1. Purpose of Experiments

The ICRF power will be modulated to produce a periodic heat source in the plasma core. The transient behavior of the electron temperature will be measured with the grating polychromator at 9 major radius positions spanning from the center to the outboard edge. Analysis of the phase and amplitude of the perturbations of the temperature profile will yield measurements of electron thermal transport coefficients.

2. Background

The technique of using the evolution of heat pulse from sawtooth crashes to obtain transport coefficients is well established [1]. Complications which arise with these techniques include density perturbation effects and drastic temperature gradient changes. Also, the amplitude and frequency of the sawtooth crash is beyond the experimenter’s control. It is thus of interest to use independent methods to make these measurements. Inward going ‘cold pulses’ from edge impurity injections offer the opportunity for a complementary technique, and recently published results [2] describe anomalous results. This technique will also be attempted on C-Mod, but is less likely to succeed during ICRF heating. Modulating the ICRF power provides another way of creating a periodic central heat source with which to make these measurements.

3. Approach

3.1 Apparatus: The nine GPC channels will be set up to view from the magnetic axis to the outboard edge ( r/a ~ 0.87 ). The inner 3 channels will be on or within the inversion radius, channels 4 and 5 within the mixing radius region and the remaining four
channels should view the ‘source-free’ region. This set up will allow measurements of the central heat deposition profile for the electrons, observations of MHD phenomena in the reconnection region, as well as the heat pulse propagation in the outer region. The grating set has been selected and verified to eliminate the effects of higher harmonic influence on the outboard channel signals.

3.2 Analysis: Calculations of the central power deposition profiles will be made from the post sawtooth crash electron temperature reheat rates[3]. Many standard techniques may be applied to extract estimates for the electron diffusivity from the heat pulse measurements[4]. Quick estimates may be obtained from the spatial dependence of the phase lag of the response to the modulated source through the expression[5]:

\[ \chi_{hp}^e = \frac{3n\omega_{mod}}{4} \left( \frac{d\psi}{dr} \right)^{-2} \]

where : \( n\omega_{mod} \) is the \( n \)th harmonic of the modulation frequency. Existing routines may be used to obtain these estimates during the run. The presence of sawtooth perturbations during these experiments may necessitate a more sophisticated routines to determine the effectiveness of the modulation.

3.3 Plasma parameters: There are a number of different time scales which enter into the dynamics of the experiment. These are:

- \( \tau_{Mod} \): Modulation period.
  Controllable over a wide range during the experiment.

- \( \tau_{S.D.} \): Slowing down time of the hot H minority ions, (See Figure 1).
  This is sensitive to many variables including the ion tail energy which is not well known. It imposes the upper limit on the modulation frequency for a given set of parameters:

  \[ \tau_{Mod} \geq \tau_{S.D.} \]

In figure 1., values calculated from the NRL formulary expressions are shown along with points which are the result of FPPRF runs [Takase]. The minority ions slow down on both electrons and ions. The ratio of the powers lost to electrons and ions is proportional to the collision frequencies, \( \nu_{ie}/\nu_{ii} \), also shown in figure 1. Since it is the electron response that we are measuring, it is desirable to run in the regime where electrons dominate the slowing down:

\[ \nu_{ie}/\nu_{ii} \geq 1 \]

This implies high tail energies, thus setting an as yet undetermined upper limit on density and minority concentration. Some piggy backing may be required to get a better handle on this question before the designated run.

- \( \tau_{E} \): Energy confinement time, (20-50ms).

The C-Mod data base gives the scaling of the energy confinement time during RF operation (only ‘low power’ data included to date) to be:
\[
\tau_E = 0.059 \times I_p^{1.13} n_{e0}^{-0.17} P_{tot}^{-0.57}
\]

For 2.5 MW ICRF, \( n_{e0} = 1.5 \times 10^{20} m^{-3} \) ms, \( I_p = 900 \) kA, this yields approximately 25 ms.

The ratio \( \tau_{Mod}/\tau_E \) is an important parameter which determines the nature of the perturbation speed. It is desirable to be able to modulate with \( \tau_{Mod}/\tau_E \ll 1 \). Since the modulation period is bounded below by the slowing down time, then \( \tau_E \geq \sim 4 \times \tau_{S.D.} \) should be accessible. Running at high \( I_p \) and high density is the best way of achieving this.

- \( \tau_{S.T.} \): The sawtooth frequency. (3 - 14 ms)

Sawteeth cause heat pulses of their own which will complicate the analysis of the heat pulse from the ICRF modulation. With strong ICRF heating, the sawtooth period quickly increases, presumably due to partial stabilization caused by the minority tail. Modulation experiments on other machines [6,7,8] have typically been done in non sawtooothing discharges. Results at JT-60U suggest that running at high current and high minority concentration increase the likelihood of sawtooth stabilization. As sawtooth reheat rates at the center yield deposition profile information, however, sawteeth are not without use.

