1. Purpose of Experiments

Achieving steady H-modes with ITER-relevant shapes, $q_{95} \approx 3$, and $\beta_N \gtrsim 1.5$ is required for C-Mod participation in ITPA Joint Experiments IOS-1.1 (ITER demo) and IOS-1.2 (Seeding Effects). For greatest relevance, the C-Mod experiments should be carried out near the ITER field with maximum available power. An alternative approach, relying on operation at lower field using alternative ICRF heating scenarios, is the subject of a separate miniproposal, MP#574.

The purpose of this MP is to extend the successful seeding results obtained in previous work (MP#564 and MP#630) to ITER-like shape and current. Emphasis will be placed on seeding with nitrogen, because the non-recycling behavior is likely to be more amenable to feedback control than neon, and because in prior experiments N$_2$ seeding has been found to radiate more effectively outside the pedestal and in the divertor, which is favorable for H-mode performance and divertor protection.

Issues to be addressed in the context of this MP include:

1. Optimization of N$_2$ level for high power operation in ITER-like discharges
2. Dependence on puff location of divertor vs core radiation, $Z_{eff}$
3. Temporal response to N$_2$ puff, evaluation of potential for feedback control of seeding
4. Evaluation performance/utility of the cryopump with N$_2$ seeding (may require additional run-time)

This experiment will provide a basis for work on the ITPA Joint Experiment IOS-1.2, as well as ITER demo discharges to be produced in support of IOS-1.1.
2. Background

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

During a series of runs in support of MP#564 (Loarte, et al.), we demonstrated high normalized performance ($H_{98}$) with low divertor heat flux using both Ne and N$_2$ seeding in EDA H-modes. These experiments were primarily carried out at low current, $I_p \sim 800kA$ with rather low elongation. Detailed results were presented in Alberto Loarte’s APS Invited talk.

More recently, seeding has been successfully extended to higher current in MP#630 (Reinke, et al.), which demonstrated steady high power neon-seeded EDA H-modes with $W_{mhd} \sim 200kJ$, $H_{98} \sim 1$, at 1.0MA, $q_{95} \sim 3.5$, and less steady but respectable performance at 1.1MA using both neon and N$_2$. The failure to attain steady conditions at the higher current in this experiment was attributed to degradation of the boronization during the run day, rather than an intrinsic limitation of the lower $q_{95}$ discharge, a conclusion supported by the observation that later in the day we were unable to fully recover the best performance conditions previously observed at lower currents. However, successful N$_2$ seeding of high current ($I_p > 1$ MA, high power EDA H-modes has not yet been demonstrated in C-Mod.

In the present machine configuration, impurity seeding can be done from a midplane piezo-electric valve (B-side lower) and through a lower vertical port (H-bottom) piezo-electric valve, which introduce the gas through the partly through the lower divertor region; unlike the J-bottom divertor piezo valve used in the 1995 Goetz experiments, the H-bottom valve is not restricted to a reentrant pipe into the divertor, but introduces gas into the entire vertical teardrop port. There are also several NINJA capillaries located on the floor of the divertor region, which have been used to introduce impurity seed gases in earlier experiments (MP#563) which addressed toroidal asymmetries in divertor gas injection.

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.

This experiment will concentrate exclusively on nitrogen seeding, primarily because of the present perception that N$_2$ will be more amenable to feedback control and may have higher efficacy in reducing divertor heat loads than neon. A serious concern from previous C-Mod experiments is that the amount on N$_2$ required is large (up to 60 Torr-liters) and the core $Z_{eff}$ in the recent experiments seemed to be quite high ($> 3$), although not so high as to seriously suppress fusion reactivity. There is also a potential operational issue associated with shot to shot build-up of nitrogen in the vessel, which may compromise or at least modify discharge performance late in the day, and require aggressive overnight discharge cleaning to avoid contamination of subsequent runs. These issues will be addressed, explicitly or implicitly, by a full day of operation using only N$_2$ seeding.

