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Plasma Issues Associated with the Use of Electrodynamic Tethers

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Abstract

The use of an electrodynamic tether to generate power or thrust on the Space Station raises important plasma issues associated with the current flow. In addition to the issue of current closure through the Space Station, high power tethers ($\geq$ tens of kilowatts) require the use of plasma contactors to enhance the current flow. They will generate large amounts of electrostatic turbulence in the vicinity of the Space Station. This is because the contactors work best when a large amount of current driven turbulence is excited. Current work is reviewed and future directions suggested.

1 Introduction

Electrodynamic tethers have been studied as a means of providing electrical power and thrust for the Space Station. Typically such tethers would be 20-100 km in length and have power levels of 25 kw to 100 kw. The use of an electrodynamic tether offers the significant advantage of a device which is reversible in that it can produce both power (kinetic energy of the Station $\longrightarrow$ electrical energy) and thrust (electrical energy $\longrightarrow$ kinetic energy of the Station). Furthermore in the power generation mode, the tether - drag compensation system produces electrical energy more efficiently than direct conversion of the chemical energy in the rocket fuel used for drag make-up. However since the electrodynamic tether by its very nature works by its interaction with the plasma environment, the space technology plasma issues associated with its use are of critical importance.

In this paper some of the plasma issues currently under investigation are reviewed and several important plasma issues for the future are identified . The outline of the paper is as follows: in section II, work on current induced radiation from the Station is reviewed, in section III, a simple theory of plasma contactors is presented, in section IV, the role of turbulence induced transport is outlined and in section V, the implications for the future of this work are discussed.

2 Current induced radiation from the Space Station

The combination of an electrodynamic tether with the Space Station may look like the configuration in Fig. 1. Whatever the final configuration is like, one of the effects of the tether will be to draw a current through parts of the Station Structure. Of course, since the Station is itself a large conducting object in low earth orbit, it will see a motionally induced potential along its structure and a current flow even without an electrodynamic tether. The current through the system will

