Chapter 4

Oscillations Observed in Vacuum Arc Centrifuges and Related Devices

In this chapter the oscillations in electric probe signals in a VAC are reviewed, and compared to oscillations observed in other rotating plasmas. Ever since conception of the Vacuum Arc Centrifuge (VAC) in 1980 [11], oscillations have been observed in electric probe signals of the VAC plasma. Since this time, continued experimental research has provided an understanding of various properties of the oscillations. Similar oscillations have also been observed in other rotating plasmas, including those of the Q-machine, theta-pinch and magnetic mirror. A comparison of plasmas and device geometries shows that the oscillations of a Q-machine may be related to those in the VAC, and such a comparison is made in this chapter.

The chapter is organized as follows: Sec. 4.1 chronologically reviews the relevant VAC literature, and compiles an understanding of the properties of the oscillations in electric probe signals in a VAC. Section 4.2 compares the phenomena to oscillations observed in other rotating plasmas. Finally, Sec. 4.3 contains concluding remarks, and outlines the structure of the instability discussion and analysis in the remainder of this work.

4.1 Background

Ever since conception of the Vacuum Arc Centrifuge (VAC) by Krishnan et al. [11] in 1980, periodic fluctuations in the ion saturation current have been observed in Langmuir probe mea-
measurements in the rotation region of a VAC. In 1981, Geva et al. [48] presented a set of Langmuir probe measurements for a carbon plasma. At a given axial location, two probes were placed 90° apart in azimuth. The floating potential and ion density signals from both probes exhibited the same characteristic fluctuation frequency, with a phase difference of a quarter of a period. Measurements of the ion saturation current at different radii revealed that the fluctuation frequency was independent of radius, within the bulk of the Gaussian density distribution. Measurements of the ion saturation current at locations 0.3 m apart in the axial direction showed that the fluctuation occurred at the same frequency and with no phase difference. Similar results were quoted for Al-Ti and Cu-Ni plasmas, albeit at slightly lower frequencies, implying that any axial wavelength is significantly greater than the probe separation.

In 1984 Geva et al. [13] reported that for a carbon plasma, reversal of the axial magnetic field is associated with a reversal of the phase difference between azimuthally separated probes. In that work, comparison between the intensity of the ion density fluctuation as measured by a mass spectrometer, and the ion saturation current from Langmuir probes was presented for a zirconium plasma. Geva et al. [13] hypothesized that the difference in amplitudes could be explained by assuming a localized density anomaly, together with the difference in solid angles subtended to the plasma column by the mass spectrometer and Langmuir probe.

In 1986, Prasad and Krishnan [38] reported the first measurements of the Doppler shift of an emission line using a Fabry-Perot Interferometer, and thus inferred the rotation frequency of ions in a carbon plasma. In the following year, Prasad and Krishnan [27,39] reported good agreement between the oscillation frequency of Langmuir probe signals and the spectroscopically inferred ion rotation frequency, but provided no quantitative comparison. A plot of the spectroscopically inferred ion rotation frequency in a carbon plasma as a function of the axial magnetic field strength $B_z$, indicated that the rotation frequency was linear across the range $0.07 < B_z < 0.21$ T [27]. For $B_z = 0.13$ T and a discharge current of 2.1 kA, their fit of ion angular rotation frequency to magnetic field variation implies an ion angular rotation frequency of 120 krad s$^{-1}$. This is somewhat lower than the probe angular frequency of 200 krad s$^{-1}$, recorded for a carbon plasma in the same device and at the same magnetic field strength [13].

In 1987, Del Bosco et al. [37] presented the findings of a thin slit experiment in the PCEN device at the Brazilian National Space Research Institute (INPE), in which two close parallel
mylar films are placed across the plasma. The upstream film had a thin slit cut along a straight line through the centre of the film. Plasma deposition on the downstream film showed a rotated image of the slit. Using an earlier measurement of the axial ion velocity [13], together with the rotated angle of the deposit, they inferred a plasma rotation frequency which was found to be comparable to the oscillation frequency of Langmuir probe signals. Finally, they reported that the direction of rotation of the slit image reversed with the magnetic field, and the fluctuation was reported to vanish in the absence of a magnetic field. Geva et al. [33] reported findings of a similar experiment in 1987, in the Yale University device.

In 1996 Dallaqua et al. [35] compared estimates of the angular frequency inferred from displacement of the maximum peak and peak spacing of the cross-correlation of the floating potential in a magnesium plasma. They concluded that there is likely to be a single rotating non-uniformity with azimuthal mode structure $m=1$. In this work it was also reported that the fluctuations observed in Langmuir probe measurements vanish in the presence of a substantial amount of background gas.

