EXPERIMENTAL DESIGN TO EXAMINE THEORY BASED TRANSPORT MODELS USING PERTURBATIVE TECHNIQUES IN THE DIII-D TOKAMAK

Presented by

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Presented to

Joint U.S.–European Transport Task Force Workshop

APRIL 23–26, 1997
Madison, Wisconsin
IN COLLABORATION WITH

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KEY POINTS

- Two days of DIII–D experimental time have been scheduled to test theory based transport models
  - June 19, 1997 and July 24, 1997
  - Miniproposal review May 13, 1997 and July 1, 1997

- A set of experimental conditions exist where the plasma’s response to modulated ECH will allow models to be distinguished
  - We are presently designing only for the first day

- Experimental design continues and we ask for input from the theoretical and experimental community during this process
  - Ideas solicited during DIII–D Brainstorming (http://Fusion.gat.com)
  - A DIII–D Model Testing Working Group has been formed and is working on experimental design
MOTIVATION OF PERTURBATIVE EXPERIMENTS

- To move away from predictions based on empirical scaling relationships and toward predictions based on reliable local transport models

  - There is a rich history of perturbative experiments within the community and here we will try to combine perturbative techniques with model predictions

- To acquire experimental data that will allow the community to clearly differentiate between different local transport models

  - The ongoing model validation activity with the ITER profile database has not found large variations in the steady–state temperature profiles from various model predictions

  - Agreement to within approximately ±15% to ±25%
THERE ARE NOT LARGE SCALE VARIATIONS IN THE STEADY–STATE TEMPERATURE PROFILE PREDICTIONS

- Range in RMS deviation from 26.9% for GLF23, 24.1% for IIF, 21.8% for IFS/PPPL, to 14.7% for Multi–mode

\[ \text{RMS} = \Delta R_w = \left[ \frac{\sum_i (W_{s_i}/W_{x_i} - 1)^2}{N} \right]^{1/2} \]

\[ \text{Avg} = \langle R_w \rangle = \frac{\sum_i (W_{s_i}/W_{x_i} - 1)}{N} \]
DIll–D DIAGNOSTIC AND HEATING CAPABILITIES TO BE CONSIDERED DURING EXPERIMENTAL DESIGN

- Target plasma profiles determined by extensive DII–D diagnostic set
  - Thomson scattering: eight 20 Hz multipulse lasers with 44 spatial points
  - CO2 interferometers: 3 vertical and 1 radial viewing laser
  - ECE radiometer: 16 channels at 100 kHz
  - Charge exchange recombination: 40 channels with > 0.5 ms response
  - Visible Bremsstrahlung: 16 channels with 2 ms response

- The perturbed electron and ion temperature can be measured
  - CER at 1 ms response (500 records), > 50 eV with averaging
  - ECE at 1 ms response, plasma coverage optimized at 2.1 T, > 10 eV
  - Additional information from Visible Bremsstrahlung and Soft X–ray

- Experimentally the ECH system is the only suitable perturbation source
  - 1 MW deposited power for electron heating
  - 110 GHz with a toroidally fixed steerable antenna
L–MODE TARGET PLASMA FOR MODULATED ECH

- Inside wall limited L–mode
  - 6.6 MW NBI, 0.8 MA, 2.1 T
  - $3 \times 10^{19} \text{ m}^{-3}$, $T_{e,i} (0) = 4.0, 3.6 \text{ keV}$

- Sawtooth free and ELM free

\[ R (\text{m}) = 1.64 \quad a (\text{m}) = 0.63 \]
\[ \kappa = 1.8 \]
L–MODE TARGET PLASMA PROFILES

Electron density from CO\textsubscript{2} and Thomson scattering

\[ n_e (10^{19} \text{ m}^{-3}) \]

Temperatures from CER, HECE, and Thomson scattering

\[ T_i (\text{keV}) \quad T_e (\text{keV}) \]
Slope to transport solution point $\chi_{\text{eff}}$ or $\chi_{pb}$
- $\chi_{\text{eff}} = \frac{[P/SnT]}{[-(dT/dr)/T]}

Local slope at solution point $\chi_{\text{inc}}$ or $\chi_{hp}$
- $\chi_{\text{inc}} = \frac{\Delta [P/SnT]}{\Delta [-dT/dr/T]}

Define stiffness as $\chi_{\text{inc}} / \chi_{\text{eff}}$

Large stiffness tends to force marginality to critical gradient no matter how large the power flow
- Gyro–fluid ITG model: stiffness $O(100)$; multimode model: $O(10)$
- Itoh–Itoh–Fukayama model has no critical gradient. Model is a gentle concave curve with a very small stiffness $O(1)$
MODELS CONSIDERED DURING EXPERIMENTAL DESIGN

