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

The purpose of this experiment is to provide better localization of the ECDC produced ion flux to plasma-facing surfaces by application of a vertical field during ECDC. There are two ultimate goals for this line of research. The first is to obtain better localization of boronization film growth on surface near the EC resonance, and hence maximize B film growth rate, while avoid unwanted boron deposition at radial position outside the resonance, such as the ICRH antennae. The second is to develop an in-situ tile conditioning and surface heating method using ECDC discharges, which could be achieved with better plasma localization and an upgrade in RF power or frequency.

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

Recent campaigns have shown that boronizations play a critical role in C-Mod H-mode plasma performance [Lipschultz]. Circumstantial evidence points to enhanced erosion of Mo leading to core contamination by Mo and its detrimental radiation. The enhanced erosion is caused by RF sheath rectification, particularly at regions at the top of the outer divertor that are flux line connected to the ICRH antennae. It appears to be important to maintain boron films at these regions for performance. Unfortunately the RF sheath rectification apparently enhances the B film erosion, since very high net erosion rate of B, ~ 20 nm /s, are inferred based on the duration of the positive effects of a single boronization. Much of this data is inferred from the effects of moving the EC resonance R location used during boronizations. An optimal resonance location is found which corresponds in major radius, R, to the top shelf of the outer divertor. An unwanted consequence of boronization is the growth of B films on the ICRH antennae. It takes several discharges to “condition” the antennae, but this is approximately the lifetime of
the boron films on the divertor shelf. In combination, these effects are highly detrimental to C-Mod H-mode plasma performance.

It would be of great benefit to C-Mod plasma operations to better localize B film growth to a) produce thicker B films on the outer divertor shelf for a given duration of ECDC and b) avoid B film growth in the antennae.

The present situation of poor localization is largely due to application of a purely toroidal B field during ECDC. The plasma produced by the RF is dominantly lost to the walls by radially outward ExB drift, caused by grad-B and curvature polarization. This results in a radial plasma density profile (i.e. in the major R direction) that appears to be roughly a step function at the EC resonance (RF frequency =2.45 GHz, $B_{\text{resonance}}$ = 87.5 mT), i.e. the plasma density is ~ zero at $R < R_{\text{resonance}}$ and has nearly constant density ~ $10^{16}$ m$^{-3}$ at $R > R_{\text{resonance}}$ [Nachtrieb]. Therefore the ion flux or “plasma loss” is distributed over a very large area of the wall at $R > R_{\text{resonance}}$. The density $\sim 10^{16}$ m$^{-3}$ is well below the cutoff density $\sim 7.5 \times 10^{16}$ m$^{-3}$ at 2.45 GHz, indicating that higher local densities could be achieved.

It is helpful to scope the transport rates in the purely B toroidal case. Based on the observations above, one can assume that the absorbed RF power, $\sim 2$ kW, is being consumed mostly to sustain ionization in the plasma. Based on a plasma volume $\sim 4$ m$^3$ ~ vessel volume, the total plasma particle inventory is $\sim 4 \times 10^{16}$. With an estimate of 100 eV / ionization (also accounting for some finite plasma heating since $T \sim 10$ eV during ECDC [Nachtrieb]), one therefore estimates an effective particle confinement time $\sim 0.5$-1 ms.

Given the size of C-Mod ($R \sim 0.5$ m), this is consistent with an ExB radial drift velocity $\sim 250$-500 m/s. This ExB velocity is a reasonable number considering that the magnitude of $E_r$ should be $\sim 1$-$2 x T_e / e R \sim 20$-$40$ V/m, resulting in an average $E_r / B_t \sim 200$-$400$ m/s for the $B_t = B_{\text{resonance}} \sim 0.1$ T.

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.

A vertical B field can be applied during ECDC in order to “confine” the plasma density closer to the resonance. The situation is analogous to a scrape-off layer (SOL) plasma in a tokamak discharge. While ExB drift is present (although weaker due to the higher B), the transport is dominated by parallel losses caused by free-streaming of plasma parallel to the field into a terminating surface (i.e. divertor). The result is radial profile of density that is peaked near the separatrix (which is the source of energy and particle from the core through cross-field transport) and decays exponentially (e-folding length $\sim$ cm) with increasing radial distance from the separatrix.