In 1996 Yue and Simpson [36] performed a MHD two-dimensional fluid simulation of the plasma column in the rotation region of the VAC, accounting for the effects of electron-ion collisions. The simulation, which assumed azimuthal symmetry, showed oscillations in the plasma properties as a function of axial position. It was concluded that whilst azimuthal structure was ruled out by the assumptions of the model, it seemed possible that the oscillations were related to the observed non-uniformity. The oscillations were present in the limit of infinite conductivity along the field lines and finite conductivity across the field lines, suggesting that the oscillation may be associated with the effects of electron-ion collisions perpendicular to the magnetic field [36].

Also in 1996, Simpson et al. [29] concluded that the effective resistivity of the anode mesh significantly influenced acceleration in the driving region of the plasma. For the typical VAC set-up with the target negatively biased (cathode) and the mesh grounded (anode) it was argued that: (a) the radial electric field must be directed inwards in both the driving and rotation regions, and (b) the plasma must rotate in the same sense as the $\mathbf{E} \times \mathbf{B}$ drift. The arguments can be summarized as follows:
(a) The discharge current flows predominantly axially from the centre of the anode mesh to the cathode. Therefore, radial current in the anode mesh flows inwards, and the finite resistivity of the anode mesh gives rise to a radial electric field, also directed inwards. On the driving side the anode mesh is an electron collector, and so the sheath voltage should be small, and the plasma should therefore take the potential profile of the anode mesh. The plasma streams through the anode mesh, and therefore, in the rotation region, should also take the potential profile of the anode mesh.

(b) Radial current flow in the driving side plasma is also directed inwards. It is the interaction of this current \( (J_r) \) in the driving region with the externally applied magnetic field that accelerates the plasma into rotation.

In 1997, Dallaqua et al. [40] adapted the slit technique to minimize disturbance to a magnesium plasma. Rather than interrupt all but a thin strip of the plasma, a thin ceramic rod was placed upstream of the mylar film. Images of the deposition on the film showed a rotated shadow cast by interruption of the plasma by the upstream rod. In 1998, Dallaqua et al. [25] used the shadow technique to verify rigid rotor plasma column behavior for a magnesium plasma. By recording the time displacement of two axially separated Langmuir probes, an axial streaming velocity of the plasma was inferred. Combining estimates of the streaming velocity and shadow rotation values, the angular frequency of the fluid plasma was estimated at 170 krad s\(^{-1}\). For identical conditions in the same device, Dallaqua et al. [40] report an oscillation frequency measured by Langmuir probes of 200 krad s\(^{-1}\).

From these results the following picture of the non-uniformity emerges. Consistency in the phase difference between Langmuir probes separated by an azimuthal angle of 90°, across a wide range of plasmas and conditions indicates the presence of a single rotating non-uniformity with azimuthal mode structure \( m = 1 \) [13, 28–30, 33, 35, 37]. Reversal of the magnetic field has been shown to reverse the direction of plasma rotation in both experiment [13, 37] and theory [29], and the direction of non-uniformity rotation in the experiment [13]. The non-uniformity rotates in the same sense as the plasma [13, 33, 39]. In addition, the non-uniformity vanishes in the presence of a substantial amount of background gas [35], and a fluid simulation of the VAC indicates that the driving mechanism for the non-uniformity may be associated with
the effects of electron-ion collisions perpendicular to the magnetic field [36]. Whilst detailed measurements of spectroscopic and probe frequencies under identical conditions are clearly warranted, experiments to date indicate that the non-uniformity frequency is either comparable to or slightly greater than the ion rotation frequency [13,25,27,40]. Finally, measurements of the ion saturation current in Langmuir probes separated axially by 0.3 m in C, Al-Ti and Cu-Ni plasmas, have shown that the fluctuations are in phase and have the same frequency [13,48]. In this work the non-uniformity will be as an electrostatic oscillation in the rotation region of the VAC. It seems unlikely that the axial wavelength is invariant over the different plasma compositions, and so it is reasonable to infer that the axial wavelength is significantly longer than 0.3m for these three plasmas.

The approach taken in this work, which treats the non-uniformity as an electrostatic oscillation, differs to the competing hypothesis by Geva et al. [13], which suggests the non-uniformity can be explained by assuming a localized density anomaly. The density anomaly hypothesis offers no explanation as to the source of the anomaly, nor any explanation why the anomaly is present over such a wide range of plasma compositions.

4.2 Other Rotating Plasmas

Instabilities have been observed in many other laboratory rotating plasmas, including Q machines [57], theta pinches [58,59] and magnetic mirrors [60–62].

