Subject: Scoping study of N\textsubscript{2} seeding in high current ITER-like EDA H-modes

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Group: H-mode Scenarios

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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.

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 miniproposals, MP#574 and MP#698.

The purpose of this MP is to extend the successful seeding results obtained in previous work (MP#564, MP#630, and MP#690) 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\textsubscript{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\textsubscript{2} level for high power operation in ITER-like discharges, including consideration of divertor heat flux, core radiation, $Z_{eff}$, and performance

2. Temporal response to N\textsubscript{2} puff, evaluation of potential for feedback control of seeding

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 ($H_{\text{99}}$) 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 $W_{\text{mhd}} \sim 200kJ$, $H_{\text{99}} \sim 1$, 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.

MP#690 demonstrated the use of the new divertor piezo valves B-div and H-div, which connect to the volume underneath the outer divertor; these valves are presently fed from the H-bottom plenum. The evidence from the run on 1120214 was that the relative concentration of N$_2$ in the divertor relative to the core was higher when the seeding was done through these divertor valves as compared to midplane seeding using the B-side Lower valve. This experiment will build on those results and employ the divertor valves, primarily B-div, for all seeding.

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 10 Torr-liters) and the core $Z_{\text{eff}}$ 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.

Due to limited run-time availability in FY12, as well as consideration of boronization degradation due to repeated high power discharges, we will try to accomplish the goals of this experiment in half a day. The potential for residual nitrogen contamination implies some restrictions on what could be done in the second half. Alternatively, this experiment could take the second half of a run day if first half doesn’t destroy the boronization.

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. Most of the experiment will use the closed divertor source B-div piezo, with the option of additional sourcing from the H-div system. MP#690 implied that the divertor sources were better (or at least as good) as midplane seeding. 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.

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 more recent ITER-like target may be substituted if available), a low power ($P_{rf} < 1.5$ 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 flattop 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.

Recent experience indicates the ICRF boronization recovery is relatively quick, especially for the Field-Aligned J-port antenna. We will therefore begin the run with the nominal target shot and let the ICRF condition as we go.

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 ($H_{98}$, $W_{mhd}$, Neutron rate)

c. Core cleanliness ($Z_{ave}$, $Z_{neo}$, core Mo)

d. Divertor heat load. If available, monitor heat flux using IR camera as well as embedded TC’s. Langmuir probes will be used to monitor plasma parameters at the plate and detachment status.

Next we will raise the RF input power toward 4.5MW or higher, if possible, and repeat the optimization. Try to increase $P_{net}$ as well as $P_{loss}$, 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 $P_{rad}$, plasma parameters, etc. Vary period depending on observed response times. The modulation part of the experiment is intended to inform design of a feedback controller algorithm, which in any case would not be implemented at
C-Mod during the current campaign. Therefore, this section of the experiment could be curtailed or eliminated if required by time constraints.

The use of the cryopump is not called for in this experiment because we did not observe any clear advantage in using it in previous seeding experiments, e.g. the MP#690 experiment on 1120214.

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: D₂
Density: \(n_{\text{e04}} = 1.3 \times 10^{20} \text{m}^{-2} \text{target}\)

Equilibrium configuration (if possible, refer to database equilibria): Similar to 1101210010 (Note: Both seg1 and 2 must be used for consistent early divert rampup; since this is an old shot, recalculation of magnetics predictors is required when the Physop loads the shot programming)

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 plenum, 16psi), Argon (B-side Lower, 1psi).
Cryopump: No
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 HIREX. Edge TS for pedestal profiles is highly desired. Nitrogen line radiation may render some CXRS measurements invalid. As complete a set of impurity spectroscopy diagnostics (XEUS, LOWEUS, 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:

The J-antenna camera view, which includes a good view of the divertor region below the mirror, should be used with a filter to image either nitrogen or Balmer series lines in order to provide additional data for modeling the seeding effects in the divertor and X-point region. Details and trade-offs are under discussion.

Use the LOWEUS 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.

\( Z_{\text{eff}} \) 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-half run day is required. Overnight boronization is required preceding this run. This experiment requires normal (negative) field and current direction, and all three antenna systems operating at f~80MHz.

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. Shot setup and boronization recovery. Start with the reference shot. Explore slightly higher elongation by raising ZXU, as a better match to ITER shape, but don’t spend a lot of time on it. Establish EDA at low input power (< 1.5 MW was sufficient in the reference case), evaluate diagnostic response, divertor conditions, core Mo levels, in the absence of seeding [1-3 shots].

1 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 N₂ puff level (B-div), and possibly timing, aiming for steady EDA H-mode (and RF). It may be necessary to increase the target density to maintain EDA at higher net power, but we should try not to exceed NL04=1.6e20 in the target. Monitor radiation, Mo and N levels, Zave, Pnet, performance, pedestal height, status of divertor detachment, X-point Marfe, . . . [5 shots]

2 If step 1 was successful, increase RF power, starting ramp at 3.5MW and ending at 4.5MW or highest available at EOF. Reoptimize N₂ puff at the higher power, if possible [3 shots]

3 Starting from steady seeded EDA H-mode condition developed in step 1 or 2, run flattop RF power and modulate seeding waveform on B-div. 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. [3-5 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, 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. Results should contribute to A. Kallenbach’s IAEA presentation on IOS-1.2 and C. Kessel’s IAEA presentation on IOS-1.1. In addition, the results should inform our development of feedback control of impurity seeding of high power, high performance H-mode discharges.

7. References

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