REPORT ON THE ACTIVITIES OF THE ITPA TRANSPORT AND ITB PHYSICS TOPICAL GROUP

FOR THE PERIOD 3/2002 - 10/2002

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For the Topical Group:

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OVERVIEW

- Progress on 2002 priority research areas
  - Highlights of experimental progress in 2002
- Proposed 2003 scope and task definitions, priority research areas
- Recommendations for international collaboration within IEA-LT/ITPA framework
- Reports on TG meetings
- ITB Database Group (ITBDB) activities
- Conference presentations and publications, including future plans
  - Review paper on ITB physics
- Future TG meetings
- Diagnostic requirements
- Response to CC action items
- Summary

PROGRESS ON 2002 HIGH PRIORITY RESEARCH ITEMS

- Improve experimental characterization and understanding of critical issues for reactor relevant regimes with ITBs, including:
  - ITB formation and sustainment conditions
  - Impurity accumulation (low- and high-Z)
  - Compatibility with divertor requirements ($n_{sep}/n_G \geq 0.3$)
- ITB formation is now routine on many devices, sustainment is routine on large devices (JET, JT-60U, DIII-D)
  - Can eliminate this item
- Impurity accumulation with ITBs has been arrested using central ECH on AUG, DIII-D, JT-60U, and with central ICRF on CMOD
  - Proof-of-principle experiments, need further work with higher performance discharges
- Higher density ITB discharges achieved on JT-60U, $n_{AVE}/n_G \sim 0.8$

PROGRESS ON 2002 HIGH PRIORITY RESEARCH ITEMS

- Develop manage and analyze the new worldwide experimental ITB database in order to test predictive theory-based models

- Substantial progress in development and physics utilization of the ITBDB
- Will keep as priority as this is focus of collaborative international effort

- Study experimental plasma results that challenge whether ion transport is fully understood, such as flat core profiles, etc.

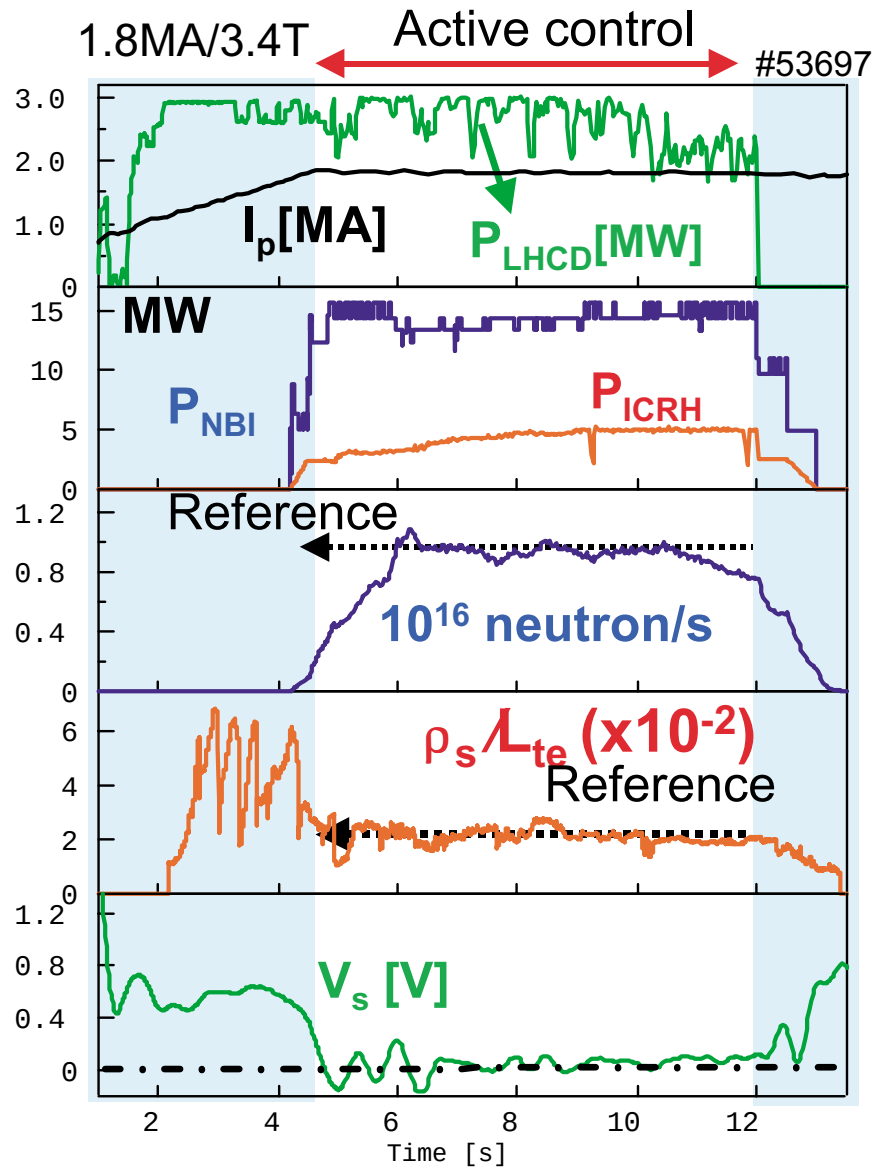
- Some progress, but not as much as anticipated due to code problems

- Test simulation predictions via comparisons to measurements of turbulence characteristics, code-to-code comparisons and comparisons to transport scalings

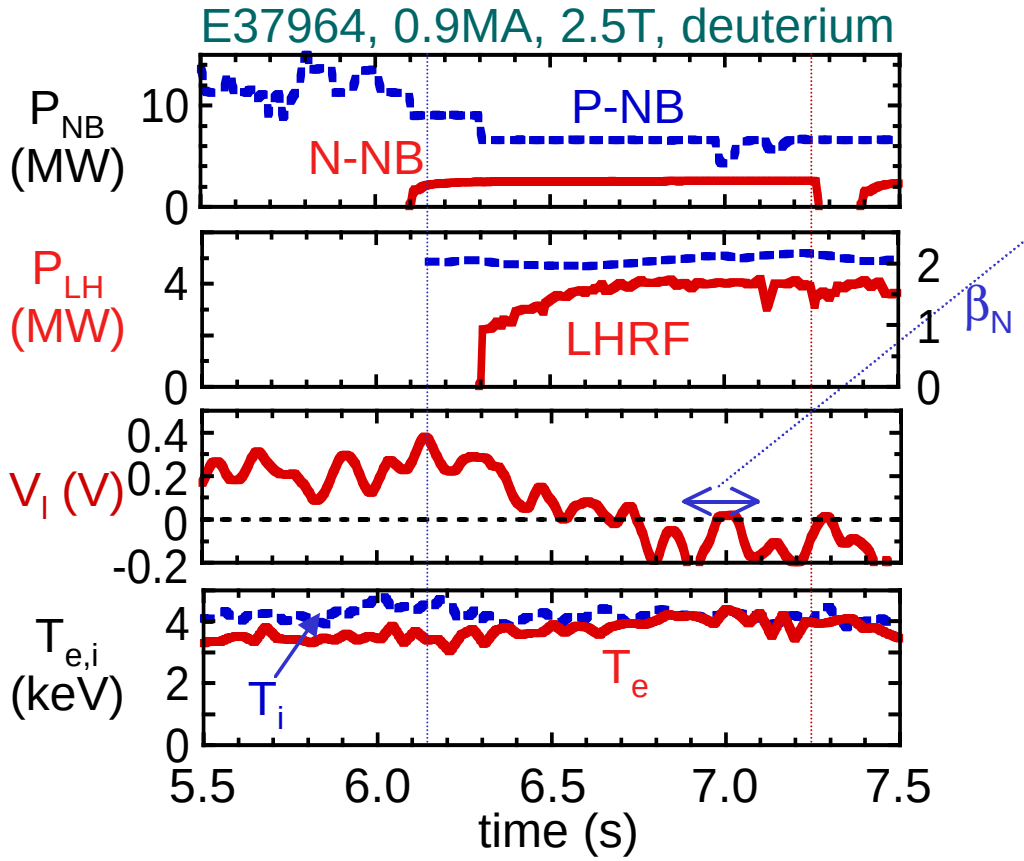
- Encouraging quantitative comparisons of turbulence properties to simulation predictions on DIII-D. Zonal flow feature identified and compared to transport model with reasonable agreement. Turbulence correlation length measurements close to gyrokinetic simulations
- Substantial progress in characterizing turbulence on T-10
  - Needs modelling/simulation support