Theta-pinches and magnetic mirrors are high beta devices with significant magnetic curvature. As such, both the plasma and magnetic field geometry in theta-pinches is vastly different to those in a VAC machine. In contrast, Q machines are low beta devices with negligible magnetic field curvature. Figure 4-1 is a schematic of a typical Q machine, whilst Table 4.1 compares the parameters of a standard Q machine [57] and a VAC. Fig. 1-2 from Chapter One, which shows a schematic of the PCEN device at INPE, is reproduced for comparison.

Both the VAC machine (in the rotation region) and Q machine exhibit similar geometry. The Q machine operates in the steady state, whereas the VAC device is pulsed with a typical life-span of approximately 10 ms. The thermal properties of both Q and VAC plasmas are comparable; they are both relatively low temperature column plasmas, and to a reasonable
<table>
<thead>
<tr>
<th></th>
<th>Q machine(\dagger)</th>
<th>VAC(\ddagger)</th>
</tr>
</thead>
<tbody>
<tr>
<td>plasma</td>
<td>Cs</td>
<td>Mg</td>
</tr>
<tr>
<td>background pressure</td>
<td>(1.0 \times 10^{-4}) Pa</td>
<td>(1.0 \times 10^{-4}) Pa</td>
</tr>
<tr>
<td>axial magnetic field, (B_z)</td>
<td>0.05 T</td>
<td>0.1 T</td>
</tr>
<tr>
<td>plasma temperature, (T)</td>
<td>0.2 eV</td>
<td>5.5 eV</td>
</tr>
<tr>
<td>sign of (\partial \phi(r)/\partial r)</td>
<td>(\partial \phi(r)/\partial r &lt; 0)</td>
<td>(\partial \phi(r)/\partial r &gt; 0)</td>
</tr>
<tr>
<td>sign of (\partial p(r)/\partial r)</td>
<td>(\partial p(r)/\partial r &lt; 0)</td>
<td>(\partial p(r)/\partial r &lt; 0)</td>
</tr>
<tr>
<td>on-axis ion density, (n_0)</td>
<td>(10^{17}) m(^{-3})</td>
<td>(4 \times 10^{20}) m(^{-3})</td>
</tr>
<tr>
<td>characteristic radius, (R)</td>
<td>15 mm</td>
<td>20 mm</td>
</tr>
<tr>
<td>plasma rotation frequency, (\omega_0)</td>
<td>-72 krad s(^{-1})</td>
<td>150 krad s(^{-1})</td>
</tr>
<tr>
<td>ion cyclotron frequency, (\omega_0)</td>
<td>36 krad s(^{-1})</td>
<td>590 krad s(^{-1})</td>
</tr>
<tr>
<td>plasma axial streaming velocity, (v_0)</td>
<td>0</td>
<td>(10^4) m s(^{-1})</td>
</tr>
<tr>
<td>axial current density, (J_z)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>mean ionization, (Z)</td>
<td>(\leq 1)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

\(\dagger\) “standard Cs plasma” [57]
\(\ddagger\) Mg plasma in rotation region [32]

Table 4.1: Comparison of Q machine and VAC plasma parameters.

approximation the ion and electron temperatures are equal. Typically, the on-axis density in a VAC machine is 10 to 100 times more dense than the Q machine. The background pressures in both devices are comparable. In a VAC, the plasma is typically multiply ionized, whereas a Q-machine plasma is generally partially ionized, and at most singly ionized.

The ion fluid velocities in both devices are significantly different. In particular, the Q-machine plasma is stationary along the magnetic field, whilst in the VAC device the plasma is swept supersonically along the magnetic field lines. Although in both machines the plasma rotates, the acceleration mechanisms are quite different. In a Q machine [57] the radial electric field is determined by the balance of electron fluxes into and out of the end plates. In an ideal device the end-plates are uniformly heated, and so \(\partial \phi(r)/\partial r < 0\) and \(\partial p(r)/\partial r < 0\), and the plasma rotates in the \(-\theta\) direction with \(v_\perp = v_E + v_D \simeq 2v_D\), where \(v_E\) and \(v_D\) are the \(E \times B\) and diamagnetic drifts respectively. In contrast, acceleration in a VAC is strongly influenced by the effective resistivity of the anode mesh and the radial magnetic field components in the driving region [29]. For the VAC plasma \(\partial \phi(r)/\partial r > 0\) and \(\partial p(r)/\partial r < 0\), and the plasma rotates in the \(+\theta\) direction.

