UT-BATTELLE

Transport/Confinement

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OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

Outline

ITPA perspective on transport/confinement

Progress in the ITER Physics Basis: *Plasma Confinement and Transport* (Chapter 2)

Non-linear feedback loops

Energy transport

Plasma rotation

Particle transport

Fueling

Summary

ITPA Perspective on Transport/Confinement

The reactor scale issues to be addressed in ITER can be broadly grouped into two classifications:

- Burning plasma physics, comprising energetic particle behavior and effects of plasma self-heating
- Scale dependent plasma physics

The ITPA confinement-related Topical Groups (Confinement Databases & Modeling; Transport Physics; Pedestal & Edge) focus on the latter:

- Creation and maintenance of multi-machine databases
- Recommending experiments to address high priority issues (IEA/ITPA)
- Identifying critical parameters that characterize data trends
- Validating models against databases

Progress in the ITER Physics Basis
Chapter 2: *Plasma Confinement and Transport*

Review of progress from 1999-2005

1 Introduction

2 Fundamental transport processes

Theory of turbulent transport; Turbulence simulation; Experimental turbulence measurements; Neoclassical transport

3 Core transport

Enhanced core confinement regimes; Ion thermal confinement; Electron thermal confinement; Particle and impurity transport; Toroidal momentum transport and spontaneous rotation; Dimensionless parameter scaling experiments; Improved core confinement regimes for advanced operation scenarios

4 Pedestal structure, transport and ELMs (to be covered by A. Leonard)

Regimes of improved H-mode confinement; Pedestal characteristics and structure; L-H transitions; Pedestal transport theory and modeling; Modelling the pedestal structure; Type I ELM structure, effects on the pedestal profiles and mitigation techniques; Alternatives to Type I ELMy H-Mode; Pedestal stability; Pedestal control scenarios

5 Predictive capability and projections for ITER

Improved database resources for modelling and scaling studies; Pedestal and edge characteristics; Global scaling; Non-dimensional scaling; Modelling codes, including edge modelling capability

6 Summary

Progress in the ITER Physics Basis Chapter 2: *Plasma Confinement and Transport*

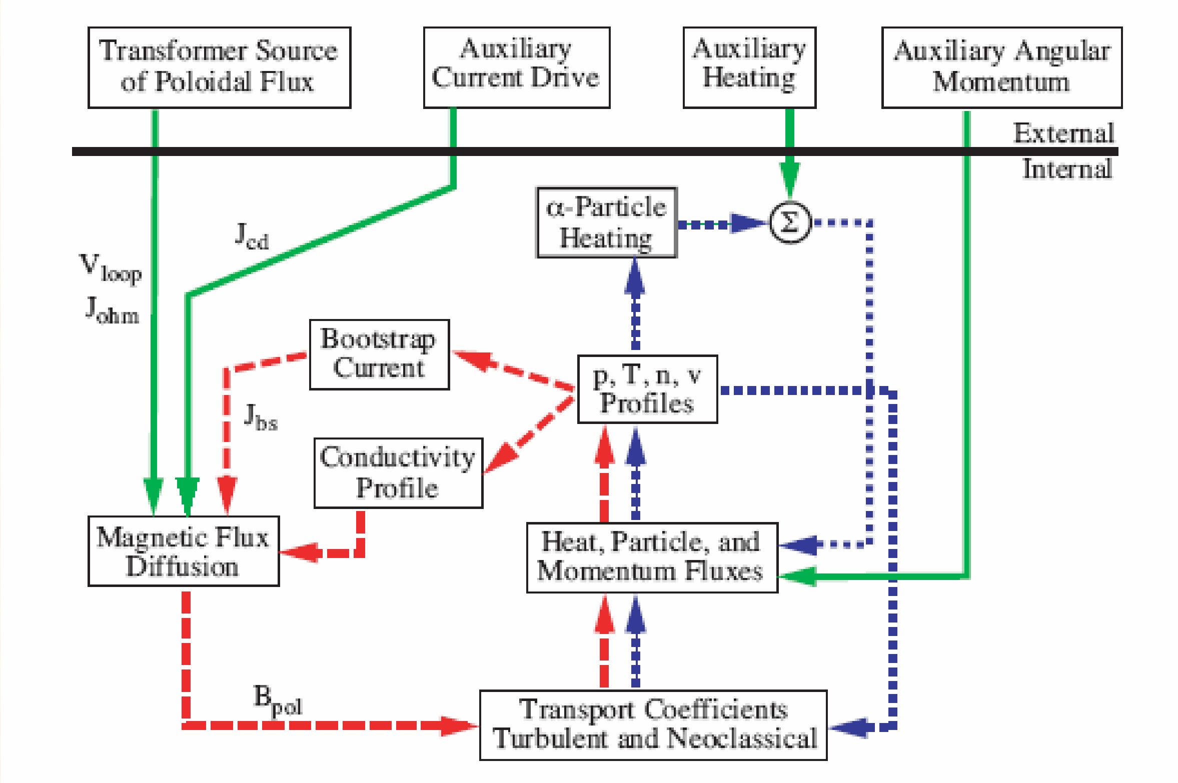
To be submitted to Nuclear Fusion:

