1. Purpose of Experiments

The purposes of this experiment are to understand the consequences of requiring that the current profile and the pressure profile be tightly coupled via the condition of high bootstrap current fraction in the collisionless regime and to study the behavior of fully noninductive plasmas when the total current is not constrained by pre-programming. Two cases will be examined: EDA H-mode and density Internal Transport Barrier (ITB) plasmas.

2. Background

Steady-state discharges in ITER and following reactors must, of necessity, be fully noninductive and dominantly of bootstrap origin. For example, it takes 30 MW of gyrotron waves (150 MW of fusion thermal power) to drive 1 MA of plasma current via ECCD in the core of ITER. For efficient operation the bootstrap fraction should be 90%. In these discharges, the current and pressure profiles as well as transport and stability are closely coupled. The objectives of this experiment are threefold: To begin to explore the self-consistent profiles of current and pressure reached by a fully noninductive, high-bootstrap-fraction, collisionless discharge; Second, to examine whether this state is dynamically stable; And third, to ascertain whether it has good confinement and high stability limits. Operationally, the present experiment is designed to produce fully noninductive, essentially 100% bootstrap current discharges and to determine what initial conditions lead to a stationary final state (and what conditions lead to collapse of the plasma), under what conditions the current and pressure profiles in this state are stable, against both MHD instability and steady decay, whether the final state is unique (for given particle and energy sources), and what is the maximum stable beta in the self-consistent stationary state. Previous experiments with transformerless operation on DIII-D have shown a marked sensitivity to small MHD perturbations. It will be important to understand the extent to which this affects the achievable beta.
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.

Alcator C-Mod is well-suited to achieve these objectives as its dominant heating method, minority ICRF, does not directly drive current and thereby mask the bootstrap current. Its small size accelerates L/R decay of unwanted inductive currents while the strong magnetic field maintains good confinement. The experimental approach will be to produce, with inductive current control and the maximum available RF power, a target plasma with the highest bootstrap fraction possible. This leads one to low-current discharges - 200-500 kA. The location of the ICRF resonance will be varied so that either EDA H-mode or ITB discharges will be available for investigations. Both on- and off-axis heating will be necessary to control ITB plasmas. One must remark that the high electron-density gradients of ITB plasmas are very favorable for increasing bootstrap current.

Planning estimates indicate that high bootstrap fraction discharges in C-Mod will occur at quite low plasma currents 200 - 300 kA. The scenario to achieve high bootstrap fraction proceeds as follows: An initial transformer current ramp will be established at 0.5s yielding a ~ 500kA ohmic plasma. Next, fast wave ICRF heating is applied, either on-axis or off-axis for H-mode or ITB discharges respectively. At this point, plasma current control is turned off and the poloidal field is determined by that necessary for plasma shape, divertor x-point, and major radius control. It is recognized that these controls have small mutual inductance coupling with the plasma, so as the plasma current decays, the plasma boundary flux will change, indicating that holding the plasma surface flux constant would not be correct. High power heating continues, maintaining the pressure gradient and hence the bootstrap current. One then simply waits and observes the plasma evolution. As the total current decays, theory predicts that the bootstrap fraction will increase. Hopefully the discharge will eventually settle into a self-consistent, self-organized, steady-state plasma with or without an internal transport barrier. The plasma current will be almost entirely of bootstrap origin driven by the pressure gradients which in turn are maintained by the ICRF heating. Since the discharge is by now steady-state, there will be no loop voltages in the system. Control of density peaking, with pellets or spontaneously via an ITB, will be very useful in increasing the bootstrap current. Scaling of anticipated results will be documented in a separate memo. Currents in the range 200-400kA are expected based on scaling from existing discharges.

If high-bootstrap discharges are found, then scans of density, heating power, rf frequency and plasma size and shape will be needed to support projections to reactor-scale devices.

A concern is that the heating - 4 MW for 5s - is too weak and thus the plasma will be on the fringes of the collisionless region.

