1. **Purpose of Experiments**

Include immediate goal of the experiments, scientific importance and/or programmatic relevance. Refer to any relevant program milestones.

Experiments on C-Mod involving non-inductive current sources, including LHCD and bootstrap current, will benefit from a feedback control scheme which enables the plasma surface voltage to be fixed at zero, such that the evolution of the plasma current proceeds independent of externally determined flux changes. In the absence of non-inductive sources, this condition would result in a plasma current decay with the characteristic L/R time of the plasma. When non-inductive sources are present the current will evolve (fall or rise) to a new level consistent with the drive. The control system must maintain the equilibrium shape and position as the current and internal inductance evolve, without producing a net change in the external flux. The problem is therefore not equivalent to fixing the current in the primary ohmic solenoid.

The purpose of this experiment is to validate a suitable observer for the surface flux (or voltage), and determine satisfactory values for the signal conditioning and actuator gain parameters, as described below. The development work can be carried out under ohmic conditions during the pre-physics phase of C-Mod operation. Successful operation would then correspond to free decay of the plasma current on the L/R time. The resulting control scheme should then be transferable to current drive or advanced scenario experiments with minimal modification.

2. **Background**

Discuss Physics basis of the proposed research, Prior results at Alcator or elsewhere, and any related work being carried out separately.

Standard C-Mod operation employs control of the plasma current following an initial ramp-up phase. The current control normally begins at t=0.1 sec, when the current is typically around 500kA, and continues through ramp-down at the end of the shot. The observer consists of a single rogowski loop, and the controller consists of a vector of voltages...
applied to all of the OH and EF coils (except EFC) and is designed to provide a nearly flat flux pattern in the plasma region. Proportional gain is employed, and the gain value is varied during the discharge to provide relatively good current control without exceeding power supply limits.

During the last (2006) campaign, LHCD experiments were conducted with the standard plasma current control active, and the current drive efficiency was estimated by the change in the “loop voltage” observed [1]; in this case the loop voltage was determined either from the time derivative of the EFIT surface flux, or based on the MFLUX PSI0 value. In at least one case (shot #1060728014) the nominal loop voltage was observed to reverse and then go to zero, while the plasma current marginally increased. The zero voltage condition was maintained for $\leq 1$ current rearrangement time, and the EFIT $l_i$ did not reach a steady value during this time, indicating that the current density profile was still evolving. Subsequent TRANSP analysis indicated that the rf-driven current was in fact slightly less than the total plasma current, with the remaining ohmic drive arising from time-varying internal flux[2,3]. However, this analysis is complicated by the time-variation of the surface voltage imposed by the current feedback loop. Experiments proposed for the 2007 campaign [4] call for maintaining a zero loop voltage for multiple $\tau_{CR}$.

During the 2003 campaign, an attempt to provide zero voltage feedback control was carried out in connection with MP#344b (P. Politzer, et al., “100% bootstrap fraction plasmas”), Run #1030702. The approach was closely related to that proposed below, using an observer for the flux at a point in the plasma and employing derivative feedback with a flat target (reference) waveform to enforce the zero voltage condition. In that case, the location specified for the flux observer was taken near the plasma magnetic axis, rather than a point on the surface. Furthermore, the derivative gains applied resulted in bi-polar saturated demands to some supplies due to amplification of input noise, as well as internal saturation of the analog signal path in the Hybrid, which was being used for plasma control at that time. These issues are addressed in the approach proposed here.

3. Approach

Describe the methodology to be employed; explain the rationale for the choice of parameters, etc. Describe the analysis techniques to be employed in interpreting the data, if applicable. If the approach is standard or otherwise self-evident, this section may be absorbed into the Experimental Plan.

It is proposed to use the standard Ip control to bring the plasma current to a programmed flattop level, and then turn off the Ip feedback and replace it with feedback control of the surface loop voltage, achieved by applying derivative gain to an error signal proportional to the surface flux. For purposes of this control development experiment, the loop voltage control would be maintained through discharge termination. Whether this ramp-down strategy is suitable for application to later physics experiments employing loop voltage control remains to be seen.

The loop voltage control will be implemented using the digital plasma control system (DPCS). The key features of the proposed control algorithm are as follows:

1. Observer estimates the flux at or near the x-point
2. Low-pass filter is applied to the observer signal to reduce the impact of high frequency noise.

