1. Purpose of Experiments

The purpose of these experiments is to extend the impurity transport studies already undertaken on Alcator C-Mod. The goals are:

(1) to study impurity transport and exhaust in order to maximize divertor radiation while maintaining a clean core plasma,

(2) to extend the compression and enrichment measurements to noble gases other than argon in all operational regimes,

(3) to determine what effect the divertor bypass (induced flows in the SOL) has on impurity compression and enrichment.

2. Background

Impurity transport and exhaust are important issues for dissipative divertor operation that is realized through impurity puffing. Impurities must be confined to the divertor and SOL with minimal concentrations in the core. This will reduce the detrimental effects on the core such as fuel dilution and cooling, and will enhance the positive effects of the dissipative divertor.

Two measures of divertor impurity retention are compression and enrichment[1,2]. The impurity compression, $C_z$, can be defined as:

$$C_z = \frac{\text{number of impurity neutrals in the divertor}}{\text{number of impurity ions in the main plasma}}$$
It is seen that maximizing compression will result in more radiation in the divertor (if the
temperature is optimal) and in a cleaner core plasma (given a divertor neutral density).
The impurity enrichment $\eta_z$ is defined as:

$$\eta_z = \frac{\text{impurity compression}}{\text{deuterium compression}}$$

Impurity particle exhaust is enhanced by enriching the impurity level with respect to the
fuel gas in the divertor.

Experiments on impurity transport issues have already been performed on Alcator C-
Mod under a variety of discharge conditions[3,MP167]. In these studies, it was found that
impurity compression and enrichment depend on line-averaged density and plasma regime.
Because argon is routinely puffed for ion temperature measurements most of the previous
work concentrated on the behavior of argon. The data obtained with other impurity gases
were for a limited set of discharge conditions.

The argon compression increases with density in attached Ohmic plasmas due to the
improved screening of impurities at higher density [see Fig. 1]. After detachment, the
argon compression decreases because of the decrease in impurity screening after detach-
ment[4]. The deuterium compression increases with density in attached Ohmic plasmas
and is constant after detachment. The compression for both argon and deuterium is
decreased in H-mode plasmas relative to those in Ohmic plasmas. The argon enrichment
increases with density in attached Ohmic plasmas and drops after detachment. The argon
enrichment is also decreased in H-mode relative to Ohmic plasmas.

Some experiments have also been done with impurity gases other than argon. Those
gases used include helium-3, neon, and krypton. As is observed on other tokamaks, impu-
ritiy compression and enrichment values increase with atomic mass number. The ionization
mean-free-path for impurities in the divertor plasma appears to be a crucial variable in
describing these results. As the ionization mean-free-path decreases, the impurity com-
pression and enrichment values increase, that is, the easier it is for an impurity to be
ionized, the easier it is to compress that impurity into the divertor [see Fig. 2].

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.

The approach for measuring impurity compression and enrichment is well developed
on Alcator C-Mod. A known number of impurity molecules/atoms are puffed into the
torus, and the number that reside in the core plasma are measured with a variety of
methods. For gases such as neon, argon, and krypton, the core density is determined
spectroscopically (with HIREX or the McPherson) and the MIST impurity transport code.
For the special case of helium-3, the core density is determined with a full-wave ICRF code
in conjunction with electron power deposition profile measurements. The divertor impurity
neutral density is measured with a quadrupole mass spectrometer (RGA) that samples the
private flux region of the divertor. Densities of impurity ion species present in the upper divertor region will be measured with the omegatron.

It is desirable to extend the argon measurements to other recycling gases. To that end, many different densities will be required for Ohmic plasmas using He-3, Ne, and Kr as the injected gases. These densities should span the range from low density to detached to deeply detached. It is possible to do most of this work in piggyback mode. These measurements will also be performed under H-mode conditions and if possible under detached H-mode conditions.

The effect of the divertor bypass on the entrainment of impurities in the divertor will also be investigated. The “flappers”, which control the leakage of neutrals from the divertor to the main chamber, will be an active control of the SOL conditions. Measurements of compression and enrichment will be made for He-3, Ne, Ar, and Kr with the flappers open.

4. Resources

4.1 Machine and Plasma Parameters
Give values or range for:

**Toroidal Field:** 5.4 T, (8.0T)
**Plasma Current:** 1.0 MA
**Working gas species:** \( D_2 \)
**Density:** \( \bar{n}_e = 1.0 \) to \( 4.0 \times 10^{20} m^{-3} \) for ohmic plasmas; \( \leq 5 \times 10^{20} m^{-3} \) for EDA H-mode.
**Equilibrium configuration** (if possible, refer to database equilibria): fiducial-like
**Pulse length, typical current & density waveforms, etc.** Refer to database or sketch desired waveforms: \( \geq 0.5 \) s of flattop to allow divertor conditions to equilibrate

4.2 Auxiliary Systems

**RF Power, pulse length, phasing:** as required for good EDA H-mode
**Pellet Injection (species):** None
**Impurity blow-off injection:** if required for core transport measurements
**Special gas puffing:** Trace amounts of He-3, Ne, Ar, and Kr
**Other:** Flappers

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

interferometer; divertor probe array; ECE; bolometer arrays; fast scanning probe; Chromex, McPherson, and HIREX spectrometers; ratiometric pressure gauges; divertor pressure gauges; divertor RGA; omegatron
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.)

none for Ohmic; $1.5 \times 10^{13}$ / shot for EDA H-mode

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.

The Ohmic portions of the MP should be compatible with piggyback operation. The EDA H-mode portions of the MP should also be able to be performed piggyback. This, of course, relies on the kindness of the Session Leader. The divertor bypass section of the run plan can be included under some “flapper” MP. Unless a method of measuring the core helium concentration other than RF power deposition becomes available, a piggyback run with RF mode conversion is needed.

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) accomplish everything piggyback - no dedicated shots necessary

If everything is not accomplished in a piggyback mode:

(2) Ohmic plasmas: need several densities with puffed Ne and Kr - 12 shots; Ar should be puffed for comparison purposes

(3) EDA H-mode plasmas: couple of densities with puffed Ne and Kr - 6 shots; repeat for detached H-mode - 6 shots; Ar should be puffed for comparison purposes

(4) Need some mode-conversion experiments to measure helium compression and enrichment. Vary the density in Ohmic, hopefully obtain H-mode - 9 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.

The results will augment Alcator C-Mod’s broad program studying impurity transport. They will extend the database of $C_z$ and $\eta_z$ to recycling gases other than argon. Scaling of $C_z$ and $\eta_z$ vs. atomic mass number under a variety of plasma conditions will be obtained. This should allow for a better understanding of the role that ionization mean-free-path and SOL flows have on impurity transport in Alcator C-Mod. This information will also be used for Chung’s thesis work on impurity transport in Alcator C-Mod using the DIVIMP code. In addition, data gathered with the omegatron will be used for Nachtrieb’s thesis work on ion mass spectroscopy.
7. References

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


Compression and enrichment increase with line-averaged density in attached Ohmic plasmas

- Argon compression drops after divertor detachment
- Deuterium compression is relatively constant after divertor detachment
- Deuterium compression is decreased in H-mode relative to L-mode

Figure 1
Compression and enrichment decrease with increasing ionization mean-free-path.

Fig. 5: Impurity compression (a) and enrichment (b) are dependent on the first ionization mean-free-path. Shown are discharges with puffed krypton (square), argon (circle), neon (up triangle), and helium (down triangle).

Figure 2