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

First demonstration of Alcator C-MOD systems integration, sufficient to attempt production of a tokamak plasma.

These experiments are required for completion of Alcator C-MOD Program Milestone No. 18.0.

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

The physics requirements for breakdown are reasonably well established, at least qualitatively; see for example [1,2]. It is not the intent of the present experiments to address the details of the breakdown physics, but rather to demonstrate the ability to produce conditions which have a reasonable prospect of leading to breakdown within the constraints of low-field, non-cryogenic operation of Alcator C-MOD. The practical requirements are similar to those of the nominal Alcator specification, namely field null staying within an excursion of \( \pm a/2 \) for at least 5 ms, with gradient at the null satisfying \( dB_z/dR < 10mT/m \). The nominal spec requires that the loop voltage shall be \( \geq 20V \); however, this is considered to be extremely conservative, and probably not feasible within the constraints imposed by this phase of operation. We will be satisfied with voltages in the 10-15 V range for these experiments.

These experiments will be conducted with limited facilities, consistent with the anticipated level of readiness in late August 1991. No cryogenics will be available, and inertial cooling will be relied on, perhaps augmented by some gas flow cooling where appropriate. TF fields will be limited to 3 Tesla. The Hybrid Computer will not be employed for control of the PF power supplies; instead, control will be limited to pre-set voltage and current limits with settable initiate and inversion timing. All five commutation switches will in principal be available, but we will attempt to limit the number of circuits for which commutation is required.
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.

The approach will be to attempt to produce a satisfactory null with a minimum number of adjustable parameters, in order to simplify the operation and minimize the time spent searching for the optimum conditions. To this end, the following circuit configuration will be employed:

OH1 (max current = 25kA, commutation bank configured in series for 4kV maximum voltage.

OH2U and OH2L power supplies not connected. Both coils terminated in resistors.
EF1U and EF1L normal configuration, commutation banks connected.
EF2U and EF2L in normal configuration, using independent unipolar TMX supplies in series with external resistors.
EF3 coils in series with EF3 BBC supply (old OH3) configured for negative current. No reverse bias TMX supply is required.
EF4 coils in series; Use TMX supplies for slow bias current. May not be needed, but should be held available in reserve (see Experimental Plan).
EFC power supply not connected. Coils connected antiseries through an external resistor.

For all circuits, the only waveform programming will be by initiate-time, voltage limit, current limit, invert-time, invert voltage. Commutated coils (OH1,EF1U, and EF1L) will all be switched at the same time. Typical waveforms are shown below. In general, OH1 and EF1U,EF1L will charge positive current until commutation, then inverted and ramped to zero current; EF1U and EF1L will be programmed identically. EF2U and EF2L will be driven to positive current and forced to zero voltage either at commutation or after the nominal plasma pulse; the difference between EF2U and EF2L will be used to null the radial field. EF3 will remain off until commutation, then go to approximately full negative voltage (with respect to the other coils) and then ramped back down to zero current after the pulse; if required, EF4 will be used for bias field, with currents in the 1 kA range or lower, and will simply be ramped up and back down. In general, all circuits will be operated at a fraction of their nominal currents, but full nominal voltage will be required from the supplies. Commutation will occur simultaneously for all circuits, and the commutation SCR’s re-closed after a fixed time, typically 15 msec. For the relatively low voltages considered here, the inversion voltage available from OH1 supply is comparable to that required from the commutation resistor; typical coil voltages on OH1 will be less than 1600V, with up to 700V available from the supply.

Given these restrictions, it is unlikely that an equilibrium current will be maintained for longer than tens of milliseconds, even if breakdown is achieved. Typically, it would be necessary to crowbar, or reset the voltage on at least EF3 to an intermediate level after
re-closing the commutation switch in order to provide acceptable equilibrium fields for the early plasma current. Some additional control may be provided by delaying the re-closing of the commutation switches on some circuits.