3. Derivative gain will be used with a constant reference (target) value to feedback to zero surface voltage, \( V_{\text{surf}} = -2\pi (d\psi(a)/dt) \)

4. Controller vector will be the same as that normally used for \( I_p \) control, to produce a nearly flat flux pattern over the plasma crossection.

Initial experiments will be based on the FLUXIHH observer for PSI0, which returns an estimate of the flux at a point in space designated by parameters \( (R_{\text{center}}, Z_{\text{center}}) \)[5]. For the purposes of this experiment the values of \( (R_{\text{center}}, Z_{\text{center}}) \) will be changed from the default location near the center of the plasma to the coordinates of the nominal x-point, \((0.565, -0.394)\). A more sophisticated algorithm could be developed to return an estimate of the flux at the actual x-point, as indicated by the observers RXL and ZXL, but for the primary cases of interest, during which the x-point location is not expected to vary dynamically, this should not be required. Application of the scheme to initial current ramp-up by non-inductive means, which has been mentioned, or as an alternative ramp-down scheme, would likely require such a development, but that problem is beyond the scope of what would be attempted in the initial half run day. Note that the same technique is readily applied to limiter discharges by changing the reference point \( (R_{\text{center}}, Z_{\text{center}}) \) to a suitable point on the inner wall, e.g. \((0.44, 0.0)\).

A minor additional complication is that, for reasons known only to the programmer, the PSI0 observer does not actually return the flux in SI units, but rather a quantity scaled by a constant \( \text{CALFAC} = 2\mu_0 \left( \frac{R}{a} \right) \approx 8 \times 10^{-6} \); this matters only in that it affects the interpretation of the error signal.

Since we will be employing derivative gain to feedback on the voltage rather than a specific flux value, it is important to reduce the influence of higher frequency noise on the error signal. This will be accomplished by applying a simple digital low-pass filter on the observer value. The filter will be implemented as a callable procedure within the DPCS system. The time constant, as well as the interval of operation for the filter, will be input by the Physics Operator through the PCS Operator Interface. A typical value for the filter time constant would be \( \tau_{\text{RC}} \approx 0.05 \) sec, which should be sufficient to suppress high-frequency noise and power supply switching transients without unduly limiting the dynamic response of the control loop. The filter time constant will be optimized experimentally. Coding of the filter algorithm, \text{DPCS\_LOWPASS\_OBS} is in progress at this time.

As noted, the controller to be used for the loop voltage will be the same as (or closely related to) that normally used to feedback on the plasma current. This controller, the XCONTIH algorithm also designated PSI0, is based on providing a combination of OH and EF coil voltages which control the flux at the nominal PSI0 reference point \((0.67, 0.0)\), and are orthogonal to the main shaping parameters[5]. By using this controller to feedback on the (derivative of) the x-point flux, we should be able to control the surface voltage without perturbing the plasma shape or position. The independent feedback controls on the various shape parameters will compensate for any imperfection in the controller orthogonality, just as it does under \( I_p \) control. Some variation in the weighting of the controller voltages could
be undertaken to optimize the voltage demands and supply currents, or to improve the
flux pattern, but this is expected to be a minor consideration.

Assuming validation of the observer as a good measure of the surface flux, as indicated
by EFIT, determination of a satisfactory value for the derivative (D) gain will be the prin-
cipal product of this experiment. This constitutes a single parameter optimization, based
on a trade-off among minimization of the loop voltage, orthogonality to shape control,
stability of the control loop, and avoidance of power supply limits (voltage and current).

Development of this algorithm could benefit from pre-operation simulations using
the Alcasim code. However, since the PCS/DPCS interface to Alcasim is temporarily
broken due to recent “improvements” in the DPCS software, it is not guaranteed that
these simulations will be feasible in the available time. Testing of the observer and low-
pass filter algorithms against data from pre-existing shots can be undertaken using the
test_dpcs2_software routine, which will be used to validate these components in an
open-loop fashion prior to application to plasma. Initial values for the feedback gain can
also be validated in this test environment by observing the output actuator demands in
response to known error signals.

