JET

- For JET strong NCS discharge – 53521
- Weiland model fails to produce the T_i or T_e ITBs
- Increasing the toroidal rotation by factor of 4 produces the T_i ITB, but grossly overestimates the T_e profile
- Comparisons also performed for DIII–D and JT-60U discharges





SIMULATION RESULTS

- Overall there is limited agreement between the predictive simulations and the experimental data

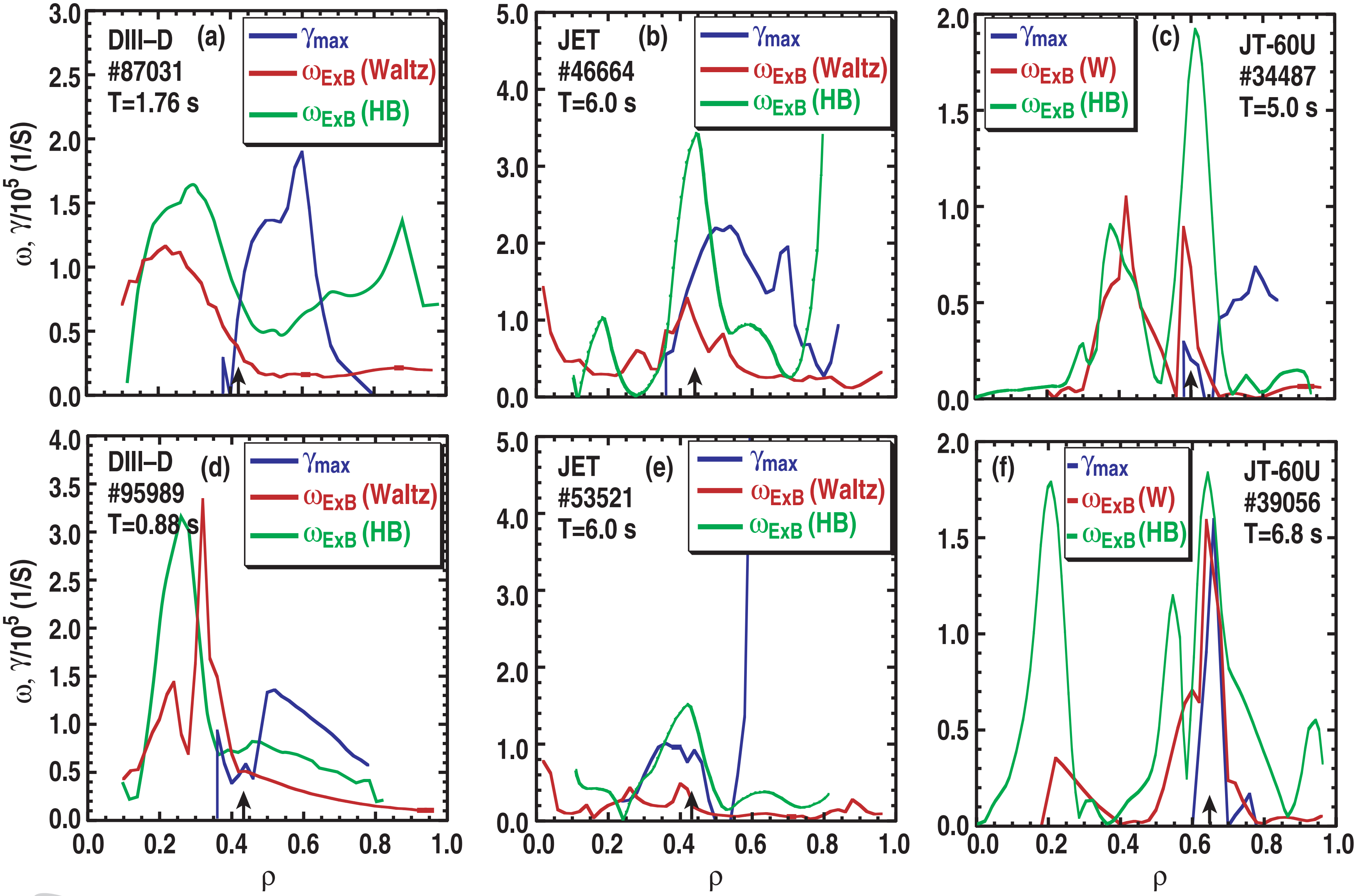
- Fair agreement is obtained in predicting the T_i profiles (c.f. to T_e profiles) by JETTO for strong NCS discharges

