Chapter 9

Key Results and Future Work

In this concluding chapter, the key results from each section are presented, and future work based on these results is identified. The chapter is divided into three sections. Section 9.1 discusses the spatial evolution of the separation profile investigated in Chapter Two. Section 9.2 summarizes the steady state model of the VAC plasma in the rotation region investigated in Chapter Three, both with and without the effects of electron-ion collisions. Finally, Sec. 9.3 discusses the bulk of the research (Chapters Four through Nine), which comprise a detailed initial analysis of the oscillations in Langmuir probe signals in a VAC, observed ever since conception of the device in 1980.

9.1 Spatial Evolution of Isotope Separation in a Vacuum Arc Centrifuge Plasma

9.1.1 Key Results

In Chapter Two, a numerically determined solution to the spatial evolution of the separation, concentration and radial diffusion velocity was presented. A key result of the solution was that the plasma should freeze at outer radii, where the ion-ion collision rate is dramatically reduced, and there should be little development of separation beyond the plasma column. For the available set of experimental data (Cu-Ni deposition measurements by Geva et al. [13]) with which results were compared, no such effect was observed, and the model did not correctly
predict the separation outside the plasma column. However, it should be noted that, for any future commercial application, it is the separation factor where a reasonable quantity of material is present which is of importance. The model does provide reasonable estimates of the axial development of separation within the plasma column, and thus provides a useful tool for evaluation of VAC designs.

9.1.2 Future Work

The discrepancy between the measured and predicted separation profile at large radius needs to be resolved. The measured separation profile for the Cu-Ni plasma increases with radius. In contrast, the predicted separation and the ion-ion collision frequency decrease significantly beyond $r \approx 1.5R$, where the plasma freezes. A number of research approaches may provide insight into the discrepancy, and are summarized below.

- Plasma contamination in the outer region. The extremely low density plasma outside the main plasma column may have properties which differ significantly from the bulk plasma. It seems likely that measurements of the plasma in the outer region will be difficult, owing to the small amount of material present. In principle however, detailed spectroscopic measurements of emission line broadening and Doppler shift should reveal any variation of the ion temperature and ion rotation frequency at outer radii, respectively. Spectroscopic measurements of the ion rotation frequency, when taken together with deposition experiments showing the rotated angle of the shadow of an upstream obstruction, should reveal any variation in the plasma bulk transport velocity at large radius. Such measurements may provide a better description of the plasma in the outer region. In turn, the appropriate modifications to the plasma model derived in Chapter Two may modify the predicted spatial evolution of separation, particularly in the outer region.

- The effects of varying charge distribution with radius. In general, a distribution of different ion charge states is present in the VAC plasma. Preferential centrifuging of higher charge states may occur, leading to an average charge $Z$ which increases with radius. Extension of the plasma model to include two or more ion species of differing charge would show the evolution of the concentration of different charge species, and modify the separation
profile for different charge states.

- A detailed experimental study of the spatial evolution of isotopes in the VAC, using a range of mass separation diagnostics. At least one set of experimental data exists that suggests the separation decays at large radius [50], consistent with predictions of the theory model developed in this work.

9.2 Steady State Models of the Vacuum Arc Centrifuge Plasma

9.2.1 Key Results

In Chapter Three, analytical solutions were derived for the steady-state plasma in the rotation region of a VAC, both with and without the effects of electron-ion collisions. In a calculation which ignored the effects of electron-ion collisions, it was shown that the diamagnetic effect caused by the azimuthal current is negligible.

The effects of electron-ion collisions were included as a perturbation to the steady-state plasma. When the radial dependence of the electron-ion collision frequency was Gaussian, closed form perturbation solutions could be found only for certain plasma conditions. For general plasma conditions an approximate technique was used. Compared to the numerical treatment of a collisional magnesium plasma in a VAC, by Yue and Simpson [36], the approximate treatment satisfactorily predicted important physical features. Differences between the solutions were attributed to the effects of ion viscosity, which were not included in the analytic model of Chapter Three.

Using solutions of the approximate treatment, the dependence of the fractional change in the separative figure of merit $\Delta A/A$, with varying temperature, rotation frequency and axial streaming velocity was investigated. For plasmas that rotate slowly compared to the thermal speed, a substantial improvement in separation was predicted, and the fractional improvement in separation was predicted to increase with decreasing temperature. For typical VAC plasma conditions a reduced (but still supersonic) streaming velocity was predicted to improve separative performance, and the improvement was predicted to increase with decreasing temperature.
9.2.2 Future Work

Extension of the analytic model to include the effects of ion viscosity should resolve the differences in physical features between the analytic treatment of Chapter Three and the numerical treatment of Yue and Simpson [36]. Understanding of the physical processes in the plasma could be further improved by the development of a three fluid model (comprising electrons plus two isotope species) which includes the effects of ion-ion collisions, electron-ion collisions and ion viscosity. The solutions of the model should at least, (i) modify evolution of the separation profile in the steady state plasma (investigated in Chapter Two) to account for the effects of electron-ion collisions, and (ii) modify the dependence of the equilibrium separation profile with temperature, rotation frequency and axial streaming velocity (investigated in Chapter Three) to account for the effects of ion viscosity.