Another consideration is the deposition profile. As the behavior in the 'source free' region gives transport properties, peaked profiles are better for this experiment. FPPRF runs, and reheat rate measurements show that running at high density density aids this consideration.

4. Resources

4.1 Machine and Plasma Parameters

Give values or range for:

- **Toroidal Field**: 5.3 T
- **Plasma Current**: Nominally 900 kA. Depending upon success, perhaps also 650 kA or lower.
- **Working gas species**: D with H minority. The nominal minority fraction should be \( \sim 1\% \leftrightarrow 10\% \), though H gas puffing should be available to vary this concentration. (See run plan).
- **Density**: The optimal target density is \( n_{e} l_{04} \sim 1.0 \times 10^{20} m^{-2} \). Scans in both directions will be attempted.
- **Equilibrium configuration** (if possible, refer to database equilibria): Standard configuration for RF runs.
- **Pulse length, typical current & density waveforms, etc.** Refer to database or sketch desired waveforms: Typical
4.2 Auxiliary Systems

**RF Power, pulse length, phasing:** Want both antennas fully operational. The capability to modulate both antennas at up to 100% amplitude variation and with frequency up to 100 Hz is desired. Modulation with just one antenna may also be of use.

**Pellet Injection (species):** No

**Impurity blow-off injection:** Yes.

**Special gas puffing:** Variable H-D mixture prefill.

**Other:**

4.3 Diagnostics

List required diagnostics, and any special setup or configuration, e.g. non-standard digitization rate.

All Standard diagnostics. GPC, RF, Xray tomography, Interferometer, Zmeter, spectroscopy, CX analysers in particular. Reflectometry and Thomson if available.

4.4 Neutron Budget

Estimate the neutron dose rate at the site boundary. Give basis for estimate. (Once some experience has been gained a standard formula will be provided for estimating dose rates.)

Standard.

5. Experimental Plan

5.1 Run sequence plan

Specify total number of runs required, and any special requirements, such as consecutive days, no Monday runs, extended run period (10 hours maximum), etc.

The completion of this proposed experiment will require one entire RF run day. Due to the uncertainties in the suggested optimal parameter values, it is likely that a significant prior effort to confirm or adjust these values will be required. Transmitter tripouts have already provided a small set of unintentional 'ICRF modulation' shots which give some idea of what to expect. These shots are being examined. In the near future, additional piggy back shots on prior RF days with plasma and GPC conditions similar to those expected in the experiment will be required. This may be more efficiently carried out during half an RF run day devoted to exploring parameter space.

5.2 Shot sequence plan

For each run day, give detailed specification for proposed shot sequence: number of shots at each condition, specific parameters and auxiliary systems requirements, etc. Include contingency plans, if appropriate.

It is desired to complete as thorough a scan as possible over the range of parameters that allow efficient modulation (see section 3). The optimal densities and modulation characteristics can not be specified currently, but the strategy for the run day has been
determined. If significant difficulties are encountered, the scans at the lower $I_p$ setting will be left out. The ideal shot plan as it can best be determined currently is given below.

The structure of the scans will be nested:

The current scan is at the coarsest level.

$I_p = 900$ kA for the first half day.

The H/D scan is scanned in one direction only (for each $I_p$).

Ramp H/D slowly from $\sim 1\% \rightarrow 10\%$

At each H/D point, three densities:

\begin{align*}
ne L_{04} & \approx 0.65 \times 10^{20} m^2 \\
\end{align*}

Take data at each density for optimal freq. & amp.:

Typically: 50% power modulation

at modulation frequencies 50 - 150 Hz

\begin{align*}
ne L_{04} & \approx 1.0 \times 10^{20} m^2 \\
\end{align*}

\begin{align*}
ne L_{04} & \approx 1.3 \times 10^{20} m^2 \\
\end{align*}

Now reduce $I_p$ to 650 kA and reverse the H/D scan.

Ramp H/D down slowly from $\sim 10\% \rightarrow 1\%$

again taking shots at three different densities on the the way down.

6. Anticipated Results

Discuss possible experimental outcomes and implications Indicate if the program may be expected to lead to publications, milestone completions, improved operating techniques, etc. Indicate if the experiments are intended to contribute to a joint research effort, or an external database.

The aim of the run is to provide as much information as possible concerning the power deposition and transport behavior of the ICRF heating using the the GPC as a primary tool. The power modulation transport measurements will complement other transient transport techniques used on Alcator C-Mod. Modulation experiments have been conducted with ICRF on other machines [6,7,8]. The high field, high density parameters of Alcator C-Mod can make a unique addition to the international database used to design future machines. In addition, this experimental work will become a part of O’Shea’s Ph.D. thesis.

7. References

Include references both to external and internal literature or communications which bear on this proposal. See Section 2.