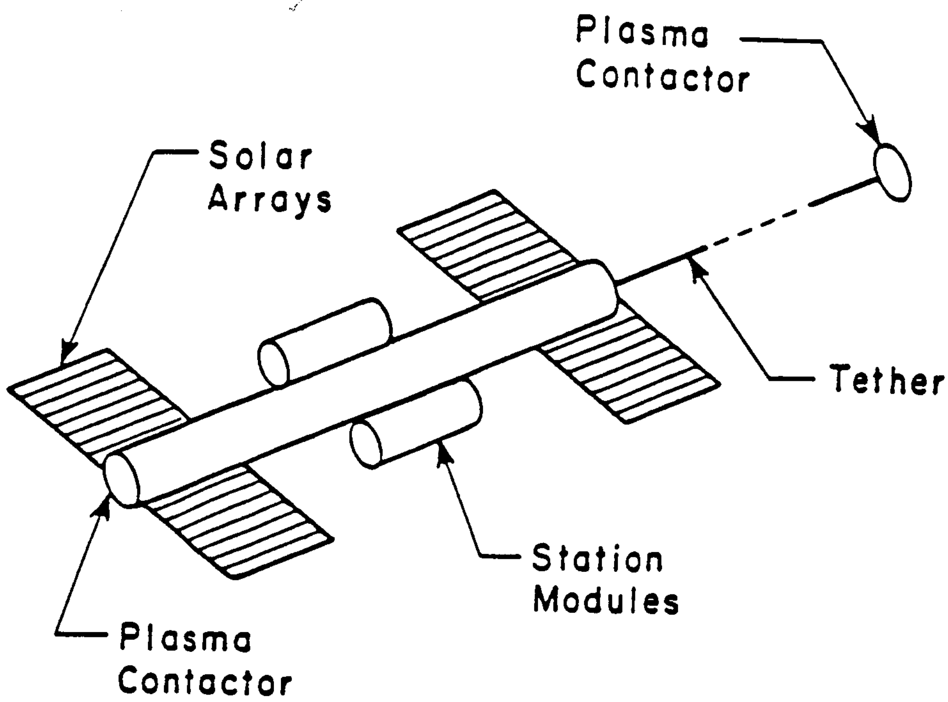

Figure 1: Space Station - Tether combination

cause the irreversible loss of power which will be emitted as electromagnetic radiation into the surrounding ionosphere. We assume that the current density flowing through the tether-station combination varies as $cos(\omega^* t)$ where $\omega^* \neq 0$ takes into account that the tether current may have an AC variation impressed on it. This can occur for two possible reasons, firstly because the power distribution system on the Station will probably be AC and there could be some inductive coupling between this current and the current in the power distribution system. Secondly, another possible use for the tether is as an antenna [M.D. Grossi, private communication, 1986] in which case the current in the system would necessarily be AC. With this assumption for a source current, Maxwell's equations for the emission into a magnetoactive medium can be solved and it can be shown that the average radiated power ($\bar{P}_{rad}$)can be written as

$$\bar{P}_{rad} = I^2 Z \tag{1}$$

where I is the current flowing through the tether-station combination and Z is the radiation impedance given by[1]

$$Z = Z_o \pi^2 \int_{Bands} d\omega \frac{1}{\sqrt{S}(\omega)} (\frac{c}{V_o c_A}) \int_{-\infty}^{\infty} dk_2 (\frac{j_{s2}}{I})^2 \frac{k_2^2}{k_\perp^2} (1 - \frac{c^2 k_\perp^2}{\omega^2 P(\omega)})^{1/2} \tag{2}$$

In (2), $Z_o = 2c_A/c^2$ in gaussian units, c_A is the Alfven velocity in the ionosphere, V_o is the orbital velocity of the system, j_{s2} is the (Fourier tranformed) current density flowing in the Station, $k_\perp^2 = k_1^2 + k_2^2$ and $k_1 = (\omega - \omega^*)/V_o$. The functions $S(\omega)$ and P(ω) are the well known perpendicular and parallel diagonal elements of the dielectric tensor[2] characterizing the ionosphere around the system. In the frequency integral in (2), the integration is only over the allowed bands of emission in the cold ionosphere. There are two possible bands, the Alfven band ($O < \omega < \Omega_i$. the ion