- Predictions for the T_e profiles are very poor
  - JETTO does not include effects such as alpha stabilization

- JETTO overestimates both the T_i and T_e profiles for low magnetic shear discharges in DIII–D and JET
  - Preference for reduced transport in the presence of low magnetic shear and moderate levels of plasma rotation

- Weiland model is unable to produce the experimental T_e and T_i profiles for JET discharges

THE E × B SHEARING RATE IS COMPARABLE TO THE MAXIMUM LINEAR GROWTH RATE (ITG/TEM) AT THE LOCATION OF THE ITB



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SUMMARY OF GYROKINETIC STABILITY ANALYSIS

- ITG/TEM linear growth rates calculated using the GKS code [1]

- E × B shearing rates from Hahm and Burrell [2] and Waltz et al. [3]
  - Neoclassical v_θ used in evaluation of Er

- Generally the ITG growth rates tend to decrease with increased negative magnetic shear
  - More favorable for ITB formation for given E × B shearing rate

- Differences between the Hahm-Burrell and Waltz shearing rates result from:
  - Flux-surface averaged evaluation for Waltz and outside midplane for Hahm-Burrell
  - Pre-derivative (r/q) factor for Waltz which can be significantly smaller in elongated plasmas than the corresponding factor (RBp/B) used in Hahm-Burrell

[1] M. Kotschenreuther, et al., Comp., Phys. Comm. 88, 128 (1995)

[2] T.S. Hahm and K.H. Burrell, Phys. Plasmas 2, 1648 (1995)

[3] R.E. Waltz et al, Phys. Plasmas 4, 2482 (1997)

CENTRAL BEAM DEPOSITION AND NEGATIVE MAGNETIC SHEAR AID ITB FORMATION

- Power requirements for ITB formation are very dependent on profile data such as the power deposition and q profiles
  - Makes scaling relationships very difficult to determine

