Subject: Scoping for feedback-controlled, radiative divertor experiments

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Group: Edge

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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 get a base set of actuator and sensor data in feedforward to assess feasibility and aid development a feedback system to radiate divertor heat flux.

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

The presently envisioned solution for ITER to the “heat flux problem” is a radiating, partially detached divertor. However, no experiment has demonstrated a successful divertor solution (surface heat flux \( q_{\text{surf}} < 5 \text{MW/m}^2 \)) while maintaining good core confinement (e.g., \( H_{98} > 1 \)) at the level of effort: parallel heat flux entering the divertor, parameterized as \( PB/R \), with >50MW-T/m expected for ITER. The \( PB/R \) scaling for the peak parallel heat flux is based on the Eich scaling of the heat flux width going as \( 1/B_p \), which translates to \( q_{\parallel,\text{max}} [\text{MW/m}^2] \approx 100 \times P[\text{MW}] \times B[\text{T}]/R[\text{m}] \).

The aim of this experiment is to assess various new tools developed for control of the divertor heat flux and radiation front. The information learned from these experiments will be used to develop control algorithms and inform the writing of a follow-on MP.
New tools for feedback control have been or are being implemented:

1. Observers:
   a. Refurbished divertor surface thermocouples and a new analog circuit that outputs real-time calculations of the divertor heat flux to the Digital Plasma Control System (DPCS), see Figure 1.
   b. Multiple channels of the divertor bolometer array connected to the DPCS.
   c. Edge Electron Cyclotron Emission (ECE) connected to the DPCS.
   d. Divertor MLP system connected to the DPCS (in development).
   e. An x-point-viewing, imaging polychromometer connected to the DPCS (in development).

2. Actuators:
   a. Piezo-controlled divertor seeding valves connected to the DPCS (tested on the run day 1120214).
   b. LH output power demand connected to the DPCS (in development).
   c. ICRF output power demand connected to the DPCS (in development).

![Figure 1](image1.png)

**Figure 1** Example of an output of the divertor surface thermocouple system. Bottom panel is the measured surface temperature. Top panel is the surface heat flux calculated post-shot with thermal analysis software (black) and real-time with an analog computer (red).

Examples of good observers for good and bad puff cases are shown in Figure 2. This data is from MP747 Toroidal power deposition asymmetries due to localized divertor N2 and Ne gas injection in support of ITER divertor power flux control. In the good puff case the N2 injected was sufficient to reduce the divertor heat flux but not reduce core confinement as indicated by the edge ECE $T_e$. In the bad puff case the N2 injected was too much and significantly reduced the edge $T_e$.

The divertor bolometer radiated powers may be observers that are fast enough to indicate too much impurities injected: In the good puff case both a channel looking through the outer strike point and a channel looking through the x-point rise and then stay relatively constant after the puff. In the bad puff case the outer strike point radiated power rises and then declines after the puff. Whereas the x-point radiated power continues to rise sharply, indicating that the radiating front has moved from near the divertor plate to near the x-point. Most importantly, these changes happen ~20ms before the edge $T_e$ decreases, which may be soon enough to “save” the confinement.
Figure 2 Comparison of two shots with N₂ seeding from the NINJA (feed forward), one with too much injected gas (left, 1140729013) and one with just enough (right, 1140729015).

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 run will utilize 1.1MA L-modes with density such that the divertor is in the high-recycling regime (10eV<T_e<20eV). Such plasmas can easily obtain high divertor surface heat fluxes ~25MW/m² (parallel heat flux ~500MW/m²). A variety of N₂ seeding duty cycles, on/off times, and ICRF powers will be utilized to assess the affects on divertor radiation, heat flux, and edge electron temperature.

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>5.4T</td>
</tr>
<tr>
<td>Plasma Current:</td>
<td>1.1MA</td>
</tr>
<tr>
<td>Working Gas Species:</td>
<td>D₂</td>
</tr>
<tr>
<td>Density:</td>
<td>n₁⁰⁴~1.3×10²⁰ m⁻², adjust to high-recycling divertor</td>
</tr>
<tr>
<td>Boronization Requested:</td>
<td>no</td>
</tr>
<tr>
<td>Equilibrium configuration:</td>
<td>1150723028, adjust to stay in lower-null</td>
</tr>
</tbody>
</table>

4.2 Auxiliary Systems

ICRF Power, pulse length, phasing: D&E, up to ~2MW, J may piggyback
LHCD Power, pulse length, phasing: not needed
Impurity blow-off injection: not needed
Diagnostic Neutral Beam: not allowed
Special gas puffing: N₂ divertor piezo valves, 15psi in H-bottom
Cryopump: yes
Non-axisymmetric Coils: standard configuration
Other: feedback inputs/outputs connected to DPCS

4.3 Diagnostics
List required diagnostics, and any special setup or configuration, e.g. non-standard digitization rate.
Absolutely necessary:
- divertor STC with real-time output to DPCS
- divertor bolometers with real-time output to DPCS
- edge ECE with real-time output to DPCS
- divertor piezo valve controlled by DPCS
- core and boundary spectroscopy, optimized for nitrogen (e.g., 1150625)
- divertor Langmuir probes

Should probably have:
- Thomson scattering
- IR camera

Nice to have:
- divertor MLP system
- x-point polychrometer
- GPI
- CXRS
- fast magnetics
- reflectometer
- PCI
- reciprocating probes
- HIREX

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 run day requested for this MP. Should not immediately follow boronization to ensure that the divertor Langmuir probes are cleaned off.

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.

1. Load shot 1150723028, set target density to $n_{104^{+}}$~1.3$m^{-2}$ and adjust upper x-point position to maintain LSN. 1-2 shots
2. Adjust target density such that divertor is high-recycling: $10eV<T_e<20eV$. 1-2 shots
3. Set divertor piezo valve(s, TBD use one or both?) to seed from 0.6 to 1.3s. Set to 25, 50, 75, and 100% duty cycle on subsequent shots. Add ICRF into ramp-down as necessary to reduce disruptivity. 4-6 shots
4. Fill in points of duty cycle scan around detachment and x-point MARFE. up to 5 shots
5. Modulate on/off time—in addition to the programmed duty cycle—of seeding. Set duty cycle levels and on/off times based on results of 3 and 4: Use duty cycles at levels well below detachment, near detachment, and ~half way between. On-times are long enough for radiation to ~equilibrate. Off-times are long enough for radiation to significantly decay. (it is acknowledge that the response, especially near detachment, will likely be non-linear) 3-6 shots

6. Set duty cycle at level for detachment, ramp to level for x-point MARFE, turn off, and watch recovery time. 1-2 shots

7. Repeat step 6, except after the recovery, program seeding such that ~partial detachment is maintained after the recovery from the x-point MARFE. 1-2 shots

8. Set duty cycle such that radiation front is at the x-point and ramp ICRF power (levels TBD during experiment) to see if/how the radiation front responds to an increase in the SOL input power. 1-2 shots

9. Use duty cycle from 8. Set ICRF power to the level where radiation moved from x-point back to divertor. Play around with ramping ICRF power and seeding duty cycle in step to maintain radiation front away from x-point. remaining 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.

This MP will result in a set of data that will inform the development of the feedback control algorithms and a subsequent MP to implement them in high $PB/R$ discharges.

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