- Dorland–Kotschenreuther–Hammett (IFS/PPPL) gyro-fluid model
  - Critical gradient model but excluding sheared $E \times B$ flow

- Itoh–Itoh–Fukuyama (IIF) model
  - One-fluid transport without critical gradient
  - Renormalized by 0.3

- Multi-Mode (MM) model
  - Combines drift wave and ballooning transport models to predict temperature
  - Critical gradient model

- Waltz’s MLT code used to predict models’ response to temperature perturbation
DIFFERENT MODEL STIFFNESS MAKES TRANSIENT TECHNIQUES AN IDEAL APPROACH TO COMPARE EXPERIMENT TO THEORY

Ion Power Flow at $\rho = 0.4$

$$-\frac{d\ln T_e}{d\rho} = -\frac{d\ln T_i}{d\rho}$$

Model stiffness across the Plasma volume

Experimental Power

neoclassical

$P_i$ (MW)

$$-\frac{d\ln T_i}{d\rho}, \quad \frac{d\ln T_i^{\text{exp}}}{d\rho}$$

0 0.5 1 1.5 2

0 1 2 3 4 5

0 0.2 0.4 0.6 0.8 1

1 10 100 1000

IFS

GLF23

IIF

MM
THE ELECTRON TEMPERATURE PHASE AND AMPLITUDE RESPONSE SEPARATES THE IFS MODEL FROM IIF AND MM

- 1 MW ECH for 20 ms on, 20 ms off deposited at $0.4 < \rho < 0.5$ ($n_e = 3 \times 10^{19} \text{ m}^{-3}$)
- Clearly detectable difference in the $T_e$ response at $\rho = 0.1$
ION TEMPERATURE RESPONSE SHOULD BE LARGE ENOUGH FOR RELIABLE PERTURBATIVE MEASUREMENTS

- 1 MW ECH for 20 ms on, 20 ms off deposited at $0.4 < \rho < 0.5$ ($n_e = 3 \times 10^{19} \text{ m}^{-3}$)

- The 100 eV peak–to–peak $T_i$ variation for IFS should be detectable
  - The 25 eV peak–to–peak $T_i$ variation for IIF will not

![Graphs showing $T_i$ (keV) versus Time (msec) for different values of $\rho$.](image)
REDUCING THE DENSITY INCREASES THE ELECTRON TEMPERATURE RESPONSE

- 1 MW ECH for 20 ms on, 20 ms off deposited at $0.4 < \rho < 0.5$ ($n_e = 1.5 \times 10^{19} \text{ m}^{-3}$)

- The $T_e$ response of the IIF model has increased in magnitude at $\rho = 0.1$
  - Phase difference between the IIF and IFS model predictions
REDDUCING THE DENSITY INCREASES THE ION TEMPERATURE RESPONSE TO A CLEARLY MEASURABLE LEVEL

- 1 MW ECH for 20 ms on, 20 ms off deposited at 0.4 < \( \rho \) < 0.5 \( (n_e = 1.5 \times 10^{19} \text{ m}^{-3}) \)
- The \( T_i \) variation is now greater than 200 eV peak–to–peak for the IFS model
  - IFS ion response is out of phase with the ECH pulse

\[
\begin{align*}
T_i (\text{keV}) & \quad \rho = 0.1 \\
3.58 & \quad 3.38 \\
5.0 & \quad 4.8
\end{align*}
\]
\[
\begin{align*}
\rho = 0.5 \\
1.7 & \quad 1.5 \\
1.8 & \quad 1.6
\end{align*}
\]
FOURIER ANALYSIS WILL BE USED TO ANALYZE ACTUAL EXPERIMENTAL DATA

- First harmonic analysis for 1 MW ECH modulated at 10 ms on and 10 ms off shows a separation between the IIF and MM models and the IFS model.
A set of experimental conditions has been found that separate the IFS model from the IIF and MM models
- Differences in the $T_e$ and $T_i$ response for both phase and amplitude

Lower target density increases central temperature response
- IFS model predicts a greater than 200 eV central $T_i$ drop at the time of the ECH pulse

The experiment as presently envisioned would include a scan to low density in an inside wall limited L–mode plasma
- Operation at several neutral beam power levels would be possible
- Several H–mode pulses can be investigated during this first day to access usability of the LH heat pulse perturbation and modulated ECH in the steady–state ELM phase

What target plasma will allow us to distinguish the IIF and MM models or under what conditions does the stiffness of the two models differ the most?
- High power H–mode?
- Elongation scan?