Chen [63] notes that the radial wall in a Q machine is usually defined by a conducting annulus, located where the steady-state ion density has dropped to approximately 10% of its
Figure 4-1: Typical Q machine (caesium plasma).

Figure 4-2: A schematic of the PCEN device (a typical VAC) at INPE.
on-axis value. In contrast, the vessel wall in a VAC is sufficiently far from plasma column such that neither the plasma density nor pressure is perturbed by the vessel wall. Consequently, whereas the Q machine plasma column is bounded in the radial direction by an aperture limiter, the VAC plasma column is de-coupled from the plasma wall.

In a typical Q machine [57] the axial boundaries are the tungsten end-plates, which are heated by electron bombardment, and in electrical contact with the plasma. A more detailed analysis of the boundary conditions by Chen [64,65], suggests that:

- the wave perturbations in the ion density and potential are non-zero at the sheath edge, and accommodated by a small change in sheath thickness and sheath voltage drop;
- under certain conditions the perturbation in the sheath voltage drop is just that necessary to give the perturbed axial current for a universal drift wave\(^1\) [67,68].

That is, the wave need not have a node at the sheath edge, and axial current continuity can be satisfied between the plasma and the sheath. Thus, it is possible to have an axial wavelength longer than twice the device length.

In a VAC, the axial boundaries in the rotation region are the anode mesh and the end plate. Plasma streams through the anode mesh from upstream in the driving region and so takes the potential profile of the anode mesh, constituting one axial boundary condition. Collector end plate conditions vary with the experiment, ranging from the conducting vacuum vessel wall to mylar film.

The similarities between the plasmas and geometry allows use of Q-machine instability research [63,65,68–75], summarized by Motley [57], to assist in an understanding of the VAC non-uniformity. In doing so however, one must bear in mind the differences in plasma properties and geometry.

In summary, the VAC plasma is multiply ionized, whereas the Q-machine plasma is at most singly ionized. In a Q machine, \(\partial \phi(r)/\partial r < 0, \partial p(r)/\partial r < 0\) whereas \(\partial \phi(r)/\partial r > 0, \partial p(r)/\partial r < 0\) in a VAC, and the plasma rotates in opposite directions. In the laboratory frame, the VAC plasma is transported supersonically along the magnetic field, whereas the Q-machine

\(^1\) The 'universal drift instability' in Motley [57] is referred to as the 'universal resistive overstability' by Chen [65], or the 'density-gradient driven drift wave' by Chu et al. [66].
plasma is stationary. The Q-machine plasma is aperture limited in the radial direction (finite-boundary), whereas the VAC plasma is isolated from the conducting walls (remote-boundary). Finally, the Q-machine plasma is in electrical contact with both end-plates. A study of the sheath region by Chen [65] suggests that the universal drift wave [68] in a Q-machine plasma may be impedance matched to the sheaths at the cathode end-plates. In contrast, the VAC axial boundary condition is that the plasma take the potential profile of the anode mesh.

4.3 Concluding Remarks

In this chapter the properties of the oscillations in electric probe signals in a VAC have been described, and the oscillations compared to instabilities observed in other rotating plasmas. In summary, experimental evidence of the oscillations in a VAC suggests a $m = 1$ non-uniformity [13,28–30,33,35,37,48] that rotates in the same sense as the plasma [13], with angular frequency either comparable to or slightly above the plasma angular rotation frequency [13,25,27,40]. The non-uniformity is present over a wide range of plasma compositions, but is suppressed when a substantial amount of background gas is present [35]. Finally, the axial wavelength is significantly longer than 0.3 m [48].

Comparison to oscillations in other rotating plasmas suggests that the instabilities observed in Q-machine plasmas [57] may be related to those in the VAC plasma, owing to the similarities in device geometry and plasma conditions. The key differences between the plasmas are: the acceleration mechanism, electric field profiles and plasma velocities, the ionization state, and the radial and axial boundary conditions. Notwithstanding these differences, the results of Q-machine research [63,65,68–75] do assist in an understanding of the possible causes of the oscillations observed in electric probe signals in a VAC.

The remainder of this work is organized as follows. Chapter Five introduces the plasma model and a wave perturbation, solves for the perturbation in the absence of electron-ion collisions, generates dispersion relations and describes unstable modes. Chapter Six includes the effects of electron-ion collisions as a further perturbation to the wave-perturbed plasma parameters, and solves for small axial wavelength modes. In Chapter Seven the axial wavenumber is scaled by the electron-ion collision parameter, and the wave perturbation numerically solved
for large axial wavelength modes. Finally, Chapter Eight describes experiments in the PCEN
device [25] to identify the instability.