1. Purpose of Experiments

To characterize the magnitude, location, and type of the volume recombination in the C-Mod divertor as a function of divertor $T_e$, divertor $n_e$, auxiliary heating power, and whether or not the divertor is detached. A secondary goal is to determine the opacity of the $Ly_\alpha$ and $Ly_\beta$ lines of atomic deuterium in the C-Mod divertor, at least as viewed alone one line-of-sight.

2. Background

Recombination, until recently, was not regarded experimentally (and in some cases, theoretically) as playing a significant role in the divertor. However, low-$T_e$ measurements from the divertor plasmas found in Alcator C-Mod [1] and DIII-D [2], suggestive measurements on divertor simulators in linear devices [3], as well as the inability to explain divertor ion current loss during detachment [4,5,6] have returned attention to recombination and to its role in divertor physics. In particular, it is important to determine its role in divertor detachment [7,8]. Direct experimental evidence of the occurrence of significant volume recombination in a tokamak divertor was first found on C-Mod in 1996. There are also as more recent measurements from a linear device [9], showing that volume recombination is present and plays a crucial role in detachment in those devices as well. Recombination in DIII-D has been suspected for some time, as well, and a recent DIII-D monthly report (April, 1997) states, “Analysis was completed for determining whether deuterium radiation from detached divertor plasmas was more representative of ionizing or recombining conditions using the $Ly_b$ and $Ly_d$ signals from the divertor SPRED instrument. The ratio of these lines is calculated to be approximately 80 under ionizing conditions and 10 under recombining conditions. In all cases the measured ratio was observed to decrease from a high value to a value between 10 and 20 as the density rose from gas puffing. The
plasmas evolved to a partially detached state indicating that recombination was becoming
the dominant mechanism for producing deuterium radiation. This interpretation is sup-
ported by the low electron temperatures (<1.5 eV) measured by Thomson scattering and
low ion temperatures (< 1 eV) measured by visible spectroscopy. Thus, the interest in the
role of recombination is quite high within the fusion community.

Several possible pathways for recombination (defined here as the conversion of hy-
drogenic ions into ground state neutrals) exist. These include 3-body recombination
(e+e+D^+ ⇒ D_0+e), radiative (2-body) recombination (e+d ⇒ D_0+hν) or various paths
through excited hydrogenic molecules (e.g. H_2^+ + e ⇒ 2H) [10]. All of the above processes
may be important in the temperature range 1-3 eV.

As mentioned above we have recently determined that significant volume recombina-
tion of the majority ion species into the neutral ground state is occurring in the Alcator
C-Mod divertor region at least under some conditions, i.e. a high density discharge with
≤ 1 MW of auxiliary heating. We have also determined what the key measurements, i.e.
a recombination edge and the Lyman or Balmer series spectrum, are for diagnosis of the
recombination and have developed the tools necessary for the analyses.

A complicating element in these analyses is the opacity of the Lyman series, since
the recombination is “complete” only after the atom is in the ground state. Under our
conditions this decay to the ground state occurs by emission of a Lyman series photon.
Thus any reabsorption of the photon may affect the analysis. In addition, significant
opacity of of Ly_α (or other Lyman lines) has other ramifications for the physics of a cold
divertor plasma, e.g. enhanced ionization rates, decreased recombination rates, and line
broadening.

The purpose of this MP is to characterize the recombination and to determine its
scalings in divertor plasmas. In doing so, we also propose to investigate the opacity of
the D_0 Lyman series lines. We believe that C-Mod is ideally suited for this study because
of its high divertor density, and because of C-Mod’s capability to achieve low divertor
temperatures even with extremely high parallel heat flow in the SOL.

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

For the study it is necessary to measure 1) the recombination edge around 370 nm, 2)
as many lines as possible of the Balmer series spectrum (of which the D_α,β,γ are the most
important), and 3) as many lines as possible of the Lyman series spectrum. The signature
of recombination through deuterium molecules should appear in the relative brightnesses
of D_α,β,γ. The spectral observation at 370 nm requires quartz optics.

The initial observations of recombination in C-Mod were made using a view of the
divertor from above. Only the D_α measurements made from this view were spatially
resolved. During the last maintenance period, our spatially resolving views of the inner
and outer divertor plates were re-made with quartz optics, and our original view from above was changed to give coverage of the divertor region with good spatial resolution.

The measurements of the recombination edge and the Balmer series lines having $n_{\text{upper}} > 4$ will be made with the Chromex which has a maximum of 13 spatial inputs. Because more then 13 Chromex views are desired, the shot sequence must be repeated with after the Chromex inputs have been switched. For the 1st set we will fill the 13 inputs with 7 chordal views from the K bottom array (viewing the inner divertor), 4 from the A bottom array (viewing the outer divertor), and 1 from the K top array. For the 2nd set of similar shots the inputs will be filled with 11 chordal views from the K top array and 1 each from the K bottom and A bottom. The spectral coverage of the Chromex spectrometer is such that the recombination edge at 370 nm and the $n = 11, 10, 9, 8, 7, 6,$ and $5 \rightarrow 2$ transitions of $D_0$ can be measured on a single shot. $D_\alpha$ and $D_\beta$ will be measured simultaneously by the reticon arrays at B top and K bottom. They will yield $D_{\alpha,\beta}$ brightnesses in the divertor with high spatial resolution.