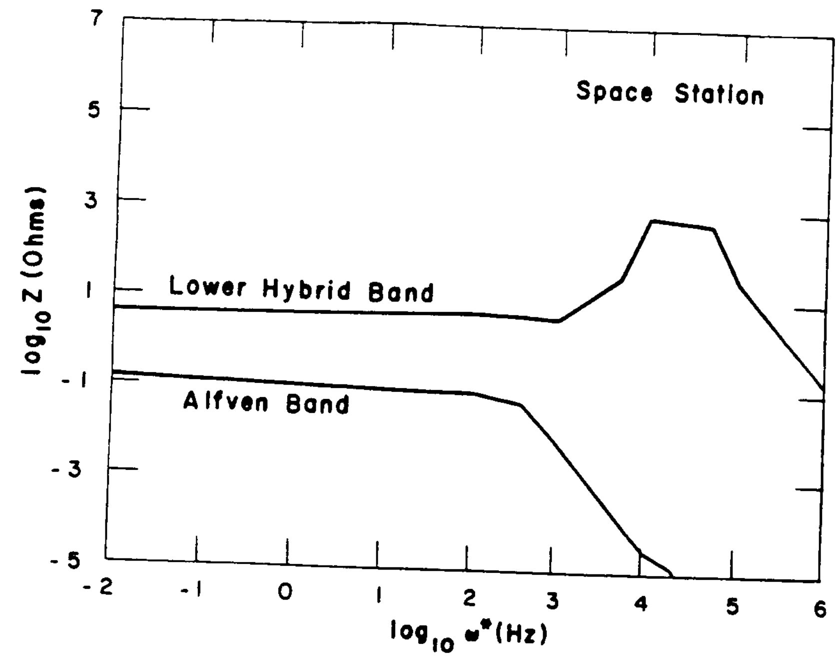

Figure 2: Radiation impedance Z against AC frequency of the current

cyclotron frequency) and the lower hybrid band ($\omega_{th} < \omega < \Omega_e$, with $\omega_{th} \simeq \sqrt{\Omega_e \Omega_i}$ and Ω_e being the electron cyclotron frequency). In fig. 2 we present a typical calculation of Z(ω^*) for probable Space Station parameters. For low AC frequencies ($\omega^* \leq 10^2$Hz) the irreversible radiation loss occurs in both the Alfven band and the lower hybrid band and for a typical current of 10 Amps is approximately 420 w. For higher AC frequencies ($\omega_* \approx 10^4$Hz) most of the radiated power is in the lower hybrid band and for a 10 Amp current, 7.5 kw of power is radiated. For very high AC frequencies the amount of power radiated in either band is negligible.

These calculations suggest a number of interesting conclusions. First, that radiative loss of power from the tether-station system may be important and secondly, that electromagnetic noise will be found around the Space Station even for very small AC frequencies. This may explain the observation of solar array hiss. [C. Purvis, private communication, 1986].

3 Theory of Plasma Contactors

The electrodynamic tether works by using the ionosphere as a source of electrons to make up the current flow. The random electron current density in the ionosphere at Station altitudes is very low ($\simeq 10^{-3} A/m^2$) and so to collect even 1 A of current would require a collection area of 1000 m^2. This has motivated research into plasma contactors where a plasma source surrounds the current collector with a plasma cloud which then provides a much larger effective collection area than the physical area of the collector. This works as long as electrons which stream along the geomagnetic field and enter the cloud can be diverted towards the anode at the end of the tether. A sufficient condition for this to occur is that

$$\nu_e > \Omega_e \tag{3}$$

where ν_e is the effective electron momentum scattering frequency and Ω_e is the electron cyclotron frequency. This condition states that in the cloud electrons will scatter before they complete their gyro-orbits. Hence they will not be bound to the field lines and can be collected at the anode. This condition is not necessary since to collect electrons all that is required is that electrons can undergo a random walk across the magnetic field at a rate sufficient to give the desired current. However use of this condition leads to a particularly simple analysis and enables us to place bounds on the current-voltage characteristics of the contactor[3]. With this sufficiency condition we can model the contactor cloud as a spherical expansion from some initial radius r_o to some critical radius r_c where $\nu_e/\Omega_e = 1$. The cloud is then described by the equations

$$\frac{\partial \Phi}{\partial r} = \frac{1}{en_e}[\frac{\partial p_e}{\partial r} - \frac{m_e \nu_e}{e}(\frac{I}{4\pi r^2})] \tag{4}$$

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 n_i v_i) = 0 \tag{5}$$

$$n_e = n_i \tag{6}$$

$$\frac{1}{2}m_i v_i^2 + e\Phi = \frac{1}{2}m_i v_i^2(r_o) + e\Phi(r_o), \tag{7}$$

$$I_{total} = I_i + I_e, \tag{8}$$

with boundary conditions

$$v_i(r_o) = c_s, \tag{9}$$

where c_s is the ion acoustic velocity

$$\Phi(r_o) = \Phi_o, \tag{10}$$

$$n_i(r_o) = I_i/(4\pi r_o^2 e c_s) \tag{11}$$

In these equations, subscript i means ions and e means electrons and the rest of the notation is standard.