Because we are mainly interested in applications in which the impurity seeding is dynamic, aiming at potential feedback control for reduction of divertor heat flux and high $Z$ core radiation, we will restrict the comparison of source localization to the “divertor”
puff using the H-bottom piezo and a midplane puff using the B-side Lower piezo. While
the divertor floor capillaries may be more representative of a truly localized divertor source
in the private flux zone, their lower throughput and slow response make a clear comparison
more difficult. If a significant difference between the existing piezo-valves is observed in
this experiment (favoring the divertor location), a subsequent experiment to evaluate the
NINJA location may be indicated.

Contrary to the systematic incremental changes in target plasma parameters employed
in MP#630, we will start with an ITER-like discharge based on 1101210010, a low power
\( P_{RF} < 1.5 \text{ MW} \), unseeded, 1.3MA EDA case from C. Kessel’s rampdown experiment
MP#575, and add power and seeding toward the maximum available input (and net)
power. The elongation may be increased slightly from the 1.7 in the reference shot to a
more ITER-like 1.8. The flat top of the reference shot ends at 1.2sec, and we’ll keep that for
awhile to reduce the total energy per shot and prolong the boronization. The EOF may be
extended to 1.5sec if evaluation of the dynamic response requires it. The emphasis will be
on making the seeding work in the ITER shape and \( q_{95} \approx 3 \). If and only if we are unable
to attain good EDA’s in this configuration, we will consider decreasing the current slightly,
perhaps to 1.2MA; anything lower will be considered uninteresting from the standpoint of
IOS-1.2.

Boronization recovery will be undertaken with nitrogen seeding, starting with 20psi
in the H-bottom plenum, with a .6sec pulse (0.4 to 1.0s) at 30% duty factor. A somewhat
longer puff at this level was used on 1101202006; note that this puff was 60 Torr-liters,
which may be excessive. The target plasma for boronization will be the ITER-like case
from 1101210010, unless the RF group prefers to condition with a lower current or lower
density target.

Once the ICRF has conditioned up to at least 3.5MW total with minimal faulting,
we will start the seeding experiment with ICRF power ramps from 2.5 to 3.5MW, \( t=0.6 \)
to 1.2sec and try optimizing the \( N_2 \) level using constant amplitude puffs. It may be useful
to extend the RF pulse into rampdown, to avoid disruptions. We may also get some data
for Chuck’s MP#575 while we’re at it. Optimization criteria include

a. Steadiness of H-mode (minimize back transitions)
b. Performance \( (H_{98}, \ W_{mhd}, \ \text{Neutron rate}) \)
c. Core cleanliness \( (Z_{ave}, \ Z_{neq}, \ \text{core Mo}) \)
d. Divertor heat load. If available, monitor heat flux using IR camera as well as embedded
   TC’s

We will attempt to optimize seeding from H-bottom and B-side Lower, interleaving
shots or blocks of shots to give the best possible comparison of puff locations. This will
necessitate doing without diagnostic argon puffing for the HIRES diagnostic, unless a
plenum other than B-side Lower and H-bottom becomes available. We will strongly con-
sider changing one of these to argon, or adding a trace amount of argon to one or both, later
in the run, in order to document ion temperature profiles for additional data to evaluate
\( Z_{eff} \) and deuteron depletion.
Next we will raise the RF input power toward 4.5MW, if possible, and repeat the optimization. Try to increase $P_{\text{net}}$ as well as $P_{\text{loss}}$, and observe scaling of H factor, stored energy. If higher power is not available, or not manageable for other reasons, then we’ll go on to the next steps at the highest reliable power.

Starting from steady conditions, modulate the $N_2$ puff and observe temporal behavior of N and Mo radiation, total $P_{\text{rad}}$, plasma parameters, etc. Vary period depending on observed response times. Modulation experiments will be done first for H-bottom and then for B-side Lower. It may be worthwhile to pump out B-side lower and add some diagnostic argon for Ti profile measurements during the first set of discharges, and then swap back, although this may cost some time.