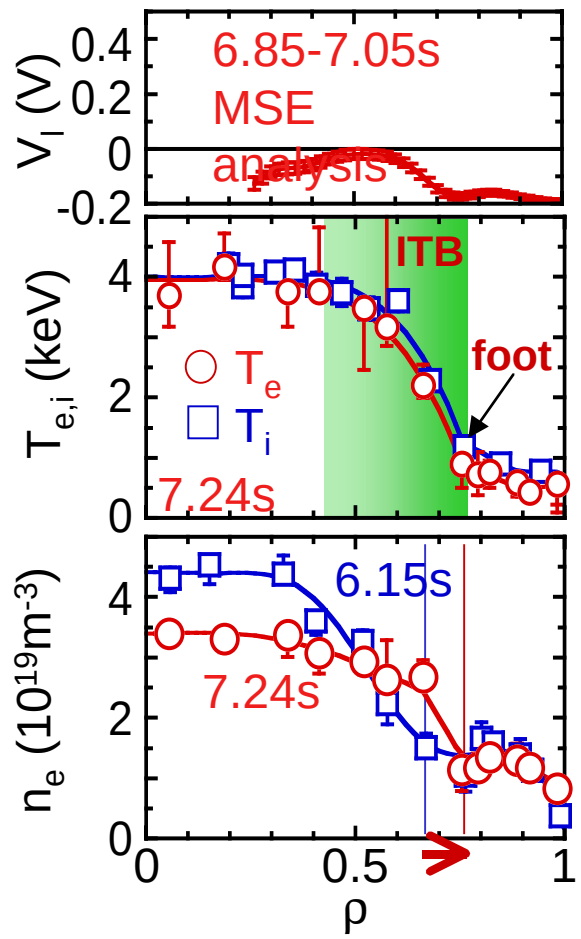
QUASI-STEADY STATE OPERATION WITH REAL TIME ITB AND q-PROFILE CONTROL DEMONSTRATED ON JET

- Example of ITB control for 7.5 s with ~ 100% non-inductive current
  - LHCD used to slow q-profile evolution
  - ICRF used to control ITB gradient
  - NBI used to control neutron rate
- Initial real time q-profile control demonstration in separate discharges



ITB OPERATION AT LARGE RADIUS WITH FULL CD AND HIGH GREENWALD DENSITY FRACTION (0.8) ACHIEVED ON JT-60U



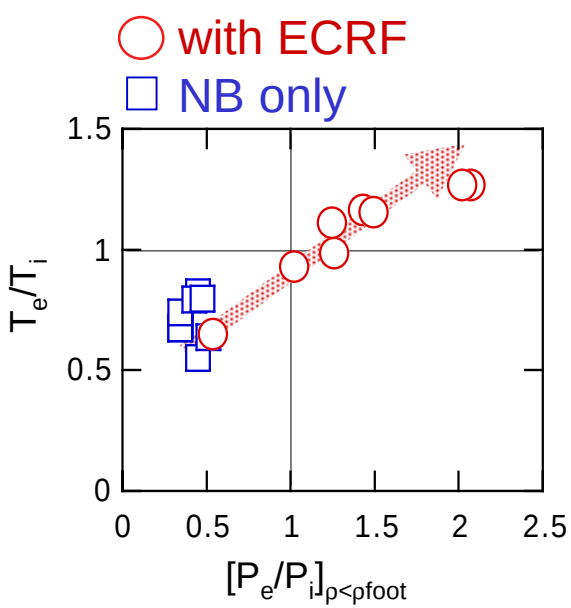


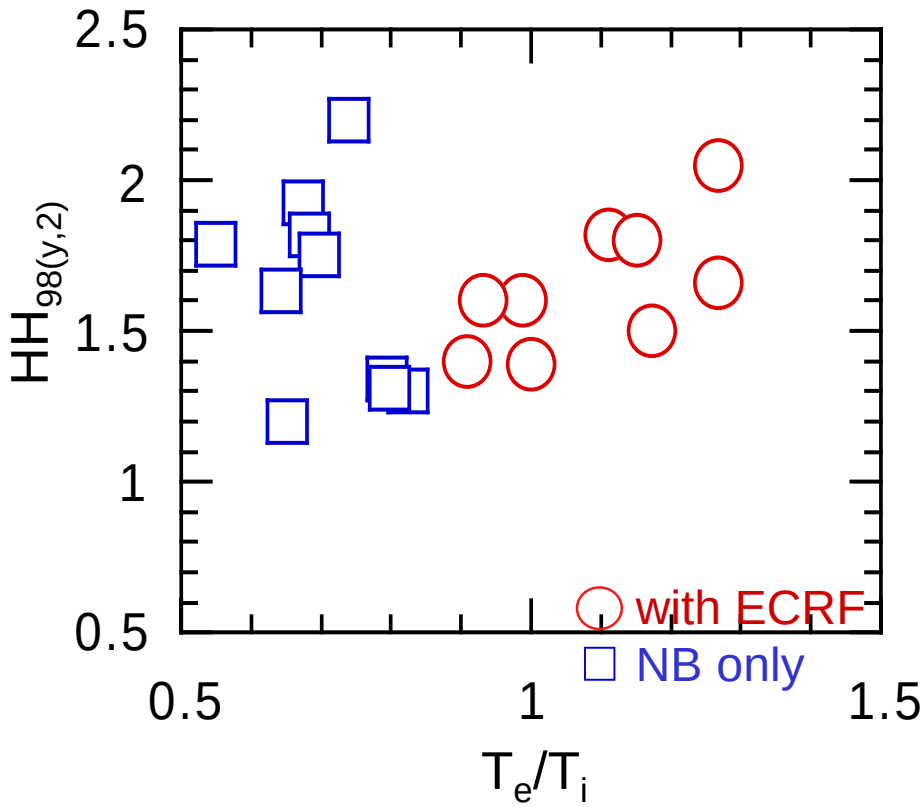
LHCD (2 GHz) + N-NBCD (E_b ~ 360keV)