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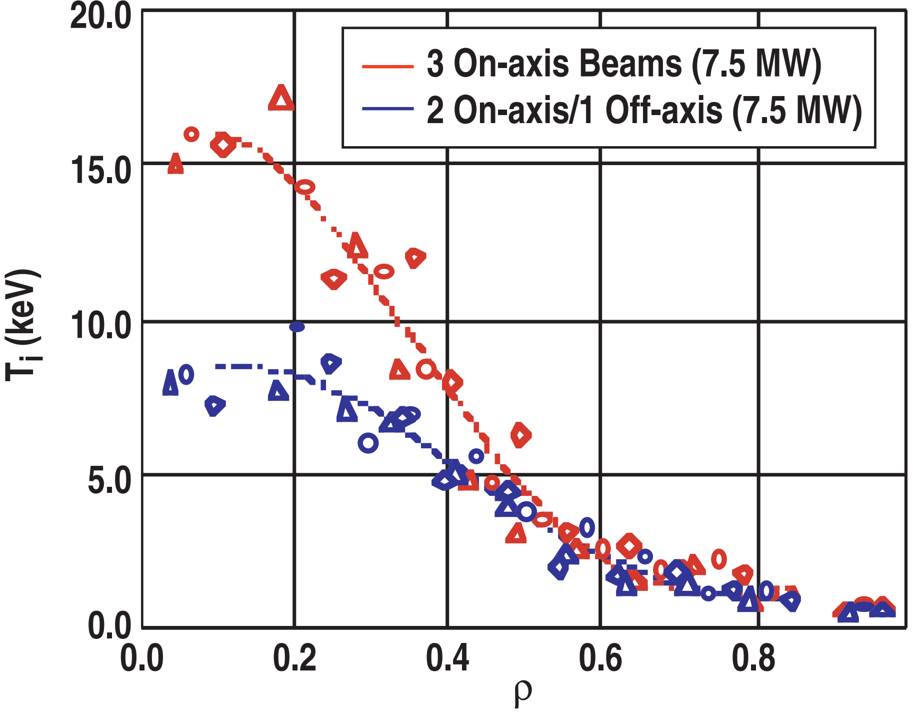
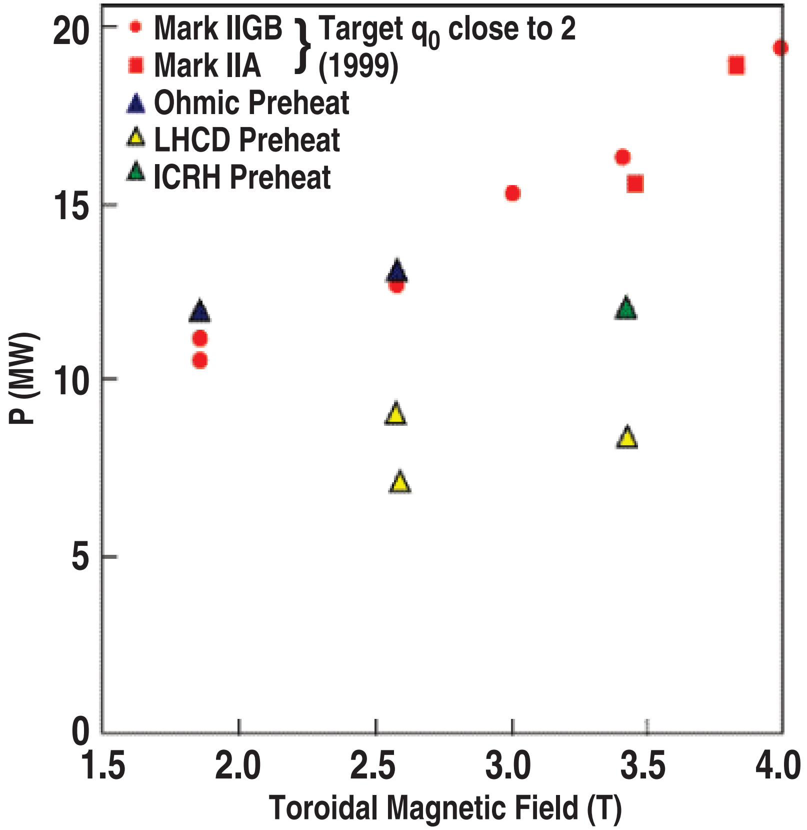
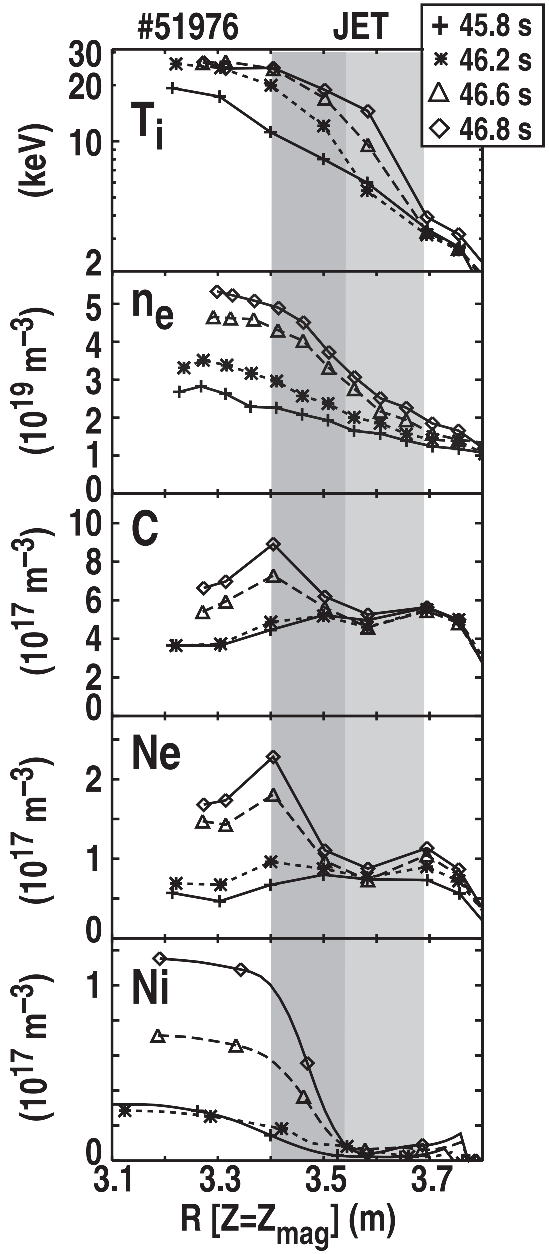