The total current I_{total} consists of outgoing ions and incoming electrons. The ions are taken as freely falling under the influence of the potential. The equations (4) - (8) are the statement that the ions are repelled by the anode at r_o while the electrons are collected. The plasma cloud stays quasineutral and the potential drop is determined from the self-consistent force balance in the radial direction. To complete this simple model a prescription for the electron scattering rate is needed as a function of density. We take the scattering as

$$\nu_e = \nu_{ei} + \nu_{en} + \nu_{eff} \tag{12}$$

where ν_{ei} is Coulomb scattering, ν_{en} is electron-neutral scattering and ν_{eff} is turbulent scattering. It is easy to show that for most contactor plasmas ($n_e \leq 10^{12} cm^{-3}, n_n(neutral) \leq 10^{12} cm^{-3}, T_e \sim 5eV$), $\nu_{ei} + \nu_{en} \leq \Omega_e$ hence turbulent scattering is essential for current collection. The turbulent scattering is modelled as

$$\nu_{eff} \simeq \alpha \omega_{pe} \tag{13}$$

where $\alpha \simeq < \delta E_k^2 > /8\pi/nT_e$ is the fraction of energy in the electrostatic turbulence relative to the thermal energy; ω_{pe} is the electro plasma frequency. We note that for saturated ion acoustic turbulence $\alpha \simeq 10^{-3} - 10^{-2}$. These one dimensional equations for the spherical cloud have been solved for an argon plasma and the results are presented in figs 3 and 4. In fig. 3 the potential drop is shown against the total current for different ion currents. In order to obtain significant currents it was found to be necessary to assume high turbulence levels ($\alpha \simeq 0.2 - 0.4$). For each contactor ion current (I_c) it was shown that the total current was limited. This is because as the total current is increased, the potential drop increases which causes the ions to gain an increasing amount of energy as they fall down the potential hill. This has the effect of making the plasma cloud contract and at some current the total current exceeds the sum of the saturation electron current and the ion current. For total currents larger than this value, a very large potential drop ($\simeq$kV) is required. From fig. 3 we see that increasing the turbulence level does increase the potential drop as expected but a far more important effect is the increase of the cloud size with turbulence level and hence the increase in the maximum total current which can be obtained. Note that in all calculations the total potential drop is relatively small ($\leq 10^3 V$). This illustrates the power of plasma contactors in that large currents ($\simeq 10's A$) can be pulled for small potential drops.

In figure 4 we see that the gain (I_{total}/I_{ion}) decreases with increasing ion current. This is due to the cloud contraction mentioned previously. For small contactors ($I_i \simeq 10^{-3} A$) it can be as high as 15 but for the bigger contactors that would be used on the Space Station a gain of 6 is more typical. This suggests that use of several small contactors may be more efficient (in terms of the mass of gas needed for the contactor) than using one big contactor. This is shown by the following calculation. Four amperes of total current can be obtained with 1 contactor emitting an ion current of 2 A and with a gain of 2, or it can be obtained by using 4 contactors emitting an ion current of 0.2 A each with a gain of 5 each. The total ion current in this case is 0.8 A. Hence by using a number of smaller contactors the total mass flow rate is less than half that needed by using one bigger contactor.

This simple model suggests that plasma contactors can work as advertised, in being low impedance current collection devices. However they will require the generation of large plasma clouds and electrostatic turbulence. Both of these may have an impact on Space Station.

A more sophisticated analysis suggests that there might still be a region of spherical expansion even when the condition $\nu_e > \Omega_e$ is not required. We can see this as follows:

The plasma cloud emitted from a contactor used in the ionosphere bears an important resemblence to barium releases in the magnetosphere. In both cases the initial energy density in the cloud