- Figures 95
- Tables 5
- References ~750
- Estimated final NF pages 100-110

Drafts of Sections 2, 3 & 4 available on the ITPA website:

- http://itpa.ipp.mpg.de
- Click on Tokamak Physics Basis in left column
- Click on TpbChapter2
- User/pw for the ITPA user panel: ChapterTwoUser/chapter2
- MS Word files – with unformatted references for editing
- PDF files – with formatted references for reviewing
- PDF file of full bibliograpy from EndNote with first authors listed alphabetically
- EndNote Library with full lists of authors, abstracts, etc, and NF style file available on request

Many non-linear feedback loops and couplings govern tokamak transport – especially in a BP



Great progress in understanding details of each element in present experiments

Much work remains to quantify the couplings sufficiently to optimize burning plasmas – complex interaction between α particle heating, transport, impurity accumulation bootstrap current and stability

Energy transport – Progress

Broad understanding of turbulence suppression mechanisms has emerged:

- ExB sheared flows
- Negative or weak magnetic shear
- Shafranov shift stabilization

Gyrokinetic and gyrofluid models have been developed and applied to a wide range of wavenumbers:

- ITG ($k_\theta \rho_s \sim 0.1\text{-}0.5$)
- TEM ($k_\theta \rho_s \sim 0.5\text{-}1.0$)
- ETG ($k_\theta \rho_s \sim 1\text{-}10$)

Fairly good qualitative agreement between theory and experiment on:

- Turbulence correlation lengths
- Changes in confinement with impurity injection
- Relative temperature/density fluctuation levels
- Correlation between turbulence reduction and changes in growth and damping rates

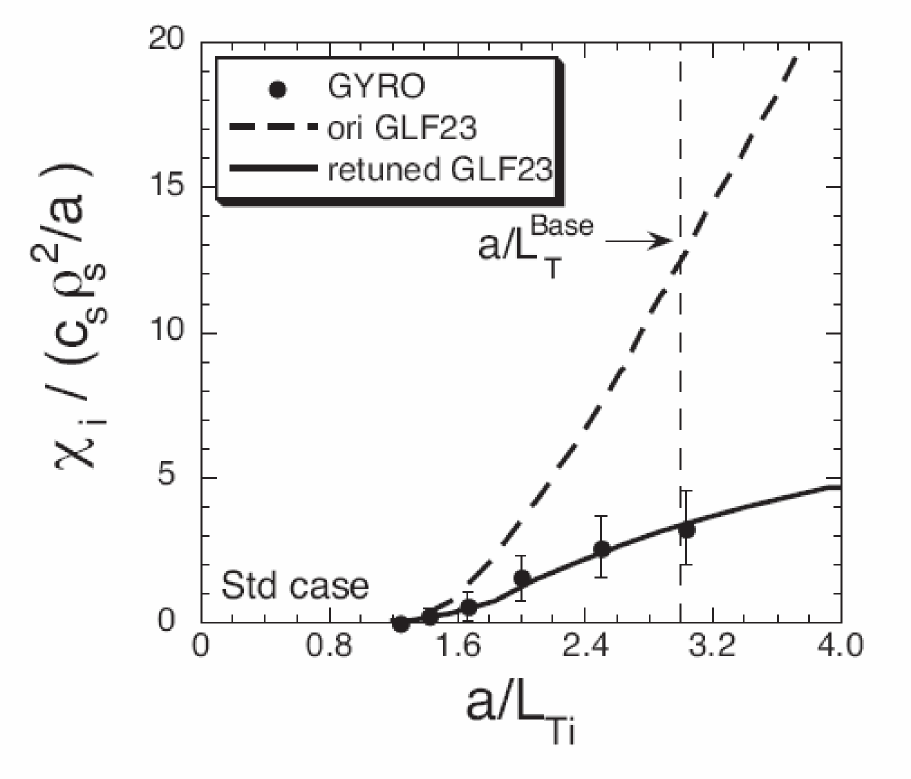
Energy transport – Challenges remain that can be addressed in the base program