During ECDC, the application of a vertical field will produce a finite connection length, $L_{\perp}$, from the plasma volume to the ~horizontal surfaces in the upper and lower divertor, with $L_{\perp} \sim (B_y / B_y) \Delta Z$ given by the ratio of toroidal to vertical field ($B_y / B_y$), and the average vertical distance to the terminating plate $\Delta Z \sim 0.5$ m in C-Mod. The expected radial decay length for the plasma is set by the competition between radial ExB convection and free-streaming convection along the field lines, namely $L_{\perp} \sim L_{\perp} (\gamma_{\text{ExB}} / c_s)$ where $c_s \sim 10^4$ (T/m)$^{1/2} \sim 2.5 \times 10^4$ m/s is the sound speed for $m=2$ deuterium plasmas with
T~10 eV [Nachtrieb]. Therefore we obtain a simple estimate \( L_R \sim \Delta Z \left( \frac{v_{\text{ExB}}}{c} \right) \left( \frac{B_B}{B_v} \right) \) or \( L_R [m] \sim 0.005-0.01 \left( \frac{B_B}{B_v} \right) \) using C-Mod parameters as above. Therefore an applied vertical field \( B_v \sim 0.1 \) \( B_B \) should result in plasma that has a density profile localized to < 0.1 m of the resonance. This is analogous again to a normal SOL where \( B_B/B_v \sim 10 \) but here the plasma is being “produced” upstream by the EC absorption on the resonance. Therefore the major radius of EC resonance should also become the \( R \) of peak ion flux losses in the divertor. To obtain this on C-Mod during ECDC implies a \( B_v \sim 80 \) mT to be applied steady-state. The EF4 equilibrium coils are appropriate for this (~130 A / coil-set) and should not raise any concerns with respect to overheating the coils. For these preliminary experiments a manually controlled power supply has been identified to provide this coil current.

It is not exactly clear if the peak plasma density will increase due to the application of the vertical field. Taking the model that RF power is used solely to sustain ionization, one realizes that the decreased plasma volume, which should tend to increase plasma density with a constant source, is approximately balanced by the decreased effective particle confinement time caused by the more rapid parallel losses. However it should be noted that the peak ion flux incident at horizontal surfaces at or near the resonance will increase greatly, exactly because these surfaces are receiving all of the ions produced by the RF, as opposed to the several m² of the entire vessel increase as in the pure \( B_B \) case. Therefore our primary objective will be met, since we want to maximize ion flux in a desired location (e.g. to maximize B film deposition), rather than volumetric plasma density. No increase in local density may be beneficial in the sense that RF cutoff will not be approached at \( n \sim 10^{16} \) m^-3. However, an increase in RF power should result in higher peak density, with the incident ion flux following of course. Upgrading the RF source to have more power (and higher frequency) would be a possible route for future experimental campaigns if it shown that the loss of the injected RF power is better controlled using the vertical field magnetic topology. There will be an upper limit of \( n_e \sim 7 \times 10^{16} \) in peak density due to cutoff of the 2.45 GHz, as well as some broadening of the power deposition due to the presence of the Upper Hybrid resonance \( (\omega_{\text{UH}} = (\Omega_e^2 + \omega_p^2)^{1/2}) \) at \( R > R_{\text{EC, resonance}} \) [Gentle]. An upgrade in RF power and frequency, with controlled localization of the incident plasma flux and energy, would also allow for more aggressive surface heating for tile conditioning (e.g. H desorption after a vent).

Langmuir probes will be the primary diagnostic for the ECDC plasma. As mentioned, the primary goal is to increase local plasma flux on horizontal divertor surfaces. This will be directly measured by two fixed probes in the upper divertor plate, radially separated by ~0.05 - 0.1 m. The probes will be selected from the present set installed in the upper divertor (probes 11 and 14 likely). The electronics of these two probes will be routed into special high gain electronics to improve signal/noise for these low density/flux plasmas. Incident ion flux will be calculated from saturation current and knowledge of the field line pitch angle, and plasma temperature will be obtained from the I-V characteristics. Small scans of the EC resonance location will provide spatial profiles using just two fixed probes. In addition we will use the Langmuir probe in the Surface Science Station (S3) if it is available. Because the probe head can be radially scanned, this diagnostic will be able to measure radial profiles of the “volumetric” plasma conditions. Qualitative diagnosis of the plasma localization will be obtained from a wide-angle visible camera.
measuring plasma emissions ~ volumetric ionization rate. In-vessel thermocouples should be monitored for any signs of undesired localized RF-produced heating.