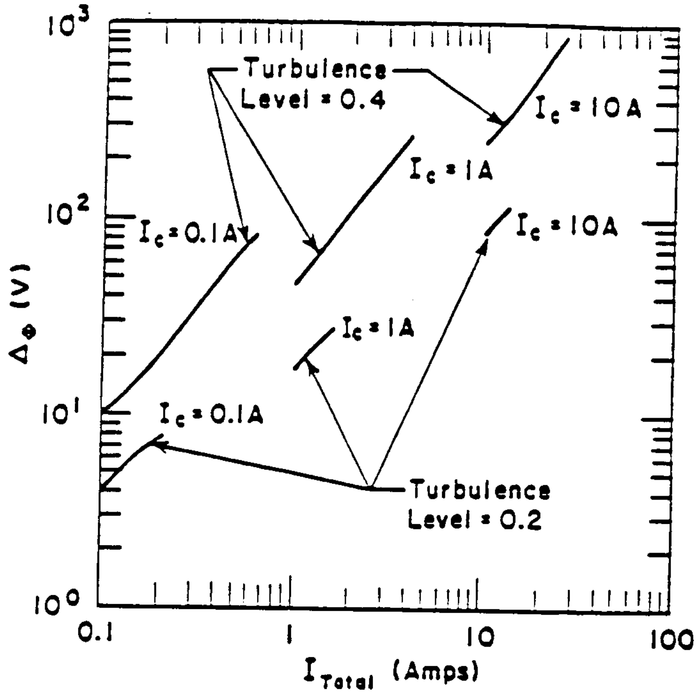

Figure 3: Potential drop through contactor cloud against total current flowing

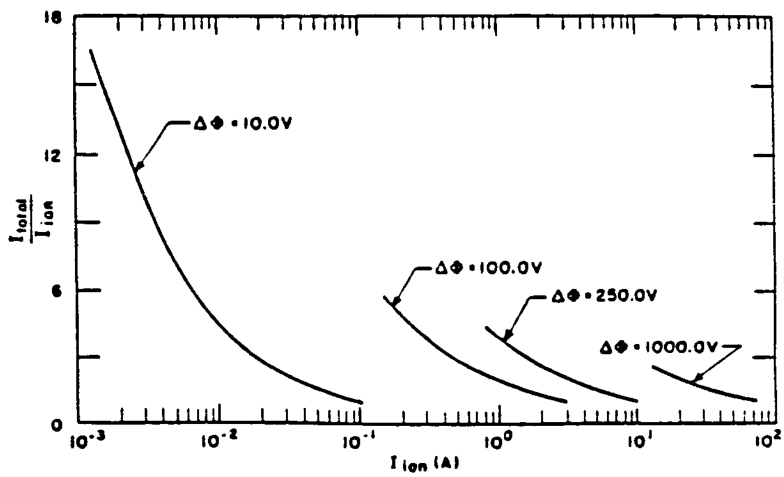

Figure 4: Gain I_{total}/I_i against ion current I_i for several potential drops

exceeds the energy density stored in the ambient magnetic field. This is conventionally measured by the plasma β defined as

$$\beta = \frac{n(T_e + T_i)}{B^2/8\pi} \tag{14}$$

where the electron temperature T_e and the ion temperature T_i are in energy units. The magnetic energy density is $B^2/8\pi$. When $\beta \geq 1$ then the plasma has more thermal energy than magnetic energy. For a contactor which emits a density n $\simeq 10^{12} cm^{-3}$ with $T_e \simeq 5$ eV and $T_i \simeq 0.1$ eV and for B = 0.45 Gauss we obtain $\beta \simeq 9.9 \times 10^2 \gg 1$. When $\beta > 1$ then the plasma will shield out magnetic fields as well as electric fields. That is, the self-consistent magnetic field in the plasma cloud will dominate the response of the cloud to magnetic fields and the effect of the ambient field will be insignificant. This suggests an explanation for the fact that ground based experiments have seen no dependance on the earth's magnetic field in the current characteristics of the cloud.

A simple model would suggest that since the ambient field is not important in the cloud then the cloud will expand spherically until we have $\beta \simeq 1$. For a release which scales as $1/r^2$ and is isothermal then

$$\frac{B^2}{8\pi} \simeq \frac{n_o r_o^2}{r_s^2}(T_e + T_i) \tag{15}$$

If the initial density is $10^{12} cm^{-3}$ and r_o is 10cm (which are the conditions of our previous contactor study) then we obtain r_s = radius of high β spherical expansion = 3.15 m. At the point at which this is reached we have $n(r_s) = 1.01 \times 10^9 cm^{-3}$. This high β core will essentially provide a collector volume which is much larger than the physical collector volume. This is because any electron that enters this region is very likely to be pulled into the center as a result of the bias on the collector. However, this expanded region will still not be enough to collect the ampere level currents necessary for viable operation of a system. Therefore the collisional enhancement we have discussed previously may still be necessary. The plasma cloud therefore will probably look as in fig. 5.