9.3 Instability of a Vacuum Arc Centrifuge Plasma

9.3.1 Key Results

In Chapter Five, a linearized perturbation treatment of waves of the form \( \exp(i(m\theta + k_z z - \omega t)) \) was developed, with \( m \), the azimuthal mode number; \( k_z \), the axial wavenumber; \( \omega = \omega^r + i\omega^i \), a complex normalized frequency; \( \Omega_c \), the ion cyclotron frequency and \( t \) time. In Chapters Five through Seven, wave perturbation solutions were found and dispersion curves generated for a range of conditions. Two unstable modes were found for the VAC plasma: the centrifugal instability, [70,77] and the density-gradient driven drift wave [68,74].

In Chapter Eight, detailed Langmuir probe measurements of a magnesium plasma in the PCEN device were presented, and compared to the predictions of theory. Comparison of experimental results with the predictions of theory concluded that the most likely candidate instability is the density-gradient driven drift wave of a plasma with finite electrical conductivity.

The density-gradient driven drift wave with \( m = 1 \) has a predicted slip of 21\%, to be compared to a slip of 17\% estimated from plasma deposition measurements in a similar magnesium plasma [25,40]. The axial wavenumber of the density-gradient driven drift wave was predicted to be \( k_z = 3.7 \) rad m\(^{-1} \), which is comparable to the measured wavenumber of \( k_z = 1.9 \pm 0.2 \) rad m\(^{-1} \). The predicted radial phase profile of the ion density compared well
to the measured profile, and agreement between the predicted and measured phase profile of
the floating potential was reasonable for \( r > 10 \text{ mm} \). For \( r < 10 \text{ mm} \) however, there was
a significant discrepancy in the profile of the floating potential between the predictions of the
density-gradient driven drift wave and experiment. Finally, the maxima in the instability ampli-
tude profiles of the floating potential and ion density are close to the predicted radial location.

9.3.2 Future Work

Explanation of the discrepancy between the predicted and observed phase profile of floating
potential oscillations at small radius is perhaps the most important of the many topics of
future research identified in this work. It seems possible that the discrepancy is related to the
deviation of the steady state floating potential profile from a parabolic fit and the observed
non-uniformity of the electron temperature across the plasma. Combining these observations,
several possible approaches (both theoretical and experimental) can be suggested to explain the
discrepancy:

- Modification of the steady-state plasma model to consistently account for both the electron
temperature non-uniformity, and the non-parabolic floating potential profile near the
plasma centre.

- A more detailed interpretation of measurements of the floating potential to account the
electron sheath surrounding the probes\(^1\). This correction is complicated because the
plasma is streaming, and the ion thermal velocity for magnesium is of the order of the ion
streaming velocity. Experimentally, the use of a hot, electron-emitting probe may reduce
the sensitivity of potential measurements to the electron temperature \([57]\).

- Perturbation of the electron temperature in the collisional model, together with inclusion
of an electron energy equation for the electron fluid.

- Measurements of any oscillation in the electron temperature. As discussed in Chap-
ter Eight, oscillations in the electron temperature could be detected by measuring any

\(^1\)This gives the ‘space potential’.
change in slope of a plot of the logarithm of the electron current against the probe voltage in the transition region of the Langmuir characteristic curve, on a time scale much shorter than the periodicity of the oscillations. Electron temperature phase measurements could be made by referencing the phase of any oscillations in the slope to a downstream probe measuring the floating potential. Both procedures require fairly sophisticated signal processing techniques.

Of these, the first two are arguably the most promising, because they relate to the steady state model, which is known to fail at small radius. Further possibilities for research associated with the oscillation phenomena have been identified. These include the following:

- Detailed spectroscopic measurements of the ion rotation frequency and ion temperature, with comparison to the oscillation frequency inferred by Langmuir probe measurements. The objective would be to conclusively establish the slip of the wave with respect to the plasma.

- Measurement of the instability properties under different plasma conditions and compositions.

- Inclusion of FLR effects in the theory model, which is believed will provide a damping mechanism for higher order modes.

- Investigation of instability behavior with increasing $q$ values. In some VAC experiments [13] a fit of the ion saturation current suggests $q = 2$.

- A detailed study of the collector boundary conditions, and the anode mesh and collector sheaths. The aim would be to establish the effects of the collector boundary on plasma rotation, and the axial sheaths on the density gradient-driven drift mode.

- An energy analysis of the instability. It is hoped such an analysis would identify energy flows of the instability.