If the localization of the ECDC produced flux is successful, it would then be applied to a boronization. The boron can deposit both as an ion (molecular ion likely) or as a neutral radical created by diborane dissociation in the plasma volume. The relative importance of the two processes in setting local boronization rates is unknown. Only ionic deposition will be increased by the localized ion flux profiles, so it is important to directly determine the B film growth rate. The two QMB (quartz microbalance) diagnostics on S3 will be used for this purpose. The QMB is highly sensitive to film growth (1 Angstrom) and provides real-time film growth rates. One QMB is shielded from field lines, and therefore ion deposition, and will inform us of neutral deposition rates. The other QMB can be rotated such that its face is normal to the B field, and will therefore provide parallel ionic deposition rates. The net B deposition rate on horizontal surfaces in the divertor can then be calculated based on the known field line angles. The radial profile of the deposition will be obtained by radially scanning the S3 probe head over the course of the ECDC boronization.

4. Resources

4.1 Machine and Plasma Parameters

Give values or range for:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toroidal Field</td>
<td>0.05 - 0.1 T</td>
</tr>
<tr>
<td>Plasma Current</td>
<td>N/A</td>
</tr>
<tr>
<td>Working Gas Species</td>
<td>Deuterium</td>
</tr>
<tr>
<td>Density</td>
<td>~10^{16} - 10^{17} m^{-3}</td>
</tr>
</tbody>
</table>

Equilibrium configuration (if possible, refer to database equilibria):

- EF4 coils with constant current <= 130 Amps.

4.2 Auxiliary Systems

- RF Power, pulse length, phasing: 2.45 GHz RF source, variable power?
- Pellet Injection (species):
- Impurity blow-off injection:
- Diagnostic Neutral Beam:
- Special gas puffing:
- Non-axisymmetric Coils (Connections, Current):
- Other:

4.3 Diagnostics

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

Two fixed Langmuir probes with high gain.
- Surface-science station Langmuir probe
- Surface-science station QMB
- Wide-angle visible camera
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.

1. Original tests will occur in the first Deuterium ECDC run of the 2007 campaign.

2. Based on diagnostic results from the first run, it would be anticipated that the vertical field be applied to during a boronization. Besides the direct QMB diagnosis, the effectiveness of the new boronization technique would be judged by the following experimental campaign using ICRH.

3. If both 1. and 2. Are successful, it would be anticipated that vertical field ECDC becomes standard procedure on C-Mod.

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.

Run 1

1. Establish base-line diagnosis of plasma and ion flux with pure B toroidal.
2. Increment vertical field in the following steps $B/B_v (%) = 2, 4, 6, 8, 10$ and measure changes in plasma conditions. Sweep the EC resonance location +/- 10 cm for diagnostic coverage.
3. At maximum $B/B_v \sim 10\%$ perform RF power scan (1, 2, 3 kW). Sweep EC resonance.

Run 2

1. Establish base-line diagnosis of plasma, ion flux and B film deposition rates with pure B toroidal.
2. Increment vertical field in the following steps $B/B_v (%) = 2, 4, 6, 8, 10$ and measure changes in plasma and B films deposition.
3. At maximum $B/B_v \sim 10\%$ perform RF power scan (1, 2, 3 kW).
4. Depending on results of 1-3, implement B field topology, EC resonance and RF power at optimal settings for localizing B film deposition on the top shelf of the outer divertor.
5. In first run after boronization, monitor ICRH conditioning and H-mode quality.
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.

If successful, the proposed method would become a standard procedure for optimizing wall coatings in C-Mod. Furthermore it would inform future decisions for upgrading RF power and frequency for conditioning purposes. This would have a significant impact not only for C-Mod, but for conditioning other tokamaks as well, including possibly ITER.

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