The distorted outer region of the cloud will play an important role in communicating information about the collector along the field lines. This is because with no cloud the physical collector will emit Alfven wings which will carry information about it down the field lines and accelerate electrons toward it. Hence the distance down the field that the moving collector can collect from is given by

$$\ell \simeq v_A(\frac{r_o}{V_o}) \tag{16}$$

where V_A is the Alfven velocity, and r_o/V_o is the transit time of the collector across a field line. Hence even with turbulent scattering the maximum current that can be collected is

$$2j_{th}[\pi r_o^2 + 2\pi r_o \ell] \simeq 2\pi j_{th} r_o^2[1 + 2\frac{v_A}{V_o}] \tag{17}$$

where j_{th} is the random electron current in the ionosphere. Since $v_A \gg 1$, we find that for a physical collector with no cloud (and with no ionization) the upper bound on collected current is

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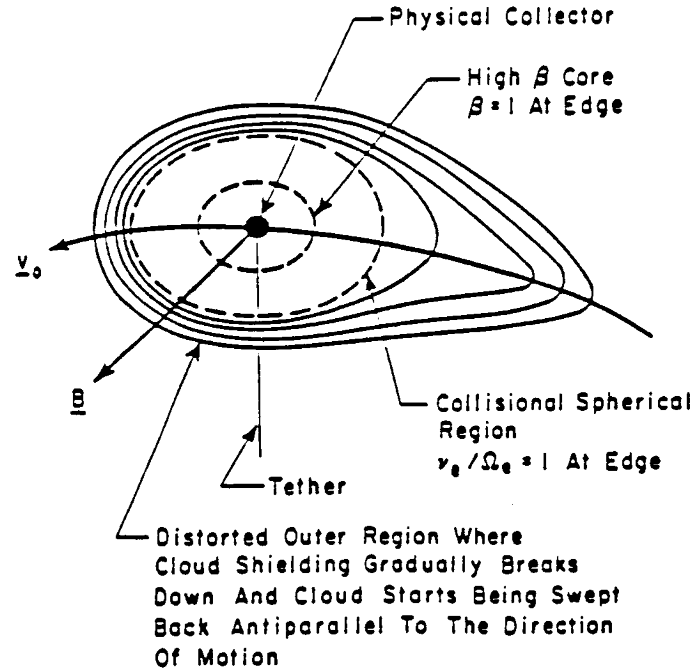

Figure 5: Cloud shape around the anodic end of the tether

approximately $2\pi r_o^2 j_{th}(2v_A/V_o)$. With a cloud which extends a distance $r_{c\ell}$ in front of the collector then the collection distance is

$$\ell \simeq v_A\left(\frac{r_{c\ell}}{V_o}\right) \tag{18}$$

The upper bound on the collected current is then $\simeq 2\pi j_{th} r_o^2(2v_A/V_o)(r_c r_{c\ell})/r_o^2$ where r_c is the radius at which $\nu_e/\Omega_e = 1$. Since $r_c r_{c\ell}/r_c^2 \gg 1$ we see that the contactor cloud will allow a much larger bound on the collected current to a moving collector.

4 Plasma turbulence excited by contactor current flow

We have shown that plasma contactors need to generate electrostatic turbulence so that enhanced scattering of electrons takes place. Ground based tests of current collection through a contactor cloud have indicated large amounts of turbulence associated with the operation of contactors [P. Wilbur, private communication, 1986]. This may provide another explanation for the observation that the current flow does not seem to be affected by the imposed magnetic field.