The Lyman series lines will be measured with the McPherson grazing incidence spectograph. Its view will be directed toward the x-point. Co-incident with this view is a new visible view, filtered for either $D_\alpha$ or $D_\beta$. This system will be employed to investigate the opacity of the Lyman series. Since lines having upper levels with $n > 2$ appear in both the Lyman and Balmer series, and since the ratio of each pair is fixed by the transition probabilities, and since the Balmer series line will not be optically thick, any change in the low-density value of a given line ratio is a quantitative measure of the self-absorption of the Lyman line. However, this method will not work for $Ly_\alpha$, the line most likely to be thick. If $Ly_\alpha$ is very thick, then it may be broadened to a degree greater than the instrumental resolution, and the optical thickness may measured from the broadening. If this broadening is not measurable, we will model the scaling of the line brightnesses in the series (using a Johnson and Hinnov type formalism) assuming no absorption. Departures from the predictions may be due to self absorption.

The plasmas which we propose to study will have an increasing density, ramped beyond the threshold for detachment from the outer divertor plate. After detachment the RF heating power will be stepped up until it is higher than that needed for H-mode. At some point the increasing RF power will most likely re-attach the divertor plasma. At the highest RF powers and with the divertor attached, we will puff $N_2$ to lower the edge temperatures and ultimately detach the divertor. The scaling of the total recombination versus $T_{e,\text{div}}, n_{e,\text{div}}, P^{SOL}$, and total ion flux to the plates will be measured.

4. Resources

4.1 Machine and Plasma Parameters

Give values or range for:

Toroidal Field: 5.3 T

Plasma Current: 0.8 MA
**Working gas species:** D₂

**Density:** see shot 950425030

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

**Pulse length, typical current & density waveforms, etc.** Refer to database or sketch desired waveforms: Flat-top to 1.1 s for parts (a) and (b) of shot sequence.

### 4.2 Auxiliary Systems

**RF Power, pulse length, phasing:** Stepped up in 0.5 MW steps to ∼2.5 MW, The steps are 0.05 s in duration.

**Pellet Injection (species):** No

**Impurity blow-off injection:**

**Special gas puffing:** N₂ for high power detachment

**Other:**

### 4.3 Diagnostics

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

- Chromex spectrometer,
- Dₐ reticon arrays,
- FSP,
- bolometer arrays,
- C-Mod video system with the Dₐ filter in the wide angle view and with a D₃ filter in the divertor view
- 2.2m McPherson Spectrometer with its co-aligned visible detector system,
- Div. Thomson Scattering if operational,
- ECE,
- TCI

### 4.4 Neutron Budget

Estimate the neutron dose rate at the site boundary. Give basis for estimate. (Once some experience has been gained a standard formula will be provided for estimating dose rates.)

### 5. Experimental Plan
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 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.

(a). If possible, load shot 950425030 (which has the X-pt raised), but with X-pt lowered to its more usual position. Keep the density ramp seen in shot 950425030, but begin with a somewhat higher density, NL04~0.8e20, ramping to first to ~1.3e20 and subsequently to ~2.0e20. Document if and when it detaches with the FSP. (This may take 5 shots.)

(b). Turn on the RF heating 0.05 ms after detachment, and step up the power in 0.5 MW increments with each RF stage lasting 0.09s. Thus on the 1st shot in this sequence the RF power is 0.5 and 1.0 MW, while on the following 2 shots the power is 1.5 → 2.0 MW, and then 2.5 → 3.0 MW. (This may take 4 shots.)

(c). With the RF power at a constant ≥ 2.5 MW and timed to turn on at 0.6 s and off at 1.0 s, the divertor will probably be attached. We desire to detach the divertor by puffing N₂. On successive shots increasing amounts of N₂ are puffed through one of the fast valves. (This may take 6 shots.)

Repeat (a) with different views for the Chromex. (3 shots) Repeat (b) with different views for the Chromex. (4 shots) Repeat (c) at the level of N₂ necessary for detachment, but with different views for the Chromex. (2 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, or an external database.

There is some urgency in studying recombination. Other tokamaks are now beginning to look for and find signatures of volume recombination. C-Mod has the best chance of studying the phenomena, because of its high density and low temperature. It is anticipated that this study will determine the scaling of the recombination rate with other divertor plasma parameters, e.g. $T_{e}^{\text{div}}$, $n_{e}^{\text{div}}$, $P^{SOL}$. For the some of the same reasons any opacity in the Lyuman series lines should be easiest to see on C-Mod. An observation of the “molecular” recombination pathway would be quite important, but a null result would also be valuable.

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