=> V_l ~0V, β_N ~ 2.2, β_p ~ 2.1, T_e ~ T_i, q_{95} = 6.9

- **full non-inductive CD**
- **T_e, T_i and n_e ITBs expand**

$T_e \sim T_i$ IN ITB PLASMAS WITH DOMINANT ELECTRON HEATING AND HIGH CONFINMENET ALSO REPORTED FROM JT-60U





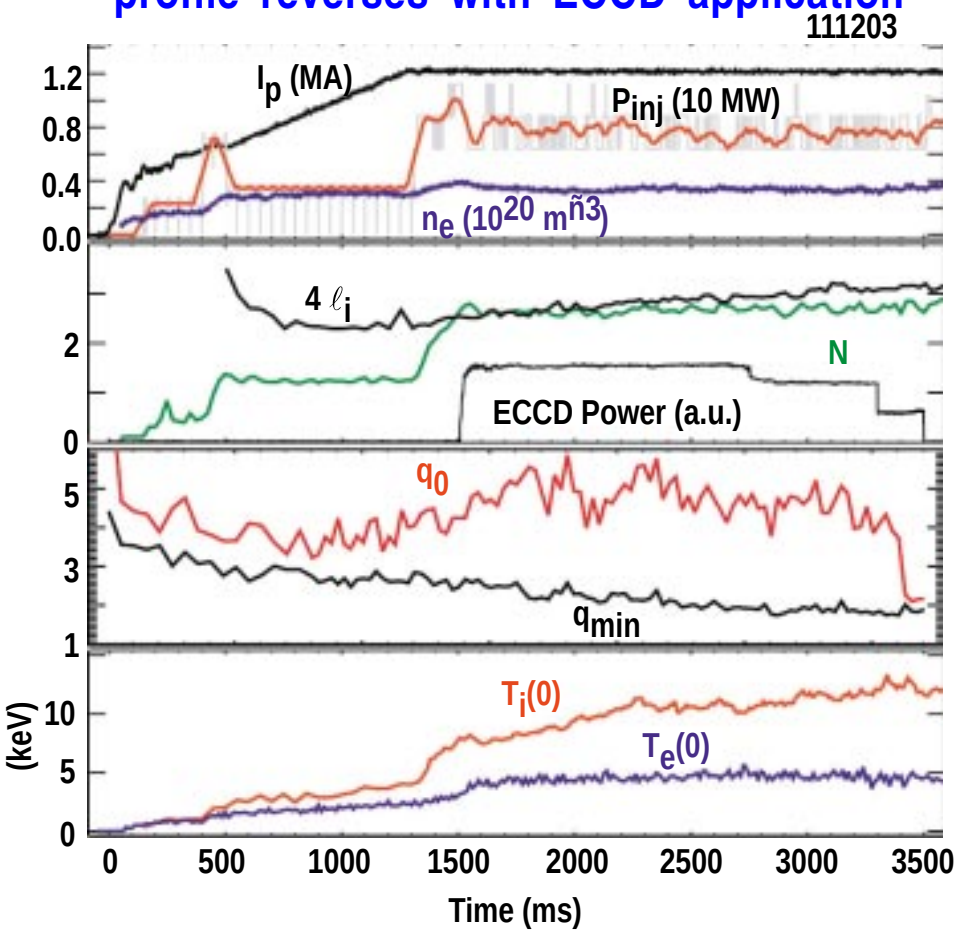
By changing combination of P_{EC} and P_{NB} P_e/P_i is varied and T_e/T_i follows it.

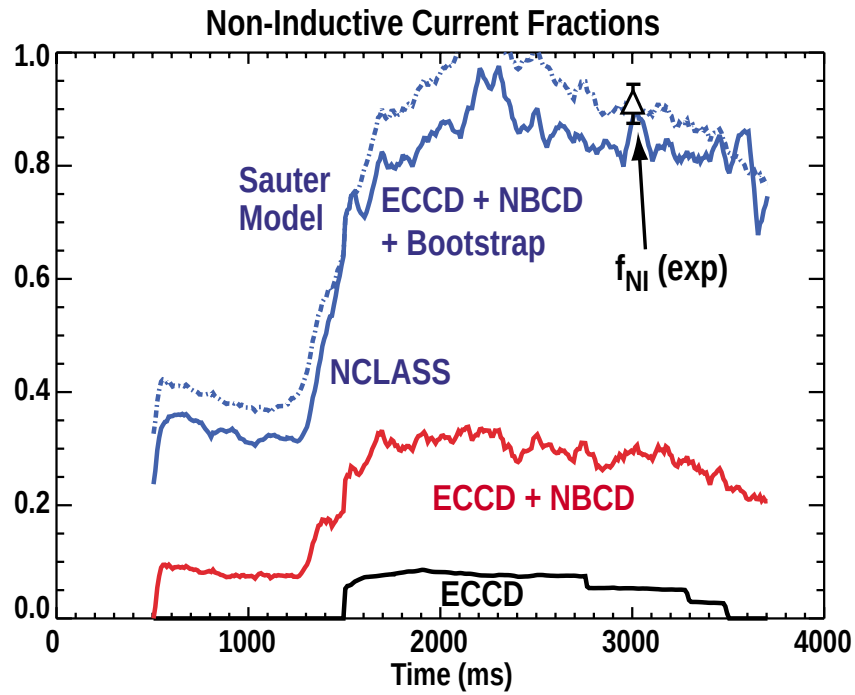
$I_p \sim 1.3$ MA for ECRF
$I_p \sim 0.8$ - 1 MA for NB

High thermal confinement of $HH_{98(y,2)} \sim 2$ is obtained independently on heating regime.