The use of the cryopump is called for in this experiment in the expectation that it may help to manage the neutral pressure for the benefit of the ICRF. To the extent that $N_2$ reaches the pump there is likely to be an effect on the seeding; potentially there could also be an impact of the seeding on the pumping, although we have never seen any indication of this. A full evaluation of the interaction of the cryopump and the $N_2$ seeding would require more time than is available in one day of this MP, but a very preliminary assessment can be accomplished by turning off the pump at the end of the day and repeating a few shots, time permitting. In this case, “turning the pump off” means not filling the LHe section; some pumping of $N_2$ may still be active from the LN$_2$ jacket, which will not warm up on the available timescale. A subsequent experiment in which the cryopump is left warm (vessel temperature) may be requested to further address this issue.

4. Resources

4.1 Machine and Plasma Parameters

Give values or range for:

- **Toroidal Field**: -5.4 T, Normal direction
- **Plasma Current**: -1.3 MA
- **Working gas species**: $D_2$
- **Density**: $n_{\text{LH}} = 1.3 \times 10^{20} m^{-2}$ target
- **Equilibrium configuration** (if possible, refer to database equilibria): Similar to 1101210010 (note seg1 and 2 must be used for consistent early divert rampup)
- **Pulse length, typical current & density waveforms, etc.** Refer to database or sketch desired waveforms: EOF at 1.2sec, 500msec current rampdown, as in reference shot. Flattop might be extended later in the day, if warranted by results. Typical RF waveform at high power from just after BOF to EOF, perhaps extending at lower power during rampdown.

4.2 Auxiliary Systems
ICRF Power, pulse length, phasing: up to 4.5 MW (78, 80, 80.5 MHz)

LHCD Power, pulse length, phasing: None

Pellet Injection (species): None

Impurity blow-off injection: None

Diagnostic Neutral Beam: If available

Special gas puffing: Nitrogen (H-bottom, B-side Lower). Start with $N_2$ in both plena. Later in the run use diagnostic argon in the plenum not being used for $N_2$, interchange during run.

Cryopump: Yes, preferred (if not available, then we can do the experiment without it)

Non-axisymmetric Coils (Connections,Current): Standard configuration for locked mode suppression

Boronization (previous night or between-shot): YES (overnight)

Other:

4.3 Diagnostics

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

All standard profile diagnostics should be operational; depending on early results, the Session Leader may decide to turn off the argon, starving the HIRES. Edge TS for pedestal profiles is required. Nitrogen line radiation may render some CXRS measurements invalid. As complete a set of impurity spectroscopy diagnostics (XEUS, McPherson(?), CHROMEX) as possible is requested; the ability to monitor N in the divertor and in the main chamber is of particular interest. Suggested spectroscopy setup (per MLR) is:

Use the McPherson to monitor core molybdenum and XEUS to monitor core He-like and H-like nitrogen. Fibers from the K-BOT periscope should be run into CXRS spectrometer to measure x-point N V emission.

$Z_{eff}$ from visible bremsstrahlung should be monitored, but confirmation by other means, e.g. neoclassical resistivity, will be required for analysis due to the possibility of nitrogen line contamination. Neutron rate measurements are required. Divertor heat flux measurements (TC’s and calorimeters, and IR if possible) are requested. Core bolometry, at least sufficient for generating Prad_main, is required. Divertor bolometry should be available, even if emissivity profiles are ambiguous, in order to evaluate its potential for use as feedback sensors.

Fluctuation and other transport and stability diagnostics are not essential to the main focus of this experiment, but are welcome. If the experiments are successful we should produce some potentially interesting high performance plasmas. NINJA puffing may be allowed for GPI, if requested and found to be sufficiently non-perturbative.
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.

At least one run day is required. Evaluation of the interaction of nitrogen seeding with the cryopump may require additional run-time of 0.5 to 1 day. The first day of this experiment should be scheduled while J-port is tuned for 78MHz, preferably with the existing four-strap antenna installed. Overnight boronization is required preceding this run.