The initial plasma experiments could be carried out during pre-physics (startup) op-
eration, to establish the technique and determine satisfactory parameters, mainly the value
of the derivative gain and the low-pass filter time constant. The first application to physics
plasmas would presumably be for LHCD experiments, and may require a few dedicated
set-up shots to optimize the control. The plasma parameters for the ohmic experiment
are non-critical, and this work could be piggybacked on the last half of shots designed for
another ohmic experiment. Preferably the starting condition should be a LSN discharge
at moderate current and relatively low density.

The observer and filter procedure would first be implemented on an unused PCS
wire (10V reference) and the Aout signals observed. The results will be compared with
the EFIT surface voltage, as well as previously obtained results from software testing
and (if available) Alcasim simulations. An initial setting of the Derivative gain will be
programmed for the last half of the shot (starting at \( t \approx 0.7 \) sec), with the Controller set to
zero, to verify the output of the PID stage. All of these steps can proceed with no impact
on the plasma, as a pure piggyback experiment, as long as a suitable PCS wire is available.
Once a sensible PID output is verified, the Controller for the wire will be filled in, and the
\( I_p \) Proportional gain turned off at the time the Derivative gain on the PSI0 wire is turned
on. The loop voltage should drop to zero and the plasma current decay resistively. If the
ramp-down programming does not call for a fixed x-point position, it may be necessary
to adjust this to maintain the zero voltage condition through the end of the shot. The
remainder of the experiment would consist of adjusting the D gain, and perhaps the filter
and controller values, to optimize the surface voltage feedback.

A possible refinement might be to include some proportional gain on PSI0, which
would correspond to integral gain with respect to the Voltage, and might improve the
stability of the control loop. This would require that the target value be matched to the
observer value at the time the feedback is turned on, and the initial gain value must be
kept low to avoid unpleasant transients if the actual value is not close to expectation. If it turns out that a P gain is beneficial, it should be possible to implement an algorithm that samples the instantaneous observer output and targets that value; however, it is not anticipated that such an algorithm will be available for the initial experiments.

4. Resources

4.1 Machine and Plasma Parameters

- **Toroidal Field**: -5.4 T typical (non-critical)
- **Plasma Current**: Any convenient value $0.6 \leq |I_p| \leq 1.0$ MA
- **Working gas species**: D$_2$
- **Density**: NL04 $\leq 1 \times 10^{20} m^{-2}$ (non-critical)
- **Equilibrium configuration** (if possible, refer to database equilibria): LSN, prefer constant x-point location during ramp-down
- **Pulse length, typical current & density waveforms, etc.** Refer to database or sketch desired waveforms: Standard (current will ramp-down beginning at $t \sim 0.7$ sec during active control)

4.2 Auxiliary Systems

- **RF Power, pulse length, phasing**: none
- **Pellet Injection (species)**: none
- **Impurity blow-off injection**: none
- **Diagnostic Neutral Beam**: not required, no objection
- **Special gas puffing**: none required
- **Non-axisymmetric Coils (Connections,Current)**: Standard locked mode suppression orientation
- **Other**: 

4.3 Diagnostics

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

Standard magnetics diagnostics, DPCS inputs.
5. Experimental Plan

Both sections must be filled in.

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.

About 0.5 run day required. Could be combined (piggybacked) with other ohmic experiments.

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.

1. Program “PSIO” observer, low-pass filter, initial D gain on 10V referenced wire, with controller zeroed and constant target waveform. (Note that a 10V ref is not required if we only use derivative gain, since a target value of zero will work even on an Ip-referenced wire.) Monitor observer and PID outputs, and compare with EFIT analysis, prior test and simulation results. Adjust program parameters to get smooth output with reasonable magnitude from PID stage. [3-5 shots]

2. Load the controller. To match the Ip controller, use Algorithm=\texttt{XCONTIHH}, Keywords=\texttt{TAUOPT}=0.3. Turn the Ip wire gain off at the time the D gain on the PSIO wire turns on. Observe ramp-down and adjust gain to get stable, zero surface voltage while not over-driving any power supplies. If necessary, try re-programming target waveforms for \( t > 1.5 \) sec to maintain constant x-point location through end of shot. [5-10 shots]

3. If time permits, vary target parameters (e.g. current, density) to test robustness of zero volt feedback. [5 shots]

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.

Development of a reliable feedback control scheme for clamping the surface voltage to zero will facilitate experiments calling for 100% non-inductive current drive, including LHCD and bootstrap scenarios.

7. References

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