Reconcile differences in stiffness of models:

- Gyro-fluid based simulations (IFS/PPPL and GLF23) generally exhibit greater stiffness than driftwave based models (MMM and Weiland)
- For a given ion temperature gradient, the predicted ion heat fluxes from gyro-fluid simulations have been significantly larger than gyro-kinetic simulations, necessitating retuning (see GLF23/GYRO example at right)

Extend range of validity:

- Short wavelength diagnostics becoming available to test models at high k
- Experiments exhibit strong sensitivity to shaping, so turbulence models need to include the full plasma geometry
- Extend models to the conditions in the plasma boundary
- Include the dynamics of ITB and ETB formation (threshold and evolution)

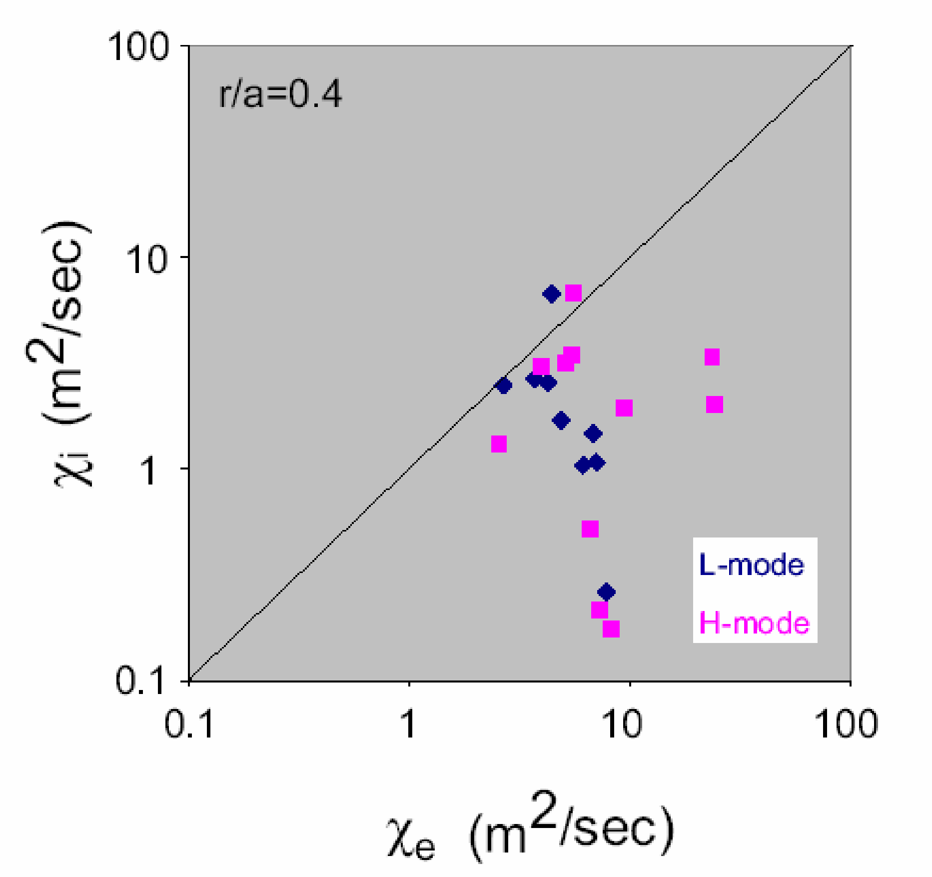


Unique experimental conditions can provide critical tests of theory and models

NSTX example:

Very low χ_i compared to χ_e in both L-mode (blue) and H-mode (red) NSTX plasmas:

- χ_i is about neoclassical and indicates the long wave-length turbulence is suppressed
- The much higher χ_e may provide an opportunity to test electron dominated transport



Energy transport – Secondary parameters have strong influence on confinement

Scatter in H-factor is often due to secondary parameters

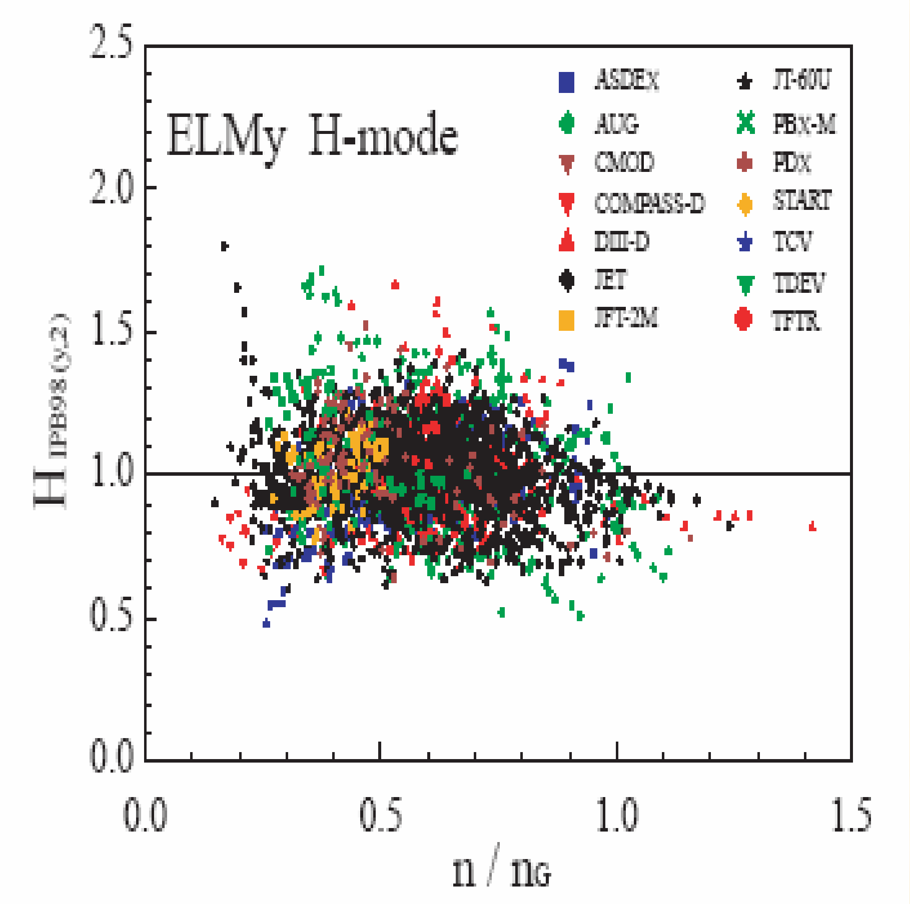
- Proximity to the Greenwald is a relatively weak factor that new analysis shows is better correlated with collisionality

Strong gas puffing reduces confinement

Increasing triangularity enhances confinement

Degradation of confinement with β:

- Indicated by analysis of global H-mode confinement database
- No degradation observed in DIII-D/JET identity experiments
- JT-60U scans see degradation
- New analysis indicates the difference in scaling may be due to difference in upper and lower triangularity



The ITER Hybrid and Steady-State Scenarios Provide the Biggest Challenges to Confinement

Reference ITER inductive operation requires extrapolation in τ_E by about a factor of 7 from the best JET shot:

- β and ν^* are more or less covered by present experiments, but low ν^* at at densities relative to the Greenwald density limit are not
- Extrapolation to ITER is about a factor of 3 in ρ^* from present data