Plasma turbulence occurs because the plasma becomes linearly unstable to some plasma oscillation, this linear instability then grows and saturates due to some nonlinear mechanism. The nonlinear saturated state is what causes the enhanced scattering. It is well known that currents in plasmas can drive instabilities and give rise to enhanced resistivity. Instabilities such as the ion acoustic instability and the Bunemann instability are well studied examples of such instabilities and will occur in the contactor clouds. However these instabilities propogate mainly along the magnetic field and so give rise to enhanced resisitivity but not very much perpendicular scattering.

Since the contactor requires that the electrons be scattered across the magnetic field this will most effectively be done by waves which have $\lambda_\perp \simeq \rho_e$ where $\lambda_\perp$ is the perpendicular wavelength and ρ_e is the electron cyclotron radius. With this in mind we model the ion distribution function as the sum of two Maxwellians (corresponding to the contactor ions and ambient ions). The electron distribution function is taken to be a drifting Maxwellian. A kinetic linear instability analysis indicates that it is possible to find an instability with

$$\omega_r = b_e^{1/2}(\frac{k}{k_\perp}\sqrt{\Omega}_e(\Omega_{i1}\frac{n_{i_1}}{n_e} + \Omega_{i2}\frac{n_{i_2}}{n_e})) \tag{19}$$

where ω_r is the oscillation frequency of the instability, $b_e = k_\perp^2 \rho_e^2\ /2$, k = $\sqrt{k_\perp^2 + k_\parallel^2}$ and Ω_{i1}, Ω_{i2} are the ion cyclotron frequencies of the two ion species. For $b_e \sim$ O(1), k $\simeq k_\perp$ this is the lower hybrid frequency. The growth rate is given by

$$\begin{aligned} \gamma \ = \ & -\sqrt{\pi}[\frac{\omega_r - k_\parallel v_D}{k_\parallel v_{the}}\Gamma_o(b_e)\exp^{-(\frac{\omega_r - k_\parallel v_D}{k_\parallel v_{the}})^2} \\ & + \frac{n_{i1}T_e}{n_e T_{i1}}\frac{\omega_r}{k v_{thi1}}\exp^{-(\omega_r/k v_{thi1})^2} + \frac{n_{i2}T_e}{n_e T_{i2}}\frac{\omega_r}{k v_{thi2}}\exp^{-(\omega_r/k v_{thi2})^2}] \\ & \frac{\omega_r^3}{k^2}\frac{1}{[\frac{n_{i1}T_e}{n_e T_{i1}}v_{thi1}^2 + \frac{n_{i2}T_e}{n_e T_{i2}}v_{thi2}^2]} \end{aligned} \tag{20}$$

where $\Gamma(b_e) = e^{-b_e}I_o(b_e), I_o$ is the Bessel function of imaginary argument and the current density is j = $-e n_e v_D$. This growth rate is maximised for

$$k_\parallel/k \simeq ((m_e/m_{i1})n_{i1}/n_e + (m_e/m_{i2})n_{i2}/n_e)^{1/2} \tag{21}$$

and for $b_e = O(1)$. This instability is called the current driven lower hybrid instability, is driven by inverse Landau damping from the electrons and is damped by ion Landau damping. In fig. 6, the marginal stability curves (in terms of current density) are shown against electron density. We see that instability will exist for an intermediate density range (5 x 10^6 ¡ n_e ¡ $10^8 cm^{-3}$) if we consider current densities of 1 A/m^2 at the collector.

This suggests that the turbulent region of the plasma cloud will be a shell or band at some distance from the plasma source. Furthermore we see that for $n_e \geq 10^6$cm^{-3}, the marginal stability curves all have minima. This indicates that the contactors will need to pull a minimum current to work effectively. Below a critical current no instability will be excited and no turbulent scattering will occur. From fig. 6 we can deduce a consistency condition for the current density versus electron density profile. If the current density for $n_e \simeq 10^5 cm^{-3}$ (ambient) is the random current density ($\simeq 10^{-3} A/m^2$) and at the collector ($n_e \simeq 10^{12} cm^{-3}$) is 1$A/m^2$ then the profile must be more like curve C rather than A or B. For curve A there is no turbulent scattering anywhere and therefore no possibility of enhancement. For curve B the only unstable region occurs for a small density range and for $T_e/T_i \simeq 10$. If the contactor is emitting a nonequilibrium plasma with $T_e/T_i \simeq 10$ at the collector then far out in the cloud we would expect $T_e/T_i \ll 10$, and so only for C the possibility of turbulent enhancement. This supports the idea of a turbulent shell around the collector.