JET



IMPURITY ACCUMULATION IS A CRITICAL PROBLEM FOR ITB DISCHARGES

- Data from JET
- Before ITB formation, impurity density profiles are hollow or slightly peaked
- On ITB formation, impurity density peaking increases with impurity charge Z (weakest for C and strongest for Ni)
- Steep impurity density gradients are inboard of the location of the T_i gradients
- Constant Ne puff for t > 44s. Central z_{eff} = 3.5 at t= 46.9 s (dominated by Ni)



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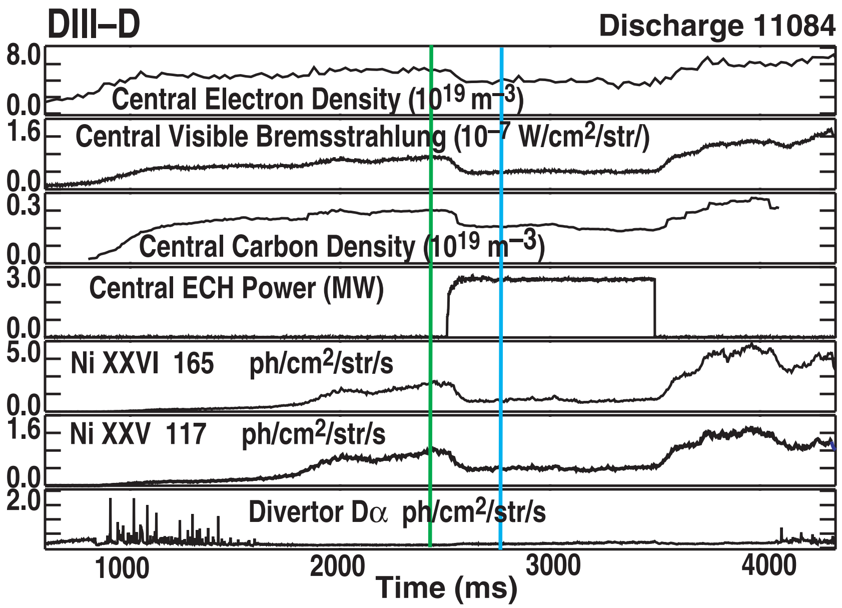
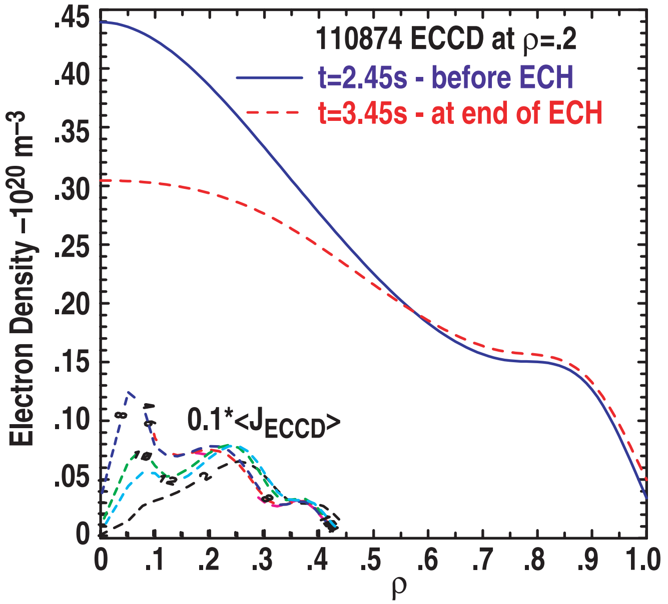
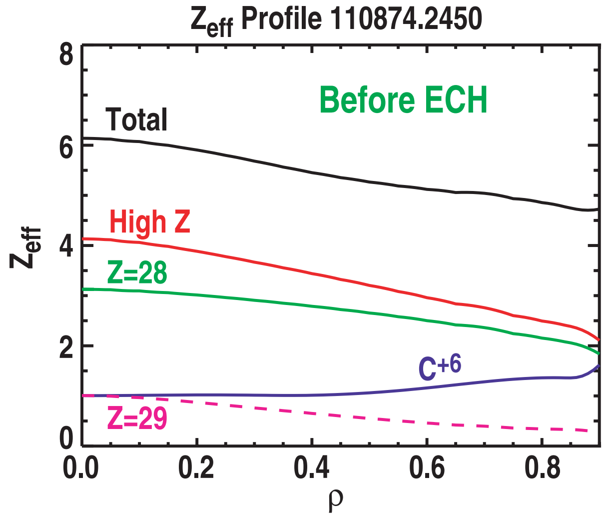
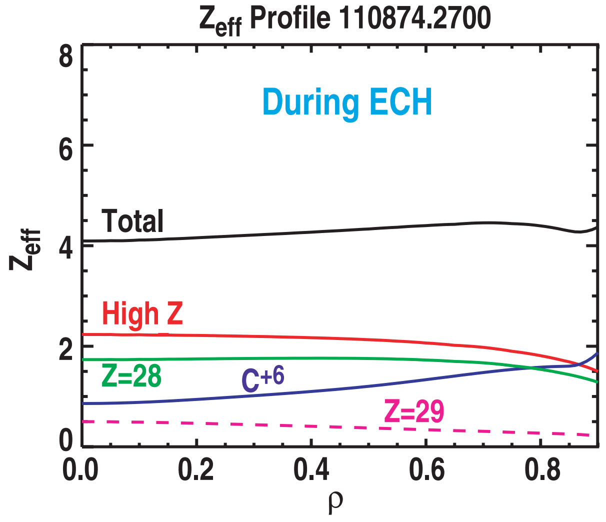
CENTRAL ECH/ECCD CAN BE USED TO CONTROL THE ELECTRON DENSITY AND IMPURITY DENSITY PROFILES IN ITBs

