Bare-tether cathodic contact through thermionic emission by low-W materials

Xin Chen, J.R. Sanmartín

Universidad Politécnica de Madrid, Madrid, Spain

In absence of a low-impedance plasma contactor, a bare tether emits current through ion collection along the cathodic segment. The current flowing along the tether vanishes at both ends and the tether is said to be completely passive and electrically floating. In this case, under OML electron/ion collection, the anodic-to-cathodic length ratio is low because the ions are much heavier than the electrons which reduces the length-averaged current.

A low-work-function electron-emitting material $C12A7:e^-$ was developed by H. Hosono's group at the University of Tokyo [1]. Due to its large lattice space, it has a work function potentially as low as 0.6eV. Thus it can emit intense current at temperature about 300K, well below values ($1300-1400$K) required by state-of-art electron emitting materials, say, LaB6 and CeB6 (2.7eV). Another feature of interest of $C12A7:e^-$ electride is its high stability compared to the state-of-art electron emitting materials.

John D. Williams brought such advances in materials science to the tether community. In work together with J. R. Sanmartin and L. P. Rand, $C12A7:e^-$ was proposed as coating for floating bare tethers [2]. Thermionic emission along the coated cathodic segment, arising from heating under space operation, might be well more efficient than ion collection. In the present work, using the same model for the thermionic currents emitted at the cathodic segment, analysis is carried out in detail considering ohmic effects. The transition between different cathodic emission regimes is identified by a transition in tether length. Basic features in the balance of currents are here presented and discussed considering typical space parameters.

With this low-W coating, each point on the cathodic segment of a kilometers-long floating bare-tether would emit current as if it were part of a hot cylindrical probe uniformly polarized at the local tether bias, under 2D probe conditions that are also applied to the anodic-segment analysis. Around a negatively biased probe with intense thermionic emission, immersed in plasma, a double layer (DL) would be established, with electrons being emitted from the tether and ions coming from the ambient plasma.

As shown in Fig. 1, the anodic segment AB collects electrons from the ambient plasma until the zero-bias point B. For a round tether with a radius R less than or equal to R_{max}, it can be assumed that the current collection follows the high-bias OML theory (except in regions very

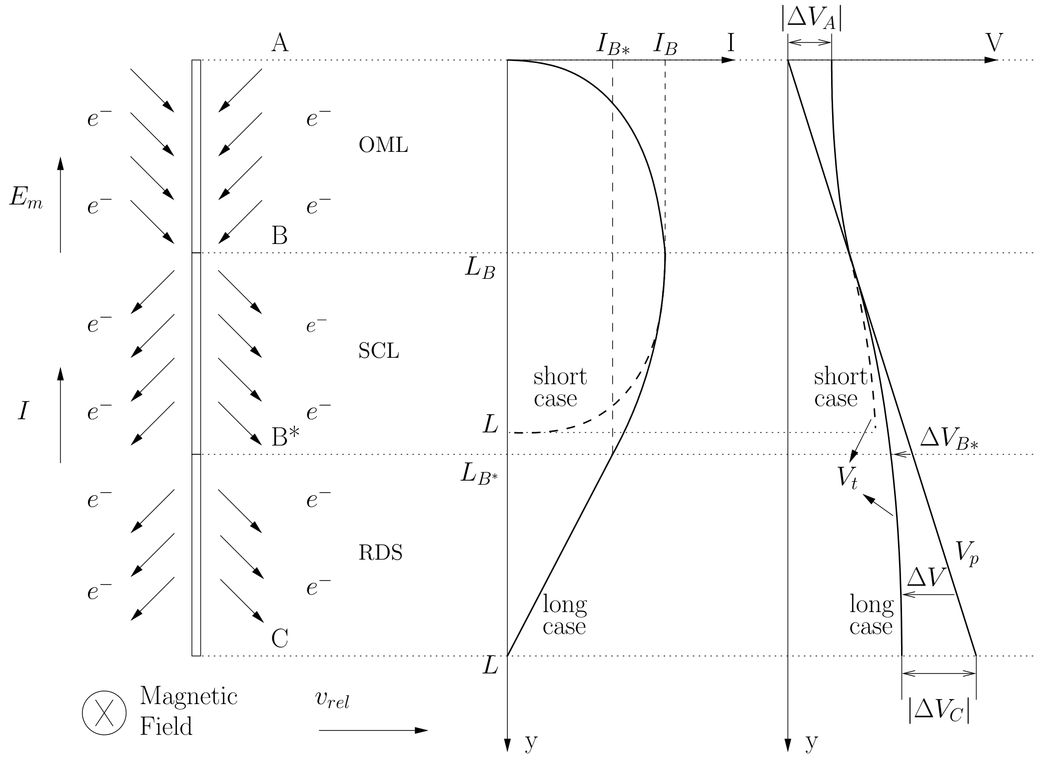

Figure 1: Scheme of plasma potential V_p, tether potential V_t and current I along a floating bare tether with thermionic emission, operating in drag mode.

close to B):

$$j_{OML}(y) = \frac{en_\infty}{\pi}\sqrt{\frac{2e\Delta V(y)}{m_e}}\,, \tag{1}$$

where n_∞ is the unperturbed plasma density and $\Delta V = V_t - V_p$.

