Subject: Current Rise Optimization

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Approved by: ___________________________  Date Approved: ________________

1. Purpose of Experiments
Include immediate goal of the experiments, scientific importance and/or programatic relevance.
Refer to any relevant program milestones or ITER R&D commitments.

This is a series of experiments that attempt to optimize the current rise to test possible ignition scenarios in a future compact high field ignition experiment. Due to run time constraints, the experiments will start out modestly with two run days devoted to optimizing the current rise at 5.4 T. One day will be devoted to L-mode studies with high power ICRF heating of inner wall limited elongated plasmas. The second day will instead attempt to achieve H-mode as early as possible in the current rise using rapid elongation to produce an early single null X point. The optimum scenario should approach relatively high temperatures ($\sim 4$ keV) at high density ($n_e \sim 4 \times 10^{20} \text{ m}^{-3}$) with $Z_{eff} \leq 1.6$ around the time the current reaches flattop and if possible maintain these conditions for several energy confinement times.

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

Ignition scenarios in tokamaks depend on optimizing the current rise to reach high current relatively quickly to save volt-seconds and to delay the onset of sawteeth through slow core current penetration. The density and temperature must also rise quickly to achieve ignition conditions. An IGNITOR ignition scenario [1,2], for example, needs to achieve at least the ideal ignition temperature ($T_{i,e} \sim 4.25$ keV) at a density of about $n_e \sim 4 \times 10^{20} \text{ m}^{-3}$ at the current flattop. These experiments should help to verify the feasibility of such a scenario.

Calculations of the confinement time required to reach these conditions in C-Mod have been done based on shots that were as close as possible to these conditions. Two example shots are 971717007 and 990225018, which were both 1.2 MA shots at 5.4 T and relatively high density. The confinement time was calculated by multiplying the density profile by a factor $\gamma_n$ such that the line averaged density would equal $4 \times 10^{20} \text{ m}^{-3}$ and multiplying the temperature profile by a factor $\gamma_T$ such that the central electron temperature was 4
keV. The time of interest was just as the current reached flattop. Then, taking an assumed total input power available $P_{in} = 7$ MW, the confinement time is calculated as follows:

$$
\tau_E = 1.5 \int 2 \gamma n T n_e T_e dV / (P_{in} - \gamma n T dW/dt)
$$

with $dW/dt$ taken from the EFIT calculation. The required $\tau_E$ came out to between 0.035 and 0.039 sec. The H factor required to achieve these confinement times calculated using the ITER89-P scaling law [3] with the assumed conditions came out to be between 1.4 and 1.6 for these cases. These simple calculations suggest that the target plasma conditions should be achievable in H-mode and may not be very far off even in L-mode with transient improvement in confinement as the current profile evolves.

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.

Start with a well conditioned boronized machine to attempt to keep $Z_{eff}$ below 1.6. The ICRF must be running well with high power up to at least 5 MW, preferably more. On the first day, inner wall limited discharges will be run with high power ICRF heating in the current rise to attempt to remain in L-mode. Start with a relatively high current ramp rate of 5 MA/s for the first 0.1 sec. Program the flattop to reach 1 MA by 0.45 sec. Then, increase the ramp rate after 0.1 sec to reach 1 MA sooner until the optimum rate is found. The elongation and radius of the plasma will also be varied to change the q profile evolution and find the optimum. The gas puffing rate will also be varied to affect the internal inductance during the current rise. To avoid current rise MHD activity, a relatively high internal inductance ($l_i \geq 1.5$) is desirable. Start with a requested density at flattop of about $n_{04} = 1.5 \times 10^{20}$ m$^{-2}$ and then attempt to increase the density with increasing current ramp rate. By combining these attempts to optimize the current rise with high power heating, it may be possible to slow down current penetration enough to delay the onset of sawtoothing and allow relatively peaked high temperature and density profiles to be maintained for several energy confinement times. If available, deuterium or lithium pellets may also be used to modify the current profile and increase the density during the current rise.