Hybrid and steady-state operation will be pursued at lower currents (~12 MA and ~9 MA respectively):

- Steady-state at $Q \geq 5$ will require an enhancement over standard H-mode (i.e. $H_{H98(y,2)} \geq 1.3$, at $\beta_N \geq 2.6$ and bootstrap current fraction $f_{BS} \geq 0.5$)
- High pedestal values are not likely sufficient to the enhanced confinement and possibly pose control issues with a large portion of the current at the boundary
- Creation and maintenance of an internal barrier at $\rho \geq 0.6$ will likely be necessary to achieve adequate confinement

We need a better understanding of secondary influences on transport to ensure access to high-Q hybrid and steady-state scenarios

Plasma rotation – Key component in turbulence stabilization, but poorly understood

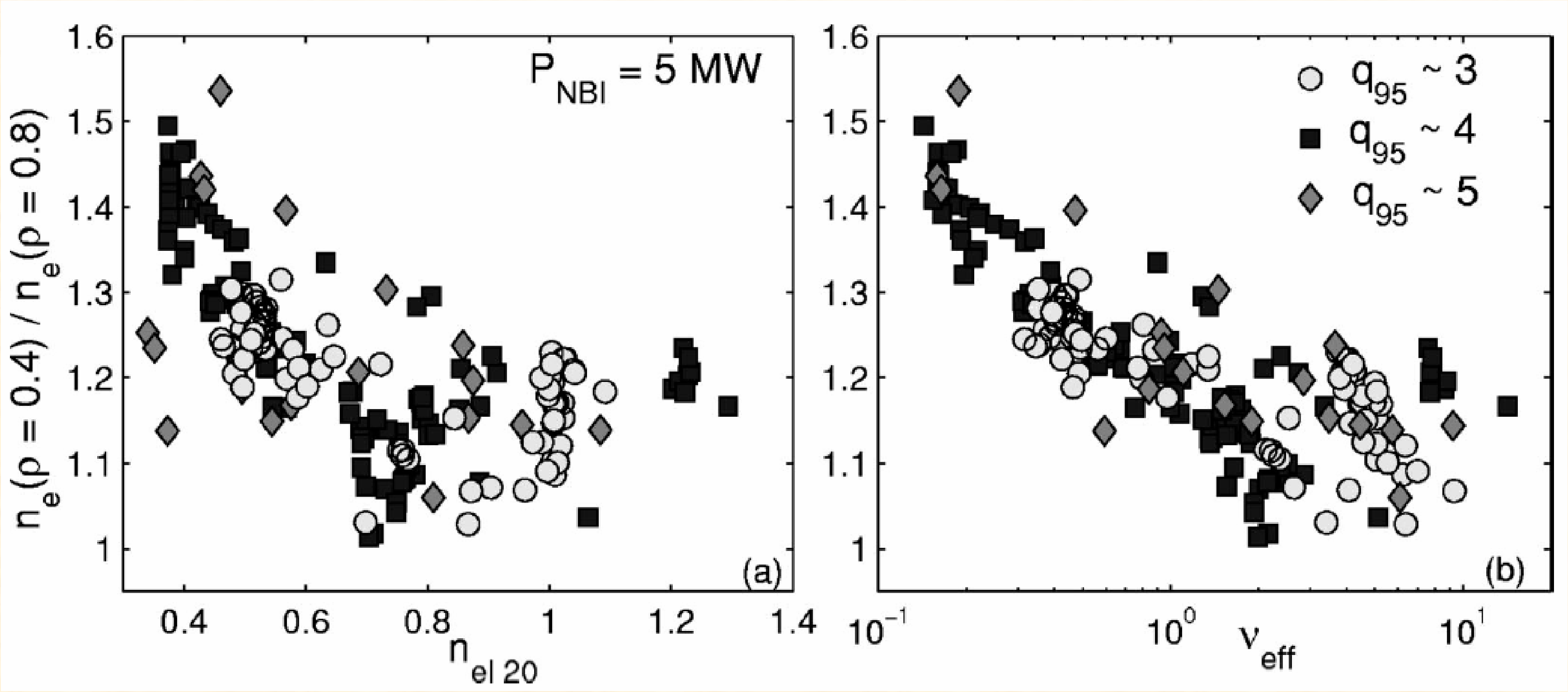
Toroidal rotation:

- ITER and fusion reactors will have low torque, so intrinsic rotation and its effect on transport needs to be better understood
- C-Mod experiments have pioneered work on toroidal rotation without external torque, and have shown that boundary effects are critical

Poloidal rotation:

- Initial DIII-D experiments have shown that impurity poloidal rotation in the core is much greater than neoclassical expectations (comparable to the expected values for main ions), and can contribute to ExB rotation shear

Particle transport – Density peaking observed at low collisionality

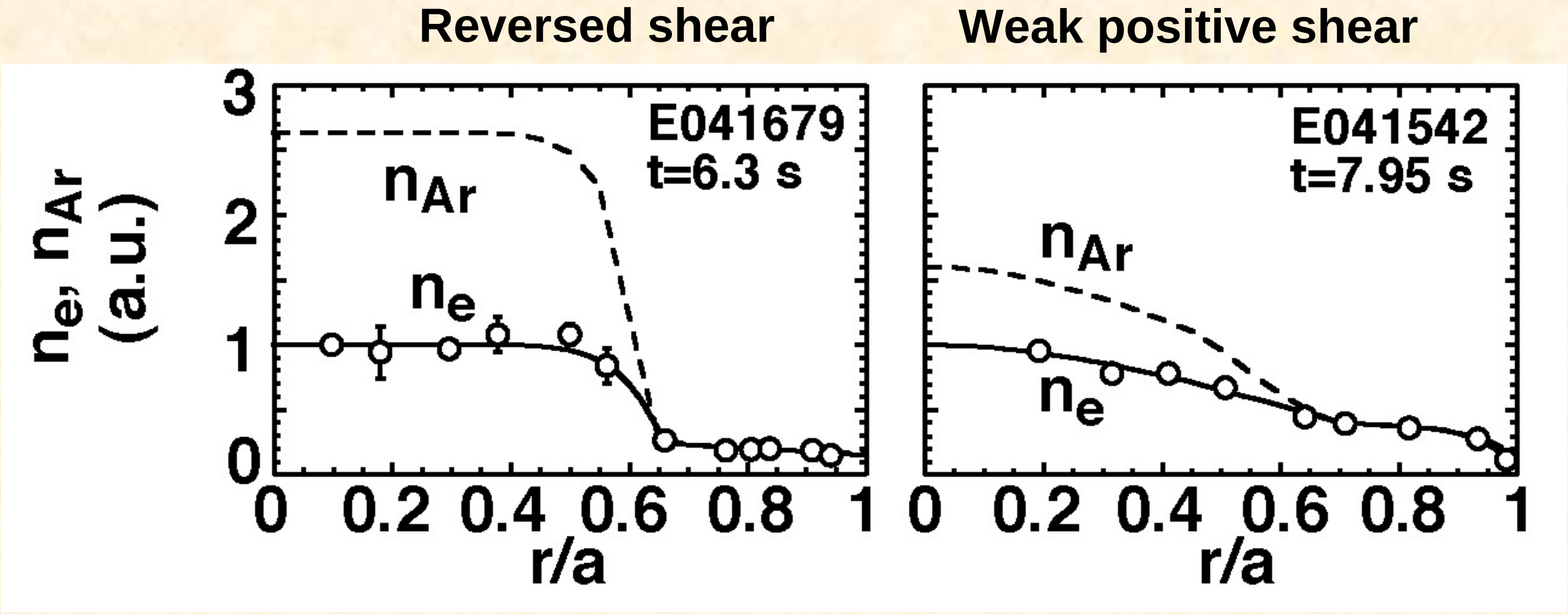


ASDEX-U showed that density peaking correlates well with decreasing collisionality

Numerous other experiments have found similar trends that cannot be attributed to the Ware pinch

Can turbulence models reproduce this behavior?

