ANALYSIS OF THERMIONIC BARE TETHER OPERATION REGIMES IN PASSIVE MODE

J. R. Sanmartín(1), X. Chen(2), G. Sánchez-Arriaga(3)

(1)Universidad Politecnica de Madrid, Plaza Cardenal Cisneros 3, 28040, Madrid, Spain, juanr.sanmartin@upm.es
(2)Universidad Carlos III de Madrid, Avenida de la Universidad 30, 28911, Leganés, Spain, xchen@ing.uc3m.es
(3)Universidad Carlos III de Madrid, Avenida de la Universidad 30, 28911, Leganés, Spain, gonzalo.sanchez@uc3m.es

ABSTRACT

A Thermionic Bare Tether (TBT) is a long conductor coated with a low work function material. Under drag mode, a tether segment extending from anodic end A to a zero-bias point B, with standard *Orbital-motion-limited* current collection and ohmic effects, is followed by a complex cathodic segment. In general, as bias becomes more negative in moving from B to cathodic end C, one first finds *space-charge-limited* emission covering up to some intermediate point B*, then full *Richardson-Dushman* emission reaching from B* to end C. An approximate analytical study, which combines current and voltage profile equations with results from asymptotic studies of the Vlasov-Poisson system for emissive probes. is carried out to determine the parameter domain covering two limit regimes. In one such regime no point B* is reached and thus no full *R-D* emission develops. In an opposite limit regime, segment BB* is too short to contribute significantly to current balance.

1. INTRODUCTION

Electrodynamic tethers systems, originally made of a long insulated conductor wire equipped with a big sphere as passive anodic contactor and an active hollow cathode or an electron gun, have gone through three important transformations towards simplicity and reliability during the last three decades. The first one happened in 1993, when the bare tether concept was introduced [1]. Instead of using big spherical collectors, the tether was left without insulation (bare) to collect electrons from the ionospheric plasma as a giant conventional Langmuir probe. The second transformation is not related with tether/plasma current exchange but with its geometry. For equal length and mass, tape-like tethers collect current more efficiently than round tethers due to their larger perimeter [2]. Tape-like geometry also improves notably tether reliability because it typically lowers more than one order of magnitude tether cut probability by small space debris [3]. The third transformation brought the electrodynamic bare tether concept to its full completion; if coated with a low-work function (W) thermionic material [4], then a tether segment emits electrons at moderate temperature as a giant emissive Langmuir probe. This is called a thermionic bare tether (TBT) [5], a propellantless device that does not require power, neither active elements like hollow cathodes or electron guns. Its operation is as simple as the one of a drag sail, except that the Lorentz drag upon a TBT is about two orders of magnitudes higher than the aerodynamic drag upon a sail in Low Earth Orbit (LEO). The absence of active elements, the robustness of the underlying physics, and the high reliability suggest that TBTs are ideal devices for deorbiting spacecraft at the-end-of-life.

The emergence of the TBT concept was possible thanks to the appearance of new materials with extremely *low work function* W and moderately high temperature stability. The most promising one is the C12A7:e$^-$ electride, capable of reaching W below 1 eV [4]. However, many aspects like the stability of this material in space conditions or the coating manufacturing process of a km-long tether, remain still open and will probably require intense research work. Meanwhile, it is necessary to develop theoretical models describing the current profile along a TBT as a function of the W value and insert them in tether flight simulators to estimate the deorbit performance. Positive results could trigger the development of the TBTs.

2. BASIC TBT EQUATIONS

Although TBT operation is passive and simple, its modelling is a tough task that involves theoretical concepts from conventional and emissive Langmuir probes. The tether-to-plasma potential bias, ΔV, varies along the distance from the anodic end s as

$$\frac{\Delta V(s)}{ds} = \frac{I(s)}{\sigma_c A_t} - E_m \qquad (1)$$

With I(s) the current intensity and σ_c and A_t the tether conductivity and cross-section area, respectively. We also introduced the motional electric field

$$E_m = (\mathbf{v}\times\mathbf{B})\cdot\mathbf{u}_t,$$

with $\mathbf{v}$ the tether-to-plasma relative velocity, $\mathbf{B}$ the geomagnetic field and $\mathbf{u}_t$ an unit vector along the straight tether with the direction of the current. Equation (1) is valid from $0 < s < L$, with L the tether length.