FULL NON-INDUCTIVE OPERATION ($f_{NI} \geq$ 90%) ACHIEVED ON JT-60U, JET, DIII-D

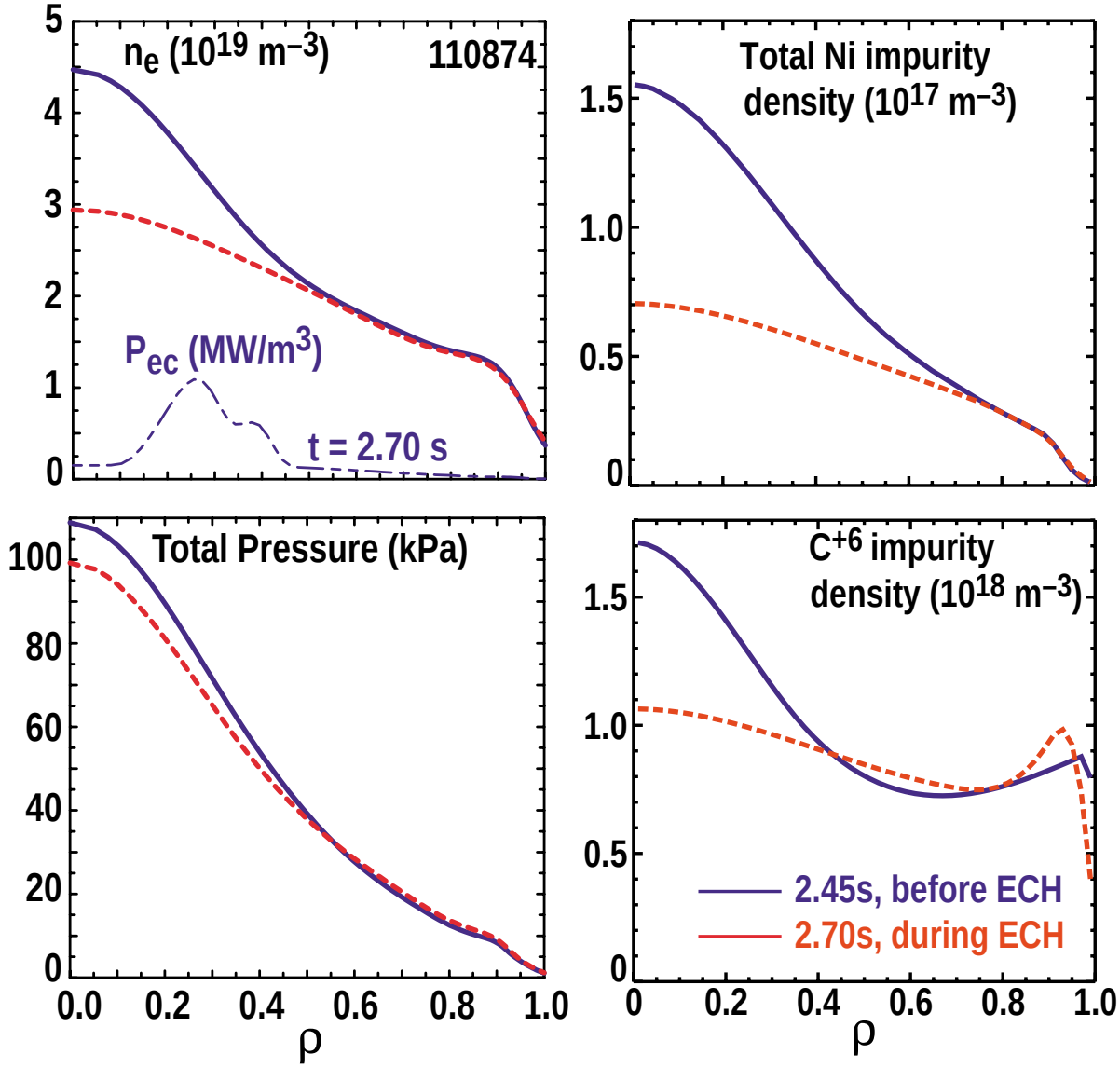
- DIII-D has achieved an AT demonstration discharge with B_N=2.8, H_{89}=2.4, q_{min}>2, f_{NI}~90%, f_{BS}~55% , using ECCD
- Interesting features include formation of ITBs in all four transport channels once q profile reverses with ECCD application





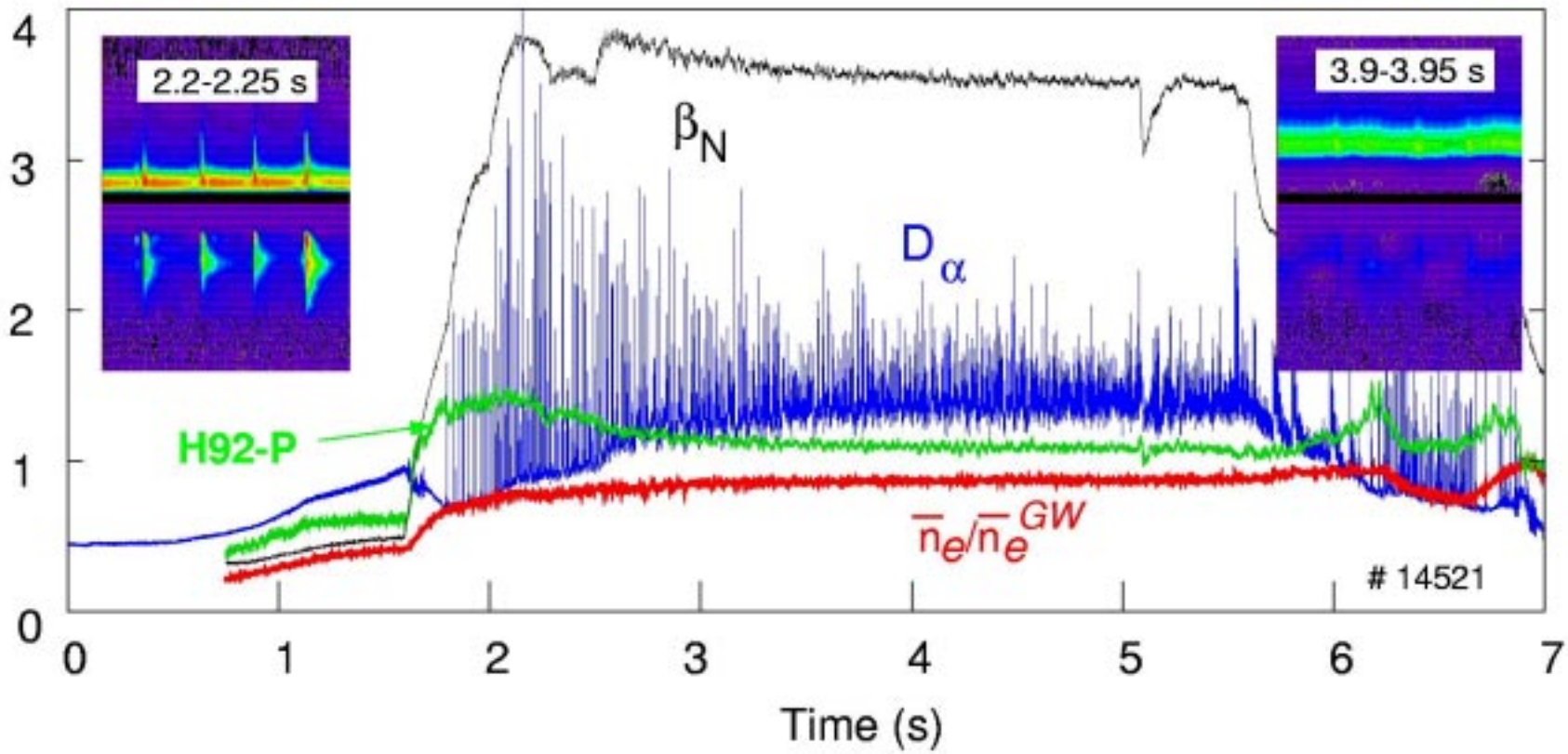
HIGH-Z IMPURITY ACCUMULATION WITH ITBs ARRESTED USING CENTRAL HEATING ON AUG, DIII-D, JT-60U, CMOD

- AUG, DIII-D, JT-60U utilize central ECH
- CMOD utilizes central ICRF
- Example shown is from DIII-D



IMPROVED/ALTERNATE BASELINE SCENARIOS FOR ITER DEMONSTRATED ON AUG AND DIII-D

- DIII-D has achieved ITER target level fusion performance at higher q_{95} (4.2), with $q_{min}>1$
  - Lower current operation with lower disruption forces
- AUG has achieved a stationary improved H-mode at high density (n/n_{GW} = 0.85), at high δ, with β_N = 3.5 and Type II ELMs



PROPOSED 2003 HIGH PRIORITY RESEARCH ITEMS

- Improve experimental characterization and understanding of critical issues for reactor relevant regimes with ITBs, including:
  - Continue to optimize and improve ITER-hybrid and AT operation demonstration discharges
  - Obtain $T_e \sim T_i$, at higher performance
  - Impurity accumulation (low- and high-Z)
  - Compatibility with edge conditions (ELMs, density..)
- Develop, manage and analyze the international experimental ITB database (profile and global parameters) to test predictive theory-based models and ITB formation conditions
- Study experimental plasma results that challenge understanding of ion transport, such as flat core profiles, electron-ion coupling, etc.
- Test simulation predictions via comparisons to measurements of turbulence characteristics, code-to-code comparisons and comparisons to transport scalings.