Note that it is probably inadvisable to schedule a boronization following this run due to potential buildup of nitrogen on the walls. Plan on at least one overnight ECDC before next run day.

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.

0. Boronization recovery. Start with the reference shot, modified to suit the RF group if necessary. They’re going to need to deal with the high current, high NL04 target eventually, but relax the demand if they need it to get started. Use N$_2$ seeding (similar to 1101202) from H-bottom, as long as it seems to be helping the recovery. Explore slightly higher elongation by raising ZXU, as a better match to ITER shape, and to improve coupling to cryopump. [4-8 shots]

1a. Using the reference shot, perhaps at higher elongation from step 0, program RF ramp to start at 0.6 sec, ramp from 2.5 to 3.5MW between 0.65 sec and EOF (1.2sec); extend some RF into rampdown if it seems to help. Vary N$_2$ puff level (H-bottom), and possibly timing, aiming for steady EDA H-mode (and RF). Monitor radiation, Mo and N levels, $Z_{ave}$, $P_{net}$, performance, pedestal height, status of divertor detachment, X-point Marfe, . . . [5 shots]

1b. Repeat seeding optimization using B-side Lower. Some shots of 1a and 1b may be interleaved to insure direct comparison of the midplane and “divertor” locations. [5 shots]

2a. If step 1 was successful, increase RF power, starting ramp at 3.5MW and ending at 4.5MW or highest available at EOF. Reoptimize N$_2$ puff at the higher power, if possible, for each valve [5-8 shots]

2b. If step 1 was not successful, back off the current (increase q$_{95}$), but no lower than 1.2MA, and/or increase density (if the RF can cope), and/or reduce maximum power, but no lower than 2.5MW. If unsuccessful with either valve, consider punting. If results are marginally acceptable, proceed to modulated waveforms (step 3) [10 shots]

3a. Starting from steady seeded EDA H-mode condition developed in step 1a or 2, run flattop RF power and modulate seeding waveform on H-bottom. Possible initial waveform is 100% square wave modulation at 10Hz (50msec ON, 50msec OFF). Observe
dynamic response and modify period and/or amplitude to develop model of system response. If indicated by results, extend the flattop pulse toward 1.5 sec EOF to accommodate longer modulation period, at the risk of hastening the degradation of boronization. Depending on observed $Z_{\text{eff}}$ level, consider putting argon in B-side lower for Ti profile measurement. [3-5 shots]

3b Repeat modulation experiments to determine dynamic response using midplane puff from B-side Lower valve. [3-5 shots]

3c If it seems to make sense, based on results of 3a and 3b, compare the two puff locations in a single shot. [0-2 shots]

4. In the unlikely event that time remains in the run, and the boronization is not completely degraded, turn off the cryopump and evaluate the effect, if any, on the dynamics and efficacy with midplane puffing. If even more time is available, repeat the “divertor puff” from H-bottom (assuming we didn’t replace it with argon). [time remaining]

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, an ITER request, or an external database.

If successful, this experiment should establish the operational parameters for C-Mod participation in ITPA Joint Experiment IOS-1.2, on seeding of ITER demo discharges, and potentially enhance our ability to operate high performance ITER-like discharges in support of other ITPA and ITER experiments, including the demo discharges of IOS-1.1, at the ITER field. In addition, the results should inform our development of feedback control of impurity seeding of high power, high performance H-mode discharges. The results of the comparison of midplane and vertical port puffing should inform the possible installation of additional seeding source locations during the next vent.

If, contrary to expectations, $N_2$ puffing is found to be unacceptable for this application, a future MP may be required to assess the use of a recycling, but pumpable, impurity, i.e. neon.

A one-day experiment is unlikely to determine the desirability of cryopumping in conjunction with $N_2$ puffing. Therefore, it may be worthwhile to further evaluate this question in a further experiment, under this or a different MP.

7. References

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