4. Resources

4.1 Machine and Plasma Parameters

Give values or range for:

- **Toroidal Field:** 5.4 T
- **Plasma Current:** 1.0 - 1.2 MA
- **Working gas species:** D$_2$
- **Density:** 1.5 - 2.5 x $10^{20}$ m$^{-2}$
**Equilibrium configuration** (if possible, refer to database equilibria): Inner wall limited, new pulse to be drawn up, then lower single null X point early in current rise also to be drawn up based on 980217013.

**Pulse length, typical current & density waveforms, etc.** Refer to database or sketch desired waveforms: rampdown at 1 sec

### 4.2 Auxiliary Systems

**RF Power, pulse length, phasing:** 4 - 7 MW for 0.5 sec  
**Pellet Injection (species):** D or Li possibly  
**Impurity blow-off injection:** none  
**Special gas puffing:** standard valves  
**Other:** This run requires a very clean machine

### 4.3 Diagnostics

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

All diagnostics should concentrate on the current rise phase from t=0 to 0.5 sec or when the current reaches flattop.  
- Fast magnetic pick-up coils (1 - 2 MHz sampling)  
- Core and Edge Thomson Scattering  
- HIREX for Ti profiles  
- Interferometer  
- ECE GPC and/or GPC2  
- Visible bremsstrahlung for Zeff profiles  
- Spectroscopy diagnostics for main impurity concentrations

### 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.)

$10^{15}$/day

### 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.

Given a well running clean tokamak, two run days (50 shots) should be sufficient to perform these experiments. Future experiments are planned at 8 T and depending on the results, more run time may be required during next year’s campaign to further optimize the current rise.
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.

Start with inner wall limited discharges with an initial ramp rate of 5 MA/s for the first 0.1 sec, then raise the current to 1 MA by 0.45 sec. Program an initial density of \( n_{\text{lo4}} = 1.5 \times 10^{20} \text{ m}^{-2} \) at flattop. Start with a couple of ohmic comparison shots to benchmark the transport simulations. Then, start ICRF heating at 0.05 sec increasing it rapidly to at least 5 MW and maintain high power throughout the current rise to at least 0.55 sec. First, increase the current ramp rate to reach 1 MA sooner to find the optimum (4 shots). Next, increase the radius and elongation of the plasma to broaden the current profile to find the optimum size growth rate of the plasma (20 - 60 cm/sec) (5 shots). Gradually increase the density shot to shot, first with gas puffing, to try to reach \( n_e \sim 4 \times 10^{20} \text{ m}^{-3} \) before the end of the current rise (5 shots). If an optimum is found for the rate of density increase, try several shots varying \( dI/dt, da/dt \), and \( d\kappa/dt \) to find the optimum of all four quantities (4 shots). Finally, a power scan will be made from 2 to 7 MW or as much as is available to determine the effects of power on the profile changes in the current rise at the optimum condition (4 shots).

The second run day will attempt to optimize the current rise with diverted plasmas as early as possible in the current rise. See for example shot 980217013, which diverted at 0.24 sec. Attempts will be made to make the plasma divert sooner (4 shots). Through high power heating in the current rise, H-mode will be achieved as early as possible during the discharge. Similar scans will be made in the current ramp rate, the rate of increase of the plasma minor radius, and in the rate of increase of the density to attempt to optimize the current rise with diverted lower single null plasmas in H-mode (12 shots). Finally, a power scan will be made from 2 to 7 MW or as much as is available to determine the effects of power on the profile changes in the current rise at the optimum condition (4 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.

The results from these experiments will be simulated using a predictive transport code (e.g., BALDUR) to help constrain possible ignition scenarios for a future high field compact ignition machine as well as determine limitations to fuelling, current rise rates, and transport. The L-mode and H-mode current rise scenarios will be compared to determine their relative merits toward achieving ignition. These results should lead to journal publications and conference presentations.

7. References

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