- QDB plasmas have peaked density profiles
- Central ECH/ECCD decreases the central electron density and Z_{eff} (from Ni and Cu) decreases by a factor of 2

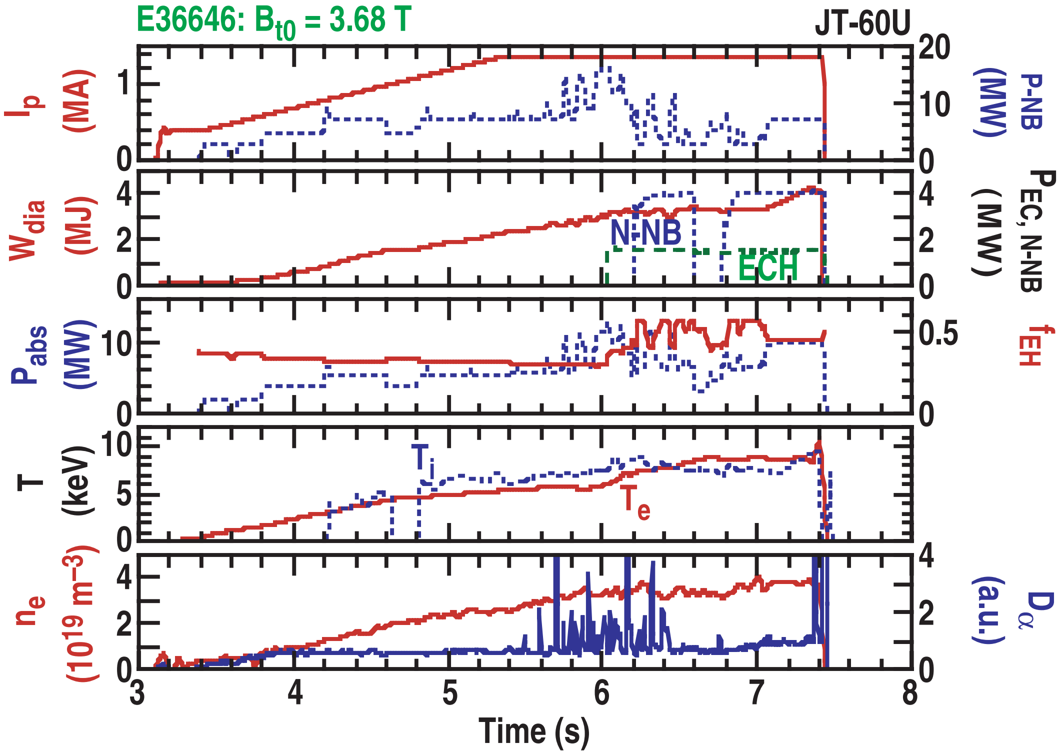


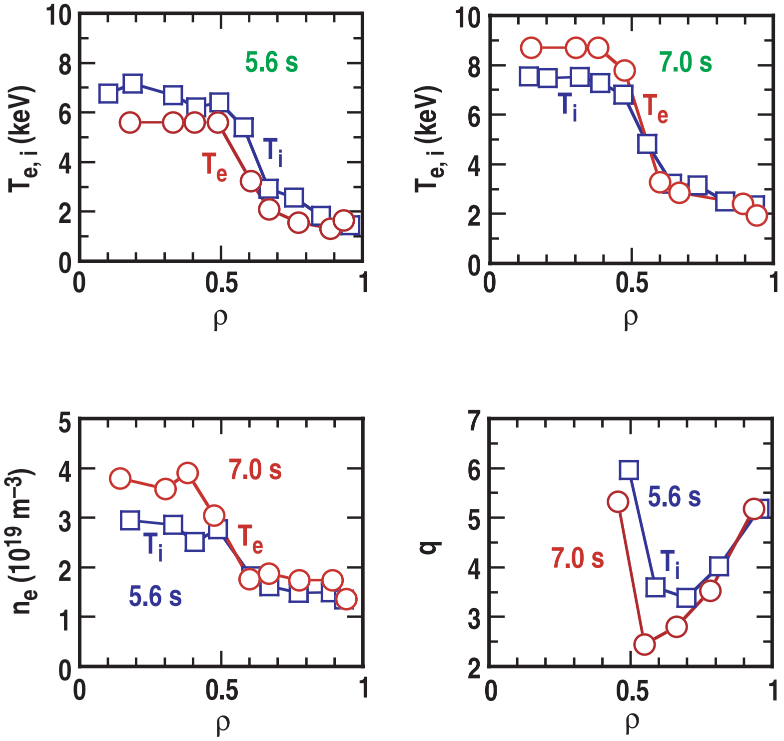






STRONG ITBs WITH $T_e = T_i$ HAVE BEEN FORMED IN REVERSE MAGNETIC SHEAR DISCHARGES





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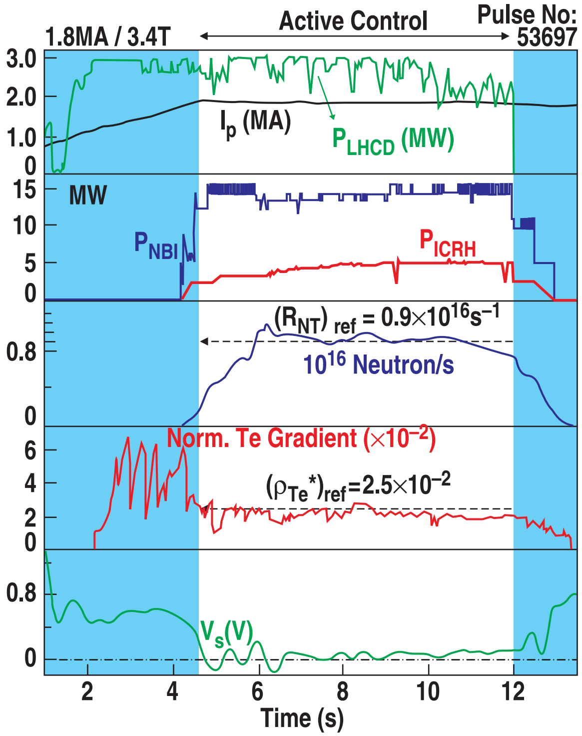
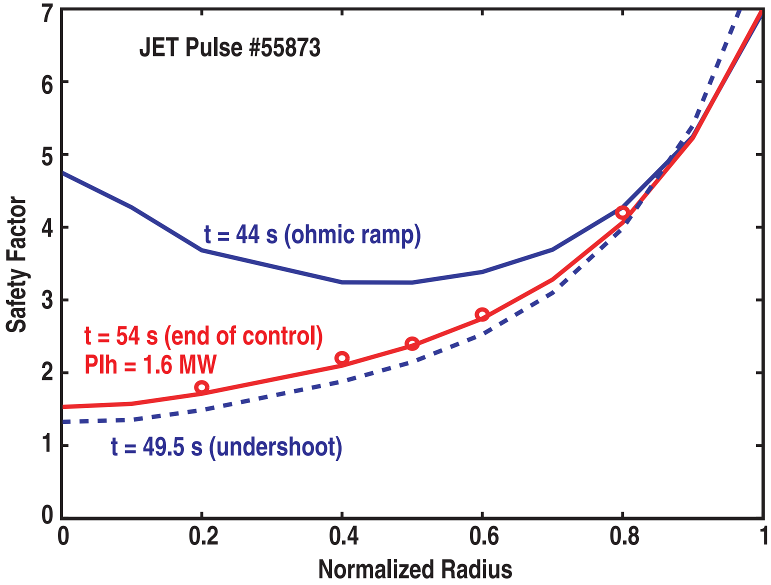
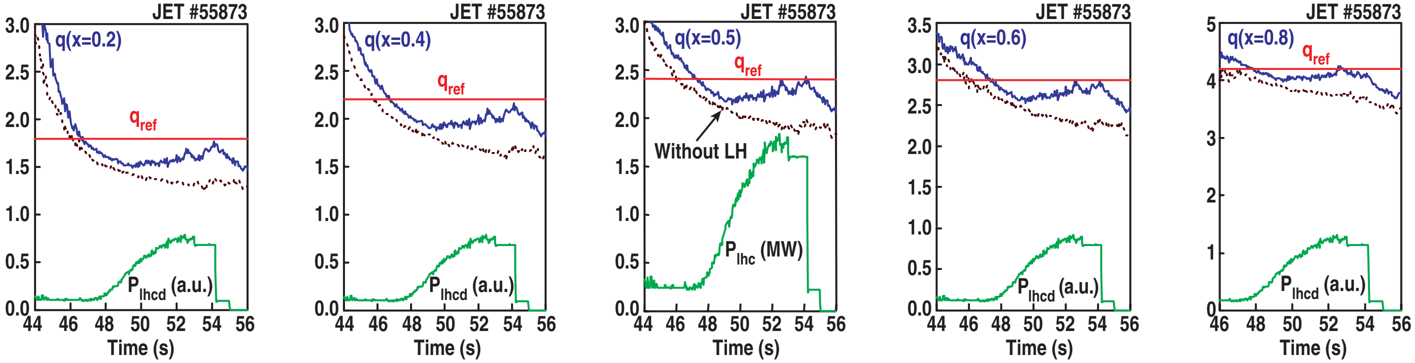
REAL TIME CONTROL OF ITB'S AND q-PROFILE HAVE BEEN DEMONSTRATED ON JET







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CONCLUSIONS

- Tests of transport models (JETTO, Weiland model) have been performed using profile data from the international ITB database

- Overall there is limited agreement between the model predictions and the experimental data from DIII–D, JET and JT-60U
  - Using data from several machines allows for model validation over a large range of conditions (reveals deficiencies and areas for improvement)
  - Important for improving predictive capability of models

- Gyrokinetic stability analysis of ITB discharges from DIII–D, JET and JT-60U indicates that the E × B shear rate is comparable to the maximum linear growth rates at the location of the ITB

- Much more interaction between experimentalists and modelers is needed to improve the predictive capability of the models

FUTURE WORK

- More work and greater interaction between modelers and experimentalists is required to perform further tests of transport models and to improve the models
    - Test more transport models (GLF23, Multi-mode, etc.)
    - Examine more linear stability codes (FULL, GS2, etc.)
    - Design experiments to test models
    - Motivate model development from experimental results
- Improvements could result from more accurate and reliable treatment of transport suppression mechanisms such as E × B flow shear, negative magnetic shear, and alpha stabilization
- Increased focus on critical issues for burning plasmas and reactor compatibility
    - Electron transport, core heating and fueling, impurity accumulation, profile control, stability, etc.
    - Need solutions to issues
- More multi-machine collaborative experiments and comparisons of experimental data, e.g., similarity experiments