Impurity transport – Peaking is often less than expected from pure neoclassical

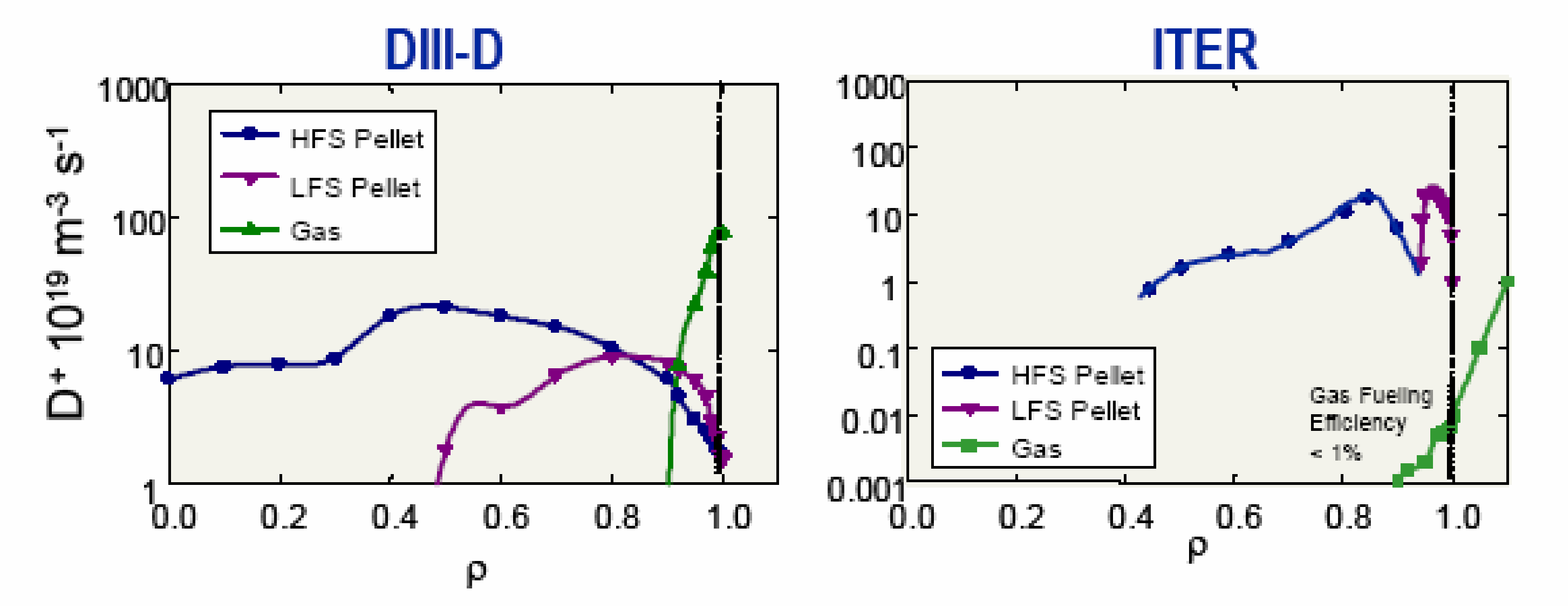


Many experiments indicate that a combination of neoclassical and turbulent transport is needed to explain impurity behavior

Very little effort has been expended on validating the effect of turbulence on impurity transport

A Particle Transport Working Group has recently been established in the ITPA to better understand transport of main ions and impurities

Fueling – ITER will require High Field Side (HFS) pellet injection



Gas and Low Field Side pellet injection will be much less efficient than in present machines

Initial model for the radial drift of the pellet ablatant have shown promise, but need much more extensive evaluation

Summary

Much progress has been made in the last several years in identifying the fundamental physics governing plasma transport

The present facilities and base program can provide better quantification of the physics:

- Linkages between the physics elements to provide a better predictive capability (e.g. barrier formation and maintenance)

Some issues will remain to be resolved by a BP experiment:

- Combination of parameters at the scale of a burning plasma
- Dynamics of a dominant internal energy source

The US has played a lead role in the theory, modeling, and experimental analysis of confinement issues, which should be maintained

The C-Mod, DIII-D and NSTX facilities cover a very broad range of parameters over which theory/models can be validated

The ITPA (or its equivalent under ITER) provides an international forum and even broader range of experimental data for validating these models