1. Purpose of Experiments

The ITER baseline gas injection system is being frozen now. An attempt is being made by the physics group to include extra redundancy and more toroidal injection locations to improve toroidal symmetry. Although almost cost neutral, this is being resisted by the project in the absence of any experimental demonstration that it is necessary. The purpose of these experiments is to use the discrete toroidal injection capability of C-Mod to directly assess the toroidal distribution of divertor radiation in response to gas puffing at one or more separate toroidal locations. This experiment is intended to help either strengthen the case for an increased number of injection points, or to demonstrate that the current baseline is adequate.

2. Background

ITER currently foresees gas injection under the divertor cassettes for detachment control via impurity seeding (a supplement to C radiation for CFC targets and mandatory for W targets, the current reference material for the nuclear phase – see Fig. 1). Each injection point is equipped with an independent gas valve box (GVB) allowing H, D, T and impurity (He, N₂, Ne, Ar) injection, with mixtures possible and max. time response ~few 100 ms to 63% of max. throughput.

A proposal has recently been made (ITER Change Control Board 1-21, 4/3/2009) to add three more toroidal injection locations to both increase redundancy (since loss of detachment control can quickly lead to dangerous heat loads during burning plasma operation) and improve the toroidal symmetry of gas injection (particularly for non-recycling or partially recycling gases). The proposal makes use of additional GVBs that have been freed following a decision to reduce the number of main chamber injection locations and to switch to another method of gas supply to the neutral beam injectors. It
suggests that three more injection points be added to provide a six-point, toroidally symmetric system (one injection location every 60° toroidally), in which the new locations are in between pumping ports rather than directly on the ports pumps (Fig. 2).

Although the proposal is (almost) cost neutral, there are issues of extra space allocations and penetrations in the cryostat. The proposal was thus provisionally rejected by CCB1 pending more quantitative evidence that the enhanced injection capability is justified. A request was thus made by the IO for experimental investigation on C-Mod.

Fig. 2: Proposed system with 6 equispaced toroidal injection points

3. Approach

Experiment

The experiment is made possible thanks to the efforts of B. LaBombard to bring the C-Mod divertor floor capillary puffers back into service. This provides for 5 equally spaced toroidal injection locations into the PFR (Figs. 3 and 4), compared with 3 currently on ITER. The time response of these puffers is ~70 ms and this, together with the puff location, provides for a system reasonably analogous to the ITER situation. All puff locations are fed by the same plenum so that only one gas type can be tested at a time. The individual flow rates at each toroidal location would be measured prior to the experiment in order to assess the toroidal uniformity and to plan for compensation, if
necessary, by adjusting the plenum drive pressures. Each capillary can be programmed to puff gas from one of two possible timing triggers with each trigger having two possible trigger times and durations. Thus it is possible to systematically vary the puff location shot-by-shot and map out potential toroidal non-uniformities in divertor radiation.

![Fig. 3: Divertor floor capillary gas injection location in C-Mod - cross-section view.](image1)

![Fig. 4: Plan view of C-Mod’s lower divertor showing capillary gas injection and diagnostic view locations.](image2)

The experiment is ideally performed in SNL at high power and preferably in H-mode (where seeding will be critical in ITER burning plasmas with all-W divertor). To begin with, however, experiments should be performed in ohmic plasmas to provide a reference point. Power (ICRH) can then be added to compare with the ohmic response.

### 4. Resources

#### 4.1 Machine and Plasma Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toroidal Field:</td>
<td>5.4 Tesla</td>
</tr>
<tr>
<td>Plasma Current:</td>
<td>1.0 MA</td>
</tr>
<tr>
<td>Working Gas Species:</td>
<td>D</td>
</tr>
<tr>
<td>Density:</td>
<td>L-mode line-integral densities of 0.6, 0.9, 1.2x10^{20} m^{-2} on chord NL04.</td>
</tr>
</tbody>
</table>

July 29, 2009
Boronization Requested (if yes, specify whether overnight or between-shot, how recently needed, and any special conditions.): Overnight boronization may be required to obtain steady H-modes.
Equilibrium configuration (if possible, refer to database equilibria): Standard lower single null

4.2 Auxiliary Systems

ICRF Power, pulse length, phasing: 2 MW (or more) from 1 to 1.5 seconds in flattop
LHCD Power, pulse length, phasing: None
Pellet Injection (species): No
Impurity blow-off injection: No
Diagnostic Neutral Beam: Not mandatory
Special gas puffing: NINJA capillary puff system.
Cryopump: No for phase 1; yes for phase 2 – see plan
Other:

4.3 Diagnostics

Target Langmuir probes, D-port divertor bolometer, K-port ledge bolometer, divertor spectrometer, VUV spectrometer (midplane), divertor neutral pressures.

5. Experimental Plan

5.1 Run sequence Plan

The experiments are divided into two run phases, nominally requiring two dedicated run days. The first day (Phase 1) will focus on the toroidal dispersion of a non-recycling impurity gas (N\textsubscript{2}). Since cryopumping is not required for gaseous impurity control in this phase, these initial scoping experiments can be performed early in the FY09 campaign, providing timely information for the Project Change Request (PCR). A second phase of experiments (Phase 2) will focus on the divertor’s response to recycling impurity injection (Ar) with cryopumping. Lower single null dominant equilibria would be used in both phases, but with a secondary upper x-point optimized for cryopumping in the second phase. In both phases, we want to map out the toroidal distribution of radiated power in response to divertor collisionality regime (sheath-limited, high recycling, detached) and confinement regime (L-mode/H-mode).
5.2 Shot sequence plan

Phase 0 – Capillary gas-flow scoping and calibration

In preparation for these experiments, some off-line and piggy-back testing of NINJA system is desired. N$_2$ and Ar should be injected through capillaries K30-012 and D30-012 and monitored with divertor bolometry/spectroscopy to determine optimum drive pressures and pulse duration times. Having identified these conditions, gas flow rate calibration measurements through each of the capillaries should be performed. Lacking such preparation, a few shots at the beginning of each dedicated run phase will need to be set aside for this purpose. Gas flow rate calibrations can be performed post run time, if necessary.