2003 RESEARCH PRIORITIES - MEDIUM TERM (NO CHANGE)

- Apply physics-based transport models to simulate burning plasma experiments. Use models to identify conditions compatible with ITB formation and sustainment

- Mature ITB database and increase physics utilization

- Improve fundamental understanding of electron thermal, particle and momentum transport to level comparable to that now available for ion transport
  - Will require improvements in both measurement and modeling capabilities
  - Continue to validate physics basis of transport models by direct comparisons to turbulence measurements

2003 RESEARCH PRIORITIES - LONG TERM

- Validate physics basis for theory-based models of plasma transport, to provide predictive capability for burning plasmas based on fundamental understanding
  - Validation will be sought on two levels; via fundamental tests of the assumed turbulent transport mechanisms and comparison of model predictions to experimental results

- Within capabilities of current devices, confirm performance of burning plasma compatible operating regimes based on improved core transport properties
  - i.e. quasi steady-state, high performance, edge compatibility, etc.

SCOPE OF WORK AND TASK DEFINITIONS — NO CHANGE FROM 2002 LIST

POSSIBILITIES FOR INTERNATIONAL COLLABORATION UNDER IEA/ITPA FRAMEWORK

List of scientifically interesting collaborative possibilities. Have not explicitly considered scheduling limitations, etc. Extensive possibilities exist, consistent with active and broadbased field. List is in priority order

- Pursue and expand on promising high performance scenarios
  - Full non-inductive ($f_{NI} \geq 90\%$) CD discharges with ITBs achieved on JT-60U, JET and DIII-D at high fusion performance
    - ★ Collaboration between JT-60U, JET, DIII-D to further improve scenarios
  - $q(0) \sim 1$, $q_{95} > 4$ high performance discharges on AUG and DIII-D
    - ★ Alternate ITER hybrid scenario
    - ★ AUG/JET experiment planned. Expand to include AUG/DIII-D collaboration on physics, with collaboration with JT-60U/JET to extend applicability.
    - ★ Consider dimensionally similar experiment if results reproducible
- Operation with $T_e \approx T_i$
  - Collaborative ECH experiments between JT-60U, AUG and DIII-D to achieve higher performance discharges

POSSIBILITIES FOR INTERNATIONAL COLLABORATION, CONTINUED

- ITBs with no momentum input
  - ECH heated electron ITBs - examine physics of dominant electron heating, q dependence, etc.
    - ★ JT-60U, DIII-D, AUG
    - ★ Many smaller machines interested in contributing, T-10, FTU, TCV, also stellarator community interested in determining common physics.
  - AUG comparison to CMOD ICRF ITBs is planned
  - JET/FTU/TS electron ITB similarity experiment at high density planned for 2004

- QDB/QH-mode comparisons
  - Further explore QH-mode physics with DIII-D/AUG/JET collaboration. QH-mode experiment scheduled for JET in 2003
  - Balanced-NBI experiment on JT-60 would provide critical test of role of counter-NBI in QH-mode plasmas, as also would RF heated attempt on AUG

- Determination and comparison of beta limits in long pulse ITB plasmas
  - Achievable beta with ITBs is major reactor issue. Limit known on JT-60U, need to determine in some DIII-D, JET regimes. Compare results to modeling.

POSSIBILITIES FOR INTERNATIONAL COLLABORATION, CONTINUED

- When mature, transfer real-time ITB and q-profile control capabilities under development on JET, leading to real-time control experiments on other machines
  - Control codes and algorithms generally applicable
  - Utilize control codes with new actuators, e.g. ECH/ECCD
  - Collaboration with DIII-D, AUG, TS, with future comparison to JT-60U real time control scheme

- Dimensionally similar ITB scaling experiments
  - Initial investigation of possibility of such comparisons has commenced between AUG, JET
  - Expand to other devices if successful

- Turbulence simulation and modeling support of T-10 work on identifying nature of tokamak turbulence

SECOND ITPA TRANSPORT/ITB TG MEETING, SAN DIEGO, USA, MARCH 4-7, 2002

- **Highlights of the meeting:**
  - Agreed and established framework for future physics utilization of the ITBDB profile database
    - ★ Described in ITBDB report section
  - Transition to unified MDSplus based ITPA profile database agreed, in collaboration with CDBM group
  - Session on experimental and theoretical aspects of electron ITBs
    - ★ Review of present experimental status and theoretical understanding, $T_e \sim T_i$ on JT-60U
    - ★ Led directly to JT-60U experiment on scaling of R/L_{Te} as function of s-α
  - Recent significant results
    - ★ Real time ITB control on JET
  - Session on burning plasma predictive modeling
    - ★ GLF23 modeling predicts Q=10 operation on ITER, FIRE at parameters close to design values
    - ★ Comparison of GLF23, Weiland, MMM modeling for ITER shows differences, due to different profile stiffness in models
    - ★ Critical issue is predictive capability for edge pedestal. Performance projections are dominated by assumptions for edge pedestal temperatures
  - First joint meeting with Diagnostics TG - interaction described later

THIRD ITPA TRANSPORT/ITB TG MEETING, CADARACHE, FRANCE, OCTOBER 21-23, 2002

- **Highlights of the meeting:**
  - Experimental progress with long pulse, "improved H-mode" and advanced ITB based scenarios is now at the level where we can commence evaluation of advanced reactor scenarios based on demonstration discharges
  - Initial evaluation and classification of scenarios was highlight of first joint session with Steady State TG
    - ★ Performed by C. Gormezano, with input from others
  - Applicability of highly reversed shear ITBs scenarios to steady state operation is questionable
    - ★ However, may be utilized in initial ITB formation phase
    - ★ Highly reversed shear operation has implications for diagnostic requirements
  - Extensive discussion of possibilities for international collaboration within proposed IEA/ITPA framework
  - Joint session with CDBM group on modeling endorsed approach of ITBDB group to database utilization
    - ★ Overlap of effort with regard to ITB modeling was observed