Truly steady-state discharges constitute a new frontier in tokamak operation physics and procedures. These discharges differ from conventional tokamaks in that they are self-organized entities which determine the plasma current from physics for a given a
power source such as minority ion cyclotron fast wave heating or thermonuclear reactions. The Run Sequence Plan in section 5 aims at establishing the fundamental properties of high bootstrap fraction conditions both for use in planning future experiments and to establish a database of self-organized plasmas. Realizing steady-state discharges calls for new operational methods that will maintain zero loop voltage at the plasma boundary. The familiar feedback control on the plasma current will be replaced by a zero surface-loop-voltage condition, which is available from the array of poloidal flux sensors. The actuator coils are the poloidal field loop array, particularly the vertical field combination that must maintain major radius position over a factor of three (200 to 600 kA) in plasma current. Specifically, the pf control system must produce $V_{\text{loop}} = 0$, major radius position, inside and outside minor radius, and divertor x-point location. Since bootstrap current profiles differ from Ohmic current profiles, MSE diagnostics will be valuable to experimentally determine exactly what current density profile is. Obtaining effective and routine $V_{\text{loop}}$ control is an essential step towards steady-state tokamak discharges.

The operational plan is to use well known procedures to produce at $t \approx 0.5 \text{s}$ an initial, SN, $\kappa \approx 1.7$, ohmic 500 kA discharge at low density $n_{20} = 2.0$ and in the H-mode confinement regime. After transition to H-mode, one switches from current feedback control to $V_{\text{loop}} = 0$ control, applies 0.2, 4 MW of central minority fast wave heating and observes the ensuing plasma current, $T_e$, and $n_e$ decay. If a 100% bootstrap is obtained, this decay will cease for plasma currents in the 200 kA range. The plan is then to vary operational parameters $n_e$, initial current profile, RF Power, ICRH resonance position, and density ITB discharges. C-Mod’s density ITB discharges look very promising because of their high density gradient, which is well-known to be more effective at generating bootstrap current than temperature gradients. We plan to vary the toroidal field to shift from high-field-side to central ICRH after the barrier has been established to avoid radiative collapse.

Concern has been expressed regarding degradation of heating resulting from direct ion orbit loss, especially at low plasma currents. This paragraph addresses this concern. A key benefit of ICRH heating is that the wave-particle energy transfer takes place in the immediate vicinity of the magnetic axis because of the combined effect of resonance absorption and refractive focusing into the plasma center. Consequently, our attention is directed to potato orbits which pass through and mirror at the magnetic axis. This orbit has $V_\parallel = 0$ at the axis. The criterion that this orbit reaches the full minor radius on the LFS is $E_{\text{keV}} > 1000 I_{MA}^2/(1 + \kappa^2)$ and is $E = 10 \text{keV}$ at the lowest currents we envision $I = 0.2 \text{ MA}$. This suffices to heat the plasma provided the heating is spread more or less uniformly through out the plasma, which must be just what happens when energy transfer is by large potato orbits. Since a typical orbit which passes through the magnetic axis has parallel velocity, its radial excursion is less and the energy required for loss will be higher. This ion orbit loss appears not to be excessive, although at the lowest current it may be at work. A more detailed study should be carried out with the data analysis.

4. Resources
4.1 Machine and Plasma Parameters

Give values or range for:

Toroidal Field: \(5.3\ T\)
Plasma Current: \(\sim 500\ \text{kA}\)
Working gas species: \(\text{D}\)
Density: \(n_{20} \approx 1.0 : 2.0\) (H-mode phase)
Equilibrium configuration (if possible, refer to database equilibria): \(\text{SN, } \kappa = 1.7\)

Pulse length, typical current & density waveforms, etc. Refer to database or sketch desired waveforms: 5sec

4.2 Auxiliary Systems

RF Power, pulse length, phasing: 4 MW @ 80MHz, at least 1 MW @ 70 MHz (not needed for initial experiments), pulse length \(\leq 5\ \text{sec}\), heating phasing

Pellet Injection: D (for later experiments)

Pellet Injection (species): D (for later experiments)

Impurity blow-off injection:

Diagnostic Neutral Beam: MSE highly desirable

Special gas puffing:

Other:

4.3 Diagnostics

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

Diagnostics needed to reconstruct equilibrium: Thomson scattering, ECE, interferometer, magnetics; will use MSE to document best achieved final plasma state.