The cathodic emission is given by either the SCL (space-charge-limited) current, being limited by the electric field at the emitting surface which arises from the space charge of the emitted electrons; or the RDS (Richardson-Dushman- Schottky) current which, for a given material, is determined by the emitter temperature, enhanced by the electric field at the emitting surface. There are two possible floating bare-tether regimes: the short tether case, as the entire cathodic segment emits SCL current, or the long tether case, as there is a transition from SCL current to RDS current at some point B*.

For an approximate description of the SCL current, we use Langmuir's SCL electron current from a hot, inner cylindrical electrode to an outer cold anode, and the simplest feature from OML ion-collection with no electrons emission, which is a sheath radius acting as r_{an}. Langmuir SCL thermionic emissions assumes that electrons are emitted outwards with negligible initial velocity and no ions are present. The SCL electron current density per unit length can be calculated using the Eq. (1) in [4], evaluating the current at the outer anodic cylinder with radius r_{an}, as large as $10r_0$, and β approaching unity. The DL outer edge represents an anode collecting electrons and being placed at the OML sheath boundary, which "emits" ions inwards, coming from the ambient plasma, $r_{an} \approx r_{sh}$. At the high bias of interest, most of the potential drop takes place inside the sheath, $\phi(r_{sh}) \approx -\Delta V$. The analysis is further simplified by assuming: the ion space charge is also negligible; the sheath radius arises from OML ion collection, $r_{sh} = \frac{R}{\sqrt{\sigma_1}}\sqrt{\frac{-e\Delta V}{kT_i}}$ [3]; under high bias, the sheath radius is indeed much larger than the probe radius $r_{an}/r_0 > 10$. As the ion current is negligible, we may now use the Langmuir SCL electron current to evaluate the total SCL current:

$$i_{SCL} = \frac{8\pi\varepsilon_0}{9}\sqrt{\sigma_1}\left(\frac{-\Delta V}{R}\right)\sqrt{\frac{2kT_e}{m_e}} . \qquad (2)$$

Considering $T_i/T_e \approx 1$ and $R = \lambda_D \approx R_{max}$, σ_1 is a constant at a value 0.24, independent of bias.

In the long-tether regime, the electron space charge at the transition point B* reduces to a level that the electric field at the surface does not impede electrons from being emitted. At the segment B*C, the current density follows Richardson-Dushman law with Schottky enhancement:

$$j_{RDS}(T,W,E_s) = j_0(T,W) \times S(T,E_s) ,$$

where S is the Shottky enhancement factor. The Schottky effect is assumed negligible in this analysis. At point B*, the SCL and RDS currents are equal.

The previous equations of j_{OML}, i_{SCL} and j_{RDS}, together with the boundary condition $I(y = 0) = 0$ and $I(y = L) = 0$, can be used to construct a system of equations to calculate the current and bias variation along the tether. In this work, the temperature is considered as constant along the tether. Several characteristic parameters are introduced as:

$$L^* \equiv l^{1/3} \times R^{2/3} \quad l = \frac{9\pi^2 m_e \sigma_c^2 E_m}{128 e^3 n_\infty^2} \quad k_s = \frac{2L^*}{3R}\left(\frac{2\varepsilon_0}{R\sigma_c}\right)^{1/2}\left(\frac{2kT_e\sigma_1}{m_e}\right)^{1/4} \quad k_t = \frac{2j_0 L^*}{\sigma_c R E_m} .$$

It is found that, if $k_t > k_s$, the tether would always work in the short case, regardless of the tether length. Under the condition $k_t < k_s$, the tether would fall in the long case if the tether length surpasses certain transition length L_{tr}, where L_{tr}/L^* depends on k_t/k_s and k_s.

Results are shown for some typical data in space: $\sigma_c \simeq 3 \times 10^7$S/m for aluminium, $E_m =$ 150V/km, $kT_e \approx kT_i \approx 0.1$eV, a low day density $n_\infty \approx 3 \times 10^{11}/\text{m}^3$, $R = \lambda_D \approx 4.29$mm and $\sigma_1 \approx 0.24$. A tentative daytime temperature for the tether $T = 300$K is used. Different values of work function - 0.6eV, 0.65eV, 0.7eV - are considered for the C12A7 : e^- coating. We then have $L^* = 17.94$km and $k_s = 9.18$, both independent of W.

For $W = 0.6$eV, one has $k_t = 14.35 > k_s$ and the tether always working in the *short* case regardless of tether length. A slight increase in the work function, say $W = 0.65$eV or $W =$

0.7eV, results however in $k_t = 2.07 < k_s$ and a transition in tether length beyond which the tether works in the *long* case $L_{tr} = 2.96$km, or $k_t = 0.52 < k_s$ and $L_{tr} = 0.25$km. With a coating which has extreme low work function, e.g., 0.6eV and 0.65eV , thermionic emission leads to a short cathodic segment, around 15% of the total length. For dominant ohmic effects, short-circuit current covers most of the cathodic segment. We can conclude that, compared to ion collection, thermionic emission by a low-W coating leads to much higher drag values for a floating bare tether and to eliminating the need for an active cathodic device, corresponding gas feed and power subsystems. This results in a truly “propellantless” tether system for such basic application as de-orbiting LEO satellites. However, for a given tether length, the average current resulting from a 0.7eV coating, is significantly smaller than the current corresponding to the other two values of work functions. Thus the new low-W material is important because it allows reaching desired emissions at lower temperatures.

References

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