STATUS OF THE ITB DATABASE

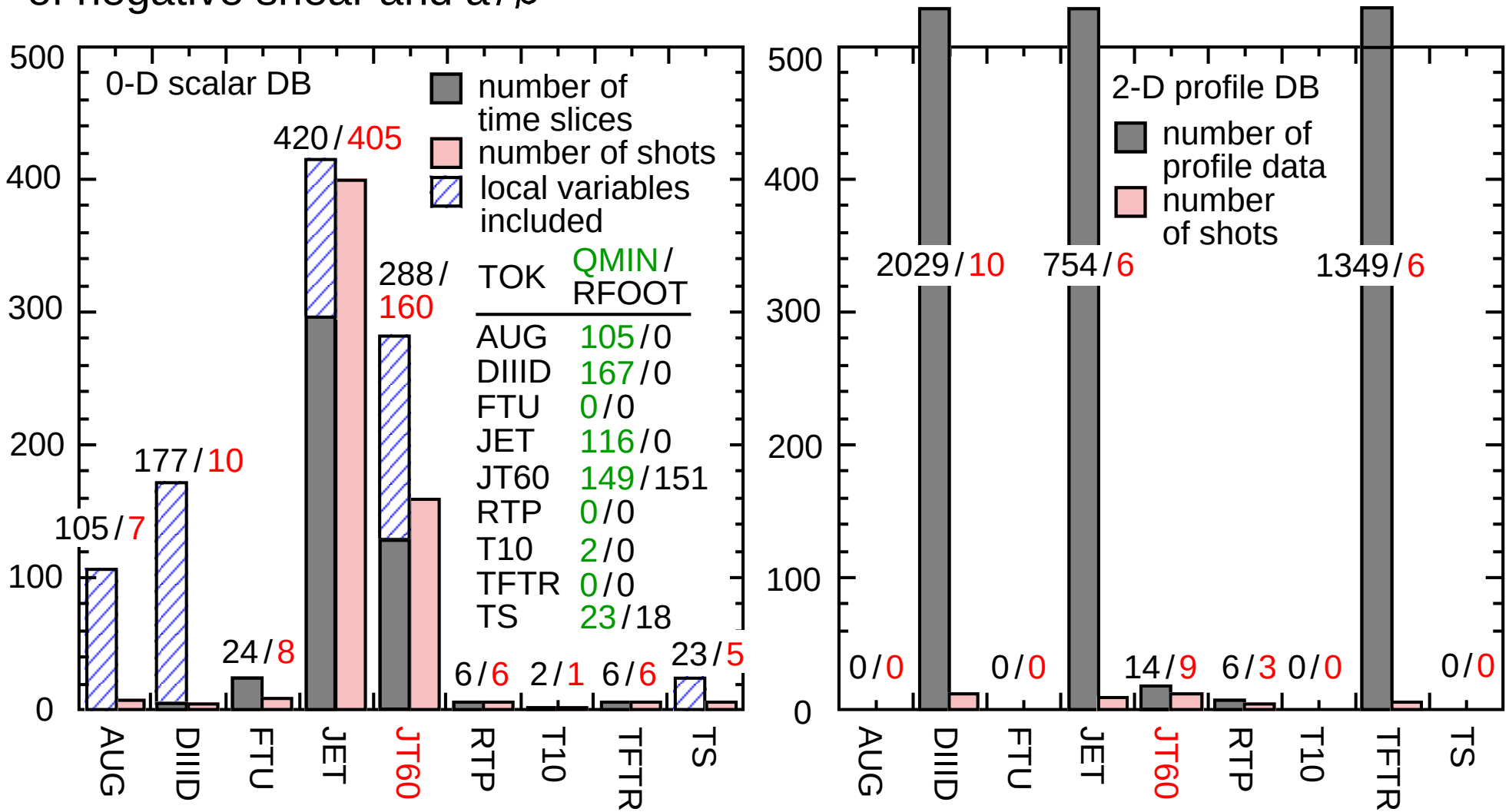
T. Fukuda for the ITB database working group

22 October 2002
CEA Cadarache, France
3rd ITPA meeting on Transport and ITB physics

- Progress made in the database after the San Diego meeting in March, 2001
  1. 4,152 profile data [1,631 in March 2002] have been accumulated [1,051 for the 0-D database] from the ITB experiment in 9 tokamaks, namely ASDEX-U, DIII-D, FTU, JET, JT-60U, RTP, T-10, TFTR, TORE SUPRA
  2. Number of variables in the 0-D scalar database was increased to 134, including ρ_T* and R/L_T, in order to accommodate the efficient cross-comparisons and model validations
  3. New contributions to the database
     - 1,760 additional DIII-D profile data
     - 754 profile data from JET ITB discharges
     - 7 additional data from JT-60U
  4. 3 publications from the group for the 15th TTF, EPS29 and IAEA19
  5. Comparative studies with T_e ITB in helical devices have been undertaken
- The ITB profile database is being transferred to the Culham server for integration with the PDB maintained by the CDM TG
- New members from TCV and MAST to participate in the ITBDB activity

Statistics of the ITB data compiled in the database as of 22 October, 2002

- Substantial update on the 2-D profile database enabled the validation of transport models and sheared EXB flow theory
- Extended analysis of the 0-D scalar database has shown the significance of negative shear and a/ρ*



STATUS OF ITBDB

- Transition from stand-alone ITB profile DB to component part of integrated MDSplus based ITPA profile database is underway
  - Majority of ITB profile data transferred to central server at JET
- Interaction with, and support of CDBM TG is vital for continued development of capabilities of profile database
  - E.g. need to add capability to store equilibria with profile data
- Current profile DB will be made public when NF paper is published
  - Also some technical issues still to be resolved, e.g. slightly diverging variable names, etc.
- Issue arises with regard to the scalar (0-D) ITB database - now divorced from complementary profile database
  - Need for common ITPA scalar database?

STRUCTURE FOR PHYSICS UTILIZATION OF ITBDB

- **Agreed and established framework for future physics utilization of the ITBDB profile database:**
  - Identify major physics issue(s) to address
  - Select consistent data sets from major machines that address these issues
  - Analyze data sets using range of available predictive/interpretive codes
- **Initial selections were to:**
  - Examine role of q-profile in ion ITB formation, and consistency of experiment with $\omega_{ExB} \geq \gamma_{LIN}$ criterion for ITB formation
  - Obtain examples of NBI driven ITBs with weak and strong magnetic shear profiles from major devices (JT-60U, JET, DIII-D)
  - Compare GLF23, JETTO and Weiland transport models, and use GKS to evaluate ω_{ExB} versus γ_{LIN}
- **The ITBDB utilization framework is flexible and expandable in multiple ways:**
  - The physics issues to address are expandable, dynamics of ITB formation, electron ITB formation conditions, role of Shafranov shift stabilization, etc.
  - Will expand matched data sets over time; possibilities include electron ITBs, quasi-steady state ITBs, ITBs with full non-inductive CD, RF versus NBI heated ITBs, etc.
  - The codes evaluated will be expanded to include GS2, MMM, KINEZERO, FULL, etc.