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.

Up to three half-day sessions to develop initial discharges. \(T_e(0) = 1.5\ \text{keV}\) is expected. Provided a successful plasma formation technique can be found, full-day scans to determine the maximum stable heating power and density as well as an optimized shape and bootstrap fraction will be carried out for both H-mode and ITB plasmas.
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.

This plan is for the initial half-day. We also give an indication of scans that should be done if the initial attempts to establish a fully bootstrap driven state show some success.

Step 1: Setup shot like 1030530024 (600kA, target density n\textsubscript{li04}=6e19 m\textsuperscript{-2}) with all shape parameters and tf extended to 2sec. Turn on 3-4MW RF at 0.6sec and switch from Ip to psi0 (derivative) control at .7sec. If necessary, adjust timing to avoid OH1 crossover. Tune up psi0 gains and adjust RF tuning trying for H-mode plasma with Vsurf=0 and RF staying on and gaps and shape approximately constant. Get MSE data at initial and late times. Note evolution of sawteeth on ECE and Soft Xrays. Monitor radiated power, strike point temperatures and antenna thermocouples. Engineers should monitor \( I^2t \) signals, magnet heating, etc. as on the long pulse runs 1010802 and 1010803. [5-10 shots]

Step 2: Extend pulse length in 0.5sec increments (or more as indicated) if and when plasma and RF are surviving that long. Try to remember to extend timebases on key diagnostics. If we go beyond 3sec, delay Thomson Scattering to insure getting profiles at the end. Keep moving the DNB pulse later as the pulse length is extended. Monitor TS profiles and VB array for signs of density peaking. Continue to monitor heating of walls, antennas, magnets. As current drops, look for indications of fast ion loss. We are looking for something that looks like a steady-state with finite current and zero loop voltage. See if MSE can tell whether angles are still changing at late times. [5 shots]

Step 3: If it looks like there will be time, optimize by varying target density +/-25% and/or RF power 2-4MW; if density is falling with current we may want to puff into the H-mode to maintain slowing down time short enough to avoid tail ion loss. [5 shots]

Step 4: Document best plasma. Assuming we have something that looks like an interesting (steady or near-steady) final state, verify that we have MSE data at the end, repeat the early state MSE, and fill in intermediate points as possible [2-4 shots]

Follow-up scans (next time, or if all works wonderfully well the first time):

Step 5. Power scan. See what happens at higher power, vary current at which RF is turned on or increased.

Step 6. Density scan. Extend scan started in step 3, at 4 MW ICRF.

Step 7. ITB control. If an ITB occurs, try to control peaking by varying B during the shot or varying power. Otherwise, we will likely want to repeat the experiments starting from an ITB discharge to take advantage of the higher bootstrap current associated with grad n relative to grad T.

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 objective is to provide an experimental basis for steady-state plasma operation with 100% bootstrap current. This is the key operational mode foreseen for a steady-state fusion reactor and has yet to be demonstrated experimentally. To date, steady-state plasmas have had a current drive fraction of 10% or higher. This experiment can also be carried out in JET or TORE-SUPRA and an early start on this research is recommended to avoid being scooped. The results of this experiment will also define rf power requirements to test toroidal beta limit. (A 100% bootstrap plasma has fixed poloidal beta)

These basic data should be a resource to anyone planning high-bootstrap research on C-Mod and, when combined with scaling relations, a guide for DIII-D as well. Use of density ITBs to achieve high bootstrap current is quite promising, but may require close to 8 MW of auxiliary power, split between on-axis and HFS resonances. Our anticipated result is that V-loop control will successfully lead to controlled current decay, but that a higher-power (8MW) two-frequency auxiliary power level will be required to stop plasma current decay and achieve full steady-state discharges. These data will tell us how much more power is required and whether density ITBs can be exploited.

7. References

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