Our general approach will consist of three stages, with the possibility of proceeding to an additional stage if warranted. Briefly, these are

1. Validate and refine electromagnetic models and verify magnetics diagnostics, using sequence of individual and combined coil current pulses, without commutation. This will be the most time-consuming phase, and will also be used to verify the operation of the control system. These tests will culminate in establishment of PF programming corresponding to the pre-blip "pre-null" fields.

2. Commutation tests on sets of coils, which will further calibrate the fast time response of the models, and establish performance of the commutation circuitry. These tests will culminate in attempts to produce an actual null.

3. Breakdown attempts. With TF on and gas in the machine, we will attempt to produce a plasma "flash".

(4) If step 3 is successful in achieving breakdown, but the current rise fizzles, we will attempt to tweak the post initiation fields by varying the crowbar times and if possible introducing a second stage of programming on the EF3 and OH1 supplies.

4. Resources

4.1 Machine and Plasma Parameters

Give values or range for:

**Toroidal Field:** $+2-3$ Tesla (i.e. $B_{\text{tor}}$ in the same direction as the plasma current.)

**Plasma Current:** $0 < I_p < +100kA$, with + direction defined as CCW viewed from above. Note: current direction is non-critical, but $B_{\text{tor}}$ and $I_p$ must be in the same sense.

**Working gas species:** H2

**Density:** $< 1 \times 10^{20}m^{-3}$

**Equilibrium configuration** (if possible, refer to database equilibria): Any. External field decay index should be $0.5 \leq N \leq 1.0$ if possible; certainly must be in the stable range $0.0 < N < 1.5$

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

See figures for power systems waveforms; plasma current and density waveforms we’ll take whatever we can get (and be lucky to get anything). Charge time should be as short as possible to reach required currents while minimizing coil heating.

During steps 3 and (4) we will want to puff gas at 100msec or so after commutation to kill any runaways that might be produced.
4.2 Auxiliary Systems

RF Power, pulse length, phasing: None
Pellet Injection (species): None
Impurity blow-off injection: None
Special gas puffing: None
Other: Steady-state gas fill and 1 pulsed gas valve. ECDC required before operation, and possibly for breakdown assist. Dry nitrogen purge of interior of the superstructure and all magnet cooling passages.

4.3 Diagnostics

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

Magnetics (full and partial flux loops required, Bp-coils should be available for checking sensitivity).
Visible light: H-alpha and/or Z-meter; TV camera desirable but not required.
RGA
Hard X-ray monitor

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.)

No neutron budget required for this experiment. Tests are conducted in hydrogen; runaway production resulting in e-D and photoneutrons is expected to be minimal.

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.

A maximum of five run days should be allocated to these experiments, allowing for systems failures and repairs. Runs should be consecutive. Referring to the steps outlined in Section 3, Step 1 should consume of order two days, Steps 2 and 3 should consume no more than two days, and Step 4, if required, will fill out the remaining time.

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.

Step1: Integrated coil tests, leading to establishment of prescribed pre-blip conditions. (17-30 shots total)
1.1 TF pulses (2-5 shots): For several TF currents, evaluate poloidal fields and fluxes arising from the single turns of the TF, as well as interference with BP-coils. Compare with model predictions and use to adjust prescription for pre-blip PF contributions. At least one, and perhaps two pulses will be at nominal field for the experiments (3Teslas); cooldown times from these will be evaluated during the rest of the day.

1.2 Single coil system pulses (10-15 shots): Fire one or two pulse each (at half and full planned currents) on OH1, EF1U and EF1L (together), EF2U and EF2L (together), EF3. In each case, charge to design voltage (and/or current) for nominal time to permit evaluation of eddy current effects. Evaluate field and flux contributions and compare with model predictions. Evaluate magnetics response. Tweak currents on any for which significant deviations from predicted behavior are observed. Note maximum available current on EF1 and EF2, since the nominal scenario calls for these coils to charge at full voltage to overcome the warm coil resistance. In particular the max current on EF1 will determine other characteristics of the achievable null and voltage swing. During this period, evaluate heating and cooldown of PF coils.