PUBLICATIONS AND CONFERENCE PRESENTATIONS BY THE ITBDB WG

- Within the period under review the ITBDB group has generated the following papers/presentations (lead author identified, all presentations collectively for the ITBDB WG and ITPA):
  - N. Kinerva (Kurchatov, RF), "Energy Confinement in Discharges with ITB," US TTF Meeting, Annapolis, USA, April 2002
  - G. Hoang (CEA, EU), "Additional Heating Power required for ITB formation in Tokamaks," EPS Conference, Switzerland, June 2002. EPS paper.
  - P. Gohil (GA, USA), "Increased Understanding of the Dynamics and Transport in ITB Plasmas from Multi-Machine Comparisons," IAEA Conf., Lyon, France, October 2002. Presented in ITER Coordinated Technical Activities session. Associated IAEA paper, and expanded version of paper submitted for publication in Nuclear Fusion.

CONTENT AND CONCLUSIONS OF ITPA/ITBDB IAEA PAPER

- Tested three models (GLF23, JETTO, Weiland model) against matched set of JT-60U, JET and DIII-D ITB data at both low and high q
  - Testing both role of q profile, and model ability to replicate experiment

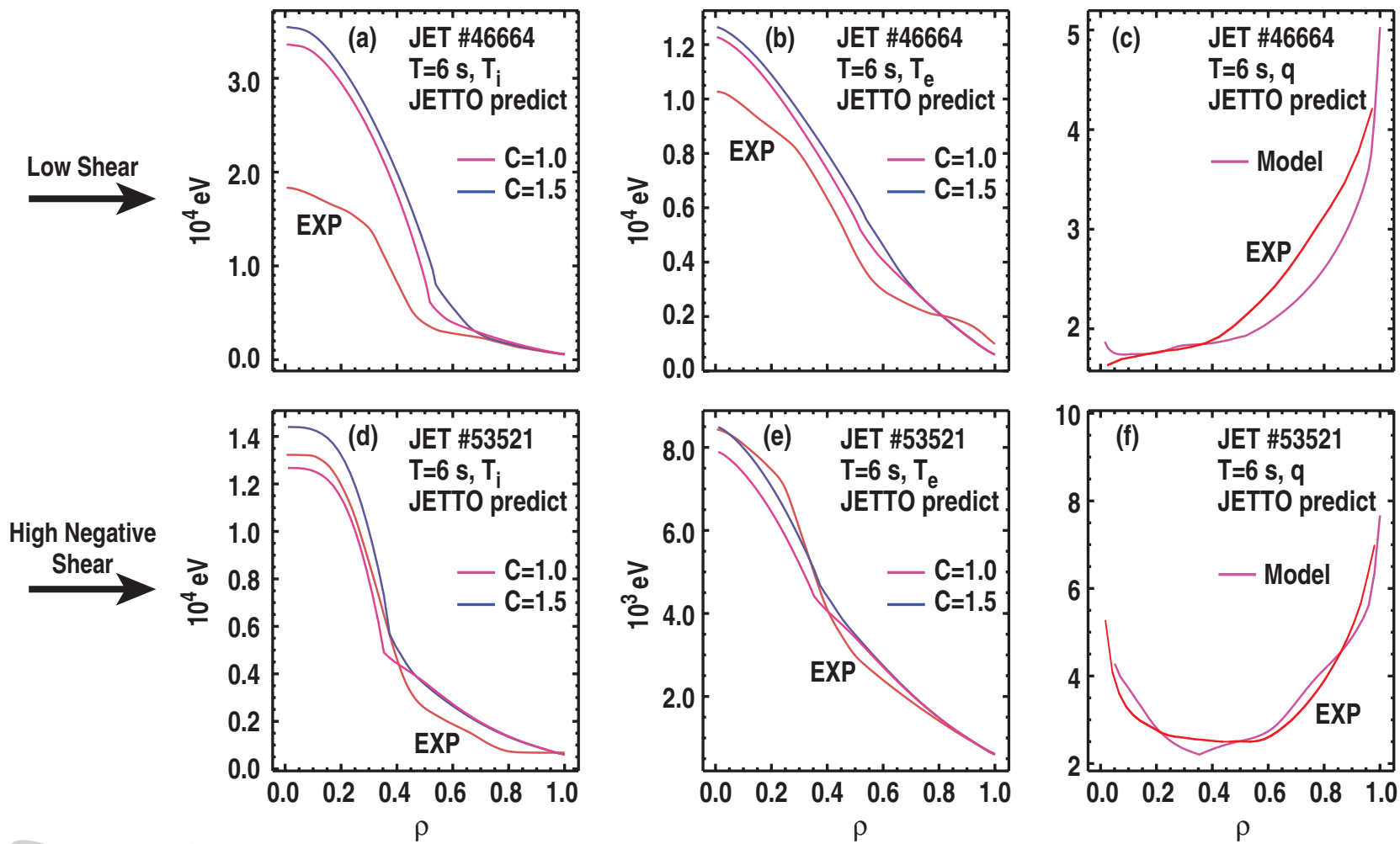
- Results: limited agreement between the JETTO and Weiland model predictions and the experimental data
  - Comparison exposed error in Shafranov shift stabilization component of the GLF23 model. No modeling of NCS discharges with GLF23 is possible until this error is corrected
    - ★ Demonstrates benefits of DB and comparisons as evaluation tool for models
  - Models perform better for T_i as opposed to T_e profiles

- On a more positive note, gyrokinetic stability analysis using the GKS code indicates that ω_{ExB} is comparable to γ_{LIN} at the location of the ITB for the tested data set, consistent with theories of ITB formation