Phase 1 – Non-recycling impurity injection experiments (N$_2$)

1.A NINJA setup

The primary goal is to map out any toroidal variation in divertor radiation that might occur in response to a toroidally-localized gas puff. We will plan on working with a 1.0 MA discharge that attains current flat-top from 0.5 to 1.5 seconds. The NINJA (Neutral INJection Array [1,2]) is capable of assigning two separate trigger signals (A or B) to two or more different capillaries. Each trigger signal can have two different trigger times and durations. Capillary A will be triggered at 0.5 and 1.0 seconds for a 0.150 ms duration. Capillary B will be triggered at 0.75 and 1.25 seconds for a 0.150 ms duration, as outlined in Fig. 5. {Note: At the time of this writing, we have some evidence that the decay time for nitrogen in the divertor may be significant, up to 0.5 seconds. If this situation persists, we will need to drop the second puff in the A and B waveforms.}

![Fig. 5: Divertor floor capillary gas injection location in C-Mod - cross-section view.](image_url)

We will select capillaries A and B to be adjacent to each other. On a shot-by-shot basis we will systematically rotate this pair around the torus. A five-shot sequence will
map a full toroidal rotation, with redundancy to correct for possible variations in gas-puff rate or plasma conditions:

<table>
<thead>
<tr>
<th>Shot</th>
<th>Capillary A</th>
<th>Capillary B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>K30-012</td>
<td>B30-012</td>
</tr>
<tr>
<td>2</td>
<td>B30-012</td>
<td>D30-012</td>
</tr>
<tr>
<td>3</td>
<td>D30-012</td>
<td>F30-012</td>
</tr>
<tr>
<td>4</td>
<td>F30-012</td>
<td>H30-012</td>
</tr>
<tr>
<td>5</td>
<td>H30-012</td>
<td>K30-012</td>
</tr>
</tbody>
</table>

**1.B Ohmic L-Mode Density Scan**

We will start with ohmic discharges, looking for the effect that divertor collisionality might have on the toroidal dispersal.

i. Set up 1.0 MA, 5.4 tesla, LSN ohmic discharge, NL04 ~ 0.6x10⁻²⁰ m⁻² – 3 shots

ii. NL04 ~ 0.6x10⁻²⁰ m⁻² with divertor puff sequence – 5 shots

iii. NL04 ~ 0.9x10⁻²⁰ m⁻² with divertor puff sequence – 5 shots

iv. NL04 ~ 1.2x10⁻²⁰ m⁻² (or as required to achieve detached divertor) with divertor puff sequence – 5 shots

**1.C H-Mode Density Scan**

We will then apply ICRF power to attain H-modes.

i. NL04 ~ 0.9x10⁻²⁰ m⁻², 2 MW ICRF from 1.0 to 1.5 seconds. Execute divertor puff sequence – 5 shots

ii. Raise density as needed to access partially detached H-mode, if possible, 2 MW ICRF from 1.0 to 1.5 seconds. Execute divertor puff sequence – 5 shots

{It should be noted that C-Mod has not been able to achieve stable detached H-modes with the NINJA system – a fast feedback system is required to handle the prompt change in impurity screening associated with detachment [3]. Thus we may treat this as a density scan, avoiding detached regimes.}

**Phase 2 – Recycling impurity injection experiments (Ar)**

**2.A NINJA and Cryopump setup**

The setup for the NINJA system will be identical to that in Phase 1. Ideally, off-line and piggy-back tests can be performed to optimize the plenum gas pressure and timing setup prior to the dedicated run day. In any case, we will need to utilize the upper divertor cryopump system in this phase and also operate with unbalanced double-null
plasmas (SSEP parameter ~ -5 mm) with upper (secondary) strikepoint optimized for pumping.

2.B Ohmic L-Mode Density Scan
   Repeat 1.B with argon injection.

2.C H-Mode Density Scan
   Repeat 1.C with argon injection. {Note the same restriction applies as above on the prospects of achieving controlled, detached H-modes.}

Depending on what we find (e.g., toroidal variation is weak or otherwise easy to map out in a few shots), we may compress the run shot plan above by ~1/2 in order to switch over to neon injection.

{Note: Previous C-Mod experiments have also shown that unlike N₂, Ar and Ne injection does not lead to high divertor radiation in C-Mod; instead, a radiating mantle tends to form, affecting the pedestal region [3].}

6. Anticipated Results
   Experiment addresses a direct IO request to provide input for a design change proposal to increase the number of toroidal injection locations in the ITER divertor.

   Experiment has interesting potential for scientific publication depending on the nature of results obtained. The issue of toroidal asymmetry of gas injection, particularly the differences between recycling and non-recycling gases has not been previously addressed in tokamak experiments.

7. References
   The only current references are internal ITER documents, available on IDM for those with access.

   The Project Change Request (PCR) delivered to CCB1-21 is available at: https://user.iter.org/?uid=2LHFH6

   A talk on the ITER divertor gas injection systems and requirements related to impurity seeding was presented at the ITER Fuelling meeting of 1-3 December 2008. The presentation can be found at the following link: https://user.iter.org/?uid=2ETG2E