1.3 Combined coil system pulses (5-10 shots): Depending on results of 1.2, try combinations of coils in an effort to produce desired pre-blip field structure. Determine if EF4 will be required and if so try using it, first alone and then in combination with remaining coils. The end point of this set of shots should be determination of PF programming needed to obtain the pre-blip conditions. A final pulse may be taken with TF to confirm the configuration, if circumstances permit. (Note: at 3 Tesla, the TF half-turns should produce about 5 mTesla and 20 mTesla/m at the nominal axis, so the effect can not be neglected.)

Step 2: Commutation tests (6-26 shots total)

2.1 Single coil system commutation tests (3-6 shots): Starting from the nominal individual coil currents established in step 1, using resistors determined by previous model analysis, fire commutation tests on OH1 and (EF1U and EF1L). Evaluate commutation system performance, timing, etc. Evaluate evolution of fields, induced coil currents, during individual coil blips and compare with model predictions. Check magnetics.

2.2 Full PF system commutation tests (3-20 shots): With all relevant PF systems energized (but not TF yet, unless cooling is not a problem) begin from the nominal scenario established in Step 1 and 2.1 and attempt to generate a satisfactory null during the blip. Once the error fields get less than the TF contribution, it may be necessary to fire TF as well. Guided by results of each attempt, adjust the following “knobs”:

- OH1 current/voltage programming before blip
- OH1 inversion voltage
- EF1U/L current/voltage programming before blip (expected to be flat out)
- EF1U/L inversion voltage
- EF2U/L current/voltage programming before blip
EF2U/L voltage during blip (either full on or zero)
EF2U/L external resistor (in no more than three steps: lowest, half, and highest)
EF3 voltage during blip (expected to be flat out)

OH1 and EF1U/L commutation resistors ($R_{OH1} \approx 30 : 100\, \text{m}\Omega, R_{EF1} \approx 200 : 350\, \text{m}\Omega$)

We will attempt to get a loop voltage during the blip of 12-15 Volts, but may have to back off in order to get a satisfactory null. As long as we have at least 10V with a reasonable null, proceed to step 3.

**Step 3:** Breakdown tests (3-20 shots total)

3.1 (3-10 shots) Put gas in the machine ($0.5 : 2 \times 10^{-4} \text{ Torr “true”}$) and give it a try. Actually, once we start running the TF during 2.2, we can go ahead and put gas in just in case. Look for light signal and plasma current on Rogowski. Try small changes in bias field, null structure, to compensate for possible errors in diagnostic interpretation. At this point, there is not a lot left to try; if there isn’t enough voltage we’re stuck.

3.2 (0-10 shots) Optimize the flash. If we get anything, we will try to improve the breakdown phase by tweaking the field structure. Principal criteria will be time to breakdown and location (if determinable). If we actually burn through the radiation barrier and get a current rise, proceed to Step 4.

**Step 4:** Current rise optimization (0-20 shots)

Evaluate post-blip field evolution, plasma dI/dt, and determine if changes in crowbar timing and inversion voltage can be made to provide suitable equilibrium. If not, ascertain feasibility of providing voltage programming for OH1 and EF3. Note that setting the current limit on EF3 may be satisfactory for a 100 msec or so pulse, if the OH1 voltage can be step controlled after the blip. Depending on the robustness of the breakdown, reducing the voltage blip may allow better field and current evolution, as well as helping determine the configuration used for first physics operation.

**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.

Minimal acceptable outcome would be completion of the integrated commutation tests, with TF pulse, but with no successful plasma initiation; in this case it would be necessary to determine the reasons for lack of breakdown (insufficient voltage, inadequate vacuum conditions, insufficient control of fields, etc.) and develop plans for overcoming these in time for start of physics operation in the fall. Such a result would minimally satisfy the milestone and qualify as demonstration of project completion. It would also provide needed experience and validation of magnetics diagnostics and allow some determination of pickup and associated problems.
Successful achievement of breakdown and current rise would further allow establishment of sufficient conditions for plasma startup, and may influence requirements for the commutation system in place for physics start-up.

7. References

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