- Also significant material in EPS and US TTF presentations

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



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

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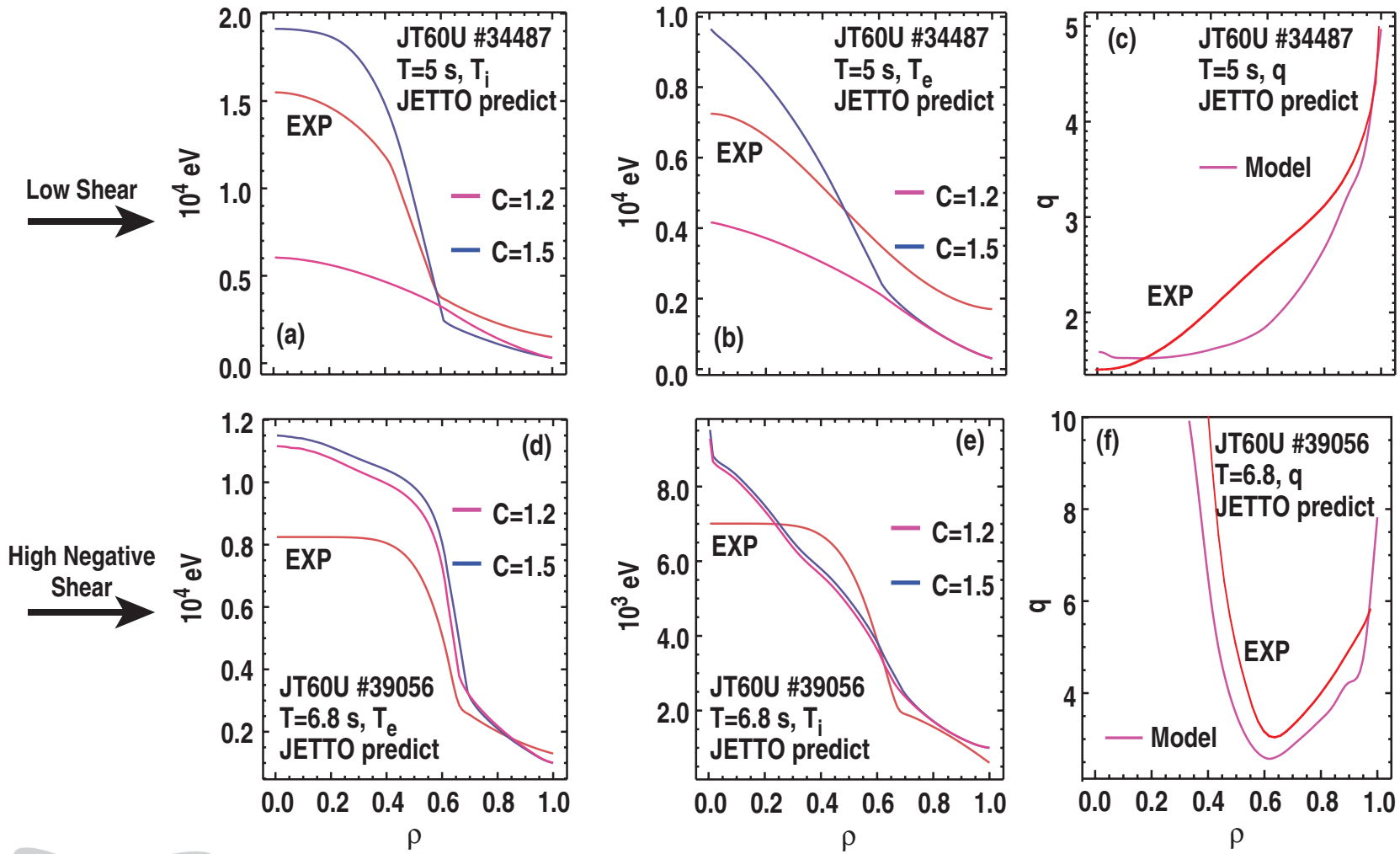
JETTO PREDICTIVE SIMULATIONS FOR JT-6OU DATA

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



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REVIEW PAPER ON ITB PHYSICS

- "A Review of Internal Transport Barrier Physics for Steady State Operation of Tokamaks", by J. W. Connor, T. Fukuda, X. Garbet, C. Gormezano, V. Mukhovatov, M. Wakatani, and the ITBDB and ITPA groups
  - Referees' reports received in March, suggesting substantial revision
  - Paper has been restructured and substantially rewritten
  - Will be resubmitted within ~ two weeks
- The review covers:
  - Theory of ITBs
  - The international ITB database
  - Steady-state ITBs
  - Extrapolation to ITER
  - Characteristics of ITBs on individual devices
- Serves to update and expand on much of the transport section of the ITER physics basis document

CONFERENCE AND PUBLICATION PLANS

- Lead authors have been selected to present the ongoing work of the ITBDB at the forthcoming EPS conference and H-mode and ITB Physics Workshop. Each of these meetings has associated papers:
  - T. Fujita (JAERI, JA), EPS, St. Petersburg, RF, July 2003
  - X. Litaudon (CEA, EU), H-mode & ITB Physics Workshop, San Diego, USA, September 2003

- Content of papers will depend on analysis priorities to be established at the ITBDB working group session currently underway in Cadarache. In general, will build and expand on recent IAEA and NF papers

PROPOSED LOCATIONS FOR FUTURE TG MEETINGS

- Proposal is to hold 4th Transport/ITB Physics TG meeting in Ioffe Institute, St. Petersburg, RF
  - Tuesday, April 8 to Saturday April 12 2003 (3 days ITPA, 2 days ITBDB WG)
  - Week following US TTF meeting in Madison, Wisconsin, April 2-5. Tuesday start is to enable US participants to reach St. Petersburg

- Proposal is to hold 5th Transport/ITB Physics TG meeting at General Atomics in San Diego, USA
  - Monday, September 29 to Friday, October 3, 2003 (3 days ITPA, 2 days ITBDB WG)
  - Week following H-mode and ITB Physics Workshop in San Diego, September 24-26, 2003.

INTERACTION WITH DIAGNOSTIC TG

- First joint meeting with Diagnostic TG at March meeting
- Initial assessment of planned ITER diagnostics focussed on two issues
  - Insufficient resolution in profile diagnostics for advanced scenario operation, e.g
    - a/20 q (resolution not being met)
    - a/10 T_i, Z_{eff}
    - T/ITB TG initial assessment is that a/30-a/50 resolution required!
    - q-profile is critical measurement
    - α particle density profile is critical for reactor transport calculations
  - Advanced diagnostics needed for physics interpretation not currently meeting requirements
    - E_r
    - Turbulence diagnostic set
- As changes to these diagnostics requirements has major implications (design effort, machine impact, cost), transport TG focused at first on providing top level feedback on this issue, and obtaining consensus that major change is needed
  - In US, discussed at Snowmass and TTF meetings
  - Discussions in JA also support above assessment
  - RF also concur

INTERACTION WITH DIAGNOSTIC TG, CONTINUED

- At September meeting of Diagnostic TG, T. Fukuda presented official position of T/ITB group with regard to top level requirements, consistent with above

- Initial assessment for reactors is that sharp ITBs cannot be excluded during formation phase

- Now in position to address need for detailed diagnostic requirements and justifications
  - Simulation work using transport codes is required, e.g. effect on accuracy of transport coefficients and neutron rate of variable levels of spatial resolution on measurements such as Z_{eff} and α particle density

CONTACT PERSONS FOR OTHER TGs

• CDBM TG	
— Confinment	V. Vershkov (RF)
— Database	T. Fukuda (JA)
— Modeling	J. Kinsey (US)
• Diagnostics	P. Gohil (US)
• Edge & Pedestal	J. Connor (EU)
• MHD, Disruption, Control	X. Litaudon (EU)
• SOL & Divertor	B. Unterberg (EU)
• Steady state, EP	T. Fujita (JA)
• Stellarator community	K. Toi (JA)

RESPONSE TO CC ACTION ITEMS

- Descriptions of ITPA databases and list of contact persons
  - Provided in March
- Coordination of profile databases
  - Work underway and ongoing
- Contact persons for other TGs
  - Nominated
- Meetings after Lyon
  - Proposing St. Petersburg, April 2003, San Diego, Sept/Oct. 2003
- Use of ITPA website
  - Difficulty encountered in posting material, using own site to post meeting presentations
- Create DB WG
  - In existence for several years
- Diagnostic input
  - Interaction ongoing
- Common format for Scope and Task definitions
  - Common format not defined by CC

SUMMARY- TRANSPORT AND ITB PHYSICS TG

- Major steps have been made towards demonstrating reactor-relevant advanced scenario/AT discharges on all major devices
  - Broadbased progress on multiple issues
  - Implication for Transport and ITB group is transition to performing evaluation of reactor applicability of demonstrated advanced scenarios
- Excellent progress in addressing ITPA high priority research items and critical ITB physics issues
- Physics utilization of ITB database is maturing and addressing relevant issues
  - Flexible, expandable approach
- Extensive possibilities for international collaborative experiments in transport & ITB area