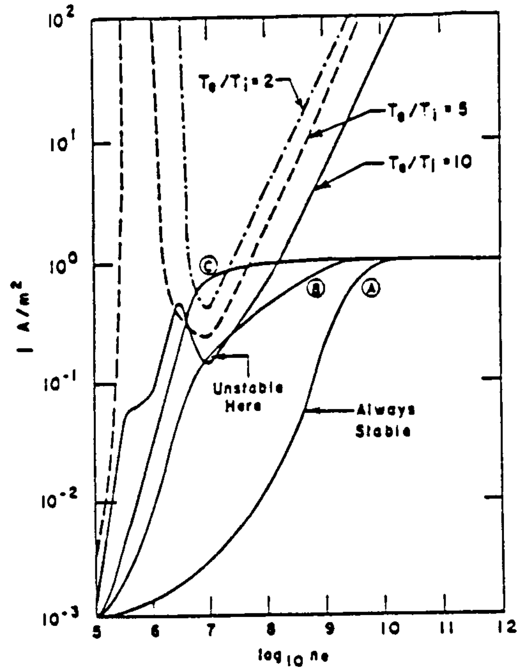

Figure 6: Marginal stability curves for lower hybrid instability.

5 Discussion

It has been shown that use of high power electrodynamic tethers involves large current flows, emission of radiation as well as hot plasma and generation of large amounts of electrostatic turbulence. All of these may impact the Space Station. In light of these we can identify some of the issues that need to be addressed by future research.

One of the most important issues is the nature of the current flows around large conductive objects close in the far field e.g. down in the E-region of the ionosphere or is current closure local? If current closure is a local phenomena then does this raise safety concerns? The issue of current closure is intimately related to the question of radiation from the Space Station and tether. We see that it is possible to lose significant amounts of power through radiation into the whistler frequency range. This would probably deposit into the local ionosphere and cause large scale changes (heating, ionization). If nothing else, this suggests a large signature to the tether/station combination. This also suggests that we need to consider whether any approaching vehicles would be affected by the radiation coming from the Station. If there were some coupling between the radiation field and the electronics of an approaching vehicle then some damage would result.

We have seen that the use of a high power tether will involve plasma contactors. These will emit hot plasma into the ionosphere. Since this will be occuring continously we need to consider what will happen to all this foreign material in the ionosphere. Will it accumulate in the orbit of the Station? Will it deposit on Space Station surfaces with possible deleterious effects? Will there be long term changes to the ionosphere as a result of this emission? Even if these things are not issues, the plasma clouds will have an affect on communications. Since the plasma density is so much higher than ambient, they will block microwave frequencies and will also generate noise over a large frequency range. This suggests that communications will have to be designed with these issues in mind.

6 Conclusions

We have reviewed some current work on the plasma issues associated with the use of high power electrodynamic tethers. All the current work suggests that the tether will have a significant impact on the ionosphere. This will occur both by deposition of electromagnetic radiation and by deposition of plasma into the ionosphere. Both types of deposition will cause possible large scale changes to the ionosphere and may have long term effects. These will be the subject of future research.

7 References

1. A. Barnett and S. Olbert, "Radiation of Plasma Waves by a Conducting Body Moving Through a Magnetized Plasma", J. Geophysical Research, 91, 10017 (1986).

2. Ya. L. Al'pert, "The Near-Earth and Interplanetary Plasma, Volume 1: General Properties and Fundamental Theory", Chapter 4, published by Cambridge University Press, 1983.

3. D.E. Hastings, "The Use of Plasma Contactors in the Ionsosphere", submitted to J. of Spacecraft and Rockets.