The equation that governs the variation of the current intensity along the tether should be splitted, in principle, in three different tether segments (see Fig. 1)

$$\frac{dI}{ds} = \begin{cases} p_t \times j_{OML} & 0 < s < s_B \\ -p_t \times j_{SCL} & s_B < s < s_{B*} \\ -p_t \times j_{RD} & s_{B*} < s < s_c \end{cases} \quad (2)$$

where p_t is the tether perimeter and j_{OML}, j_{SCL} and j_{RD} are electron collection and (two) emission laws.

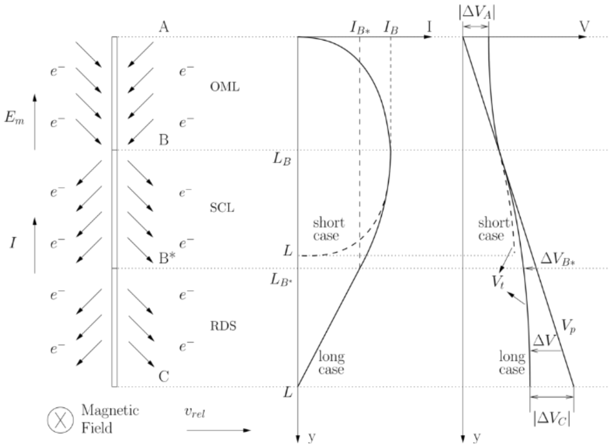

Figure 1. TBT Current and voltage profiles

As shown in Fig. 1, the TBT collects electrons from the anodic end A to a zero bias point B. Electron capture along this segment is here modelled using orbital-motion-limited theory [2]

$$j_{OML} = \frac{eN_\infty}{\pi}\sqrt{\frac{2e\Delta V}{m_e}} \quad (3)$$

with N_∞ the ambient plasma density and e and m_e the electron charge and mass, respectively. Equation (3) assumes high bias ($e\Delta V >> kT_e$) where T_e is the electron temperature. Considering round tethers for simplicity, OML current collection also requires probe radius less than some maximum radius R_{max}. In general, as bias becomes more negative in moving from B to cathodic end C, one first finds *space-charge-limited* (SCL) emission covering up to some intermediate point B*, then full *Richardson-Dushman* emission reaching from B* to end C. The electron emission law in the latter is given by

$$j_{RD} = ev N_\infty \sqrt{\frac{2kT_p}{\pi m_e}} \quad (4)$$

where $\nu = N_{emp}/N_\infty$ and the emitted electron current is related with the tether temperature T_p and work function W by

$$N_{emp} = AT_p^2 \exp(-W/kT_p)\sqrt{\pi m_e/2e^2kT_p} \quad (5)$$

with $A = 1.2 \times 10^6$ Am^{-2}K^{-2}. Regarding the former, i.e. the SCL segment, a fully consistent theory for the emitted current j_{SCL} is not available yet. A very complex plasma structure, named double layer, is developed around this tether segment. Within the sub-segment BB*, the electric field close to the tether is directed outwards and some of the emitted electrons, those with lower energy, come back to the tether. The net emitted current is only a fraction of j_{RD}, written now for brevity,

$$j_{SCL} = f \times j_{RD} \quad (6)$$

with a factor $f < 1$.

Important uncertainties exist not only on models for factor f in the current emitted within the SCL segment but also on the exact location of point B*. This work shows that, even without a precise knowledge of the SCL emission law, j_{SCL}, it is possible to determine a parametric domain where there is negligible SCL current emission, the sub-segment BB* being very short (Sec. **3**); also, in some approximate way, the parametric domain where there is no sub-segment B*C (Sec. **4**). Our analysis uses Eqs. (1), (2), and (6), as well as information from emissive Langmuir probe theory for Sec.**4**, together with the boundary conditions $I_A = I_C = 0$, $\Delta V_B = 0$.

3. NEGLIGIBLE SCL EMISSION REGIME

Integrating Eq. (1) from B to B*, with $\Delta V_B = 0$ yields

$$-\Delta V_{B*} = E_m \int_{s_B}^{s_{B*}} (1 - i(s))ds \quad (7)$$

with $i(s) = I(s)/\sigma_c A_t E_m$. Since I(s) is maximum at B, one has

$$-\Delta V_{B*} > E_m(1 - i_B)(s_{B*} - s_B) \quad (8)$$

or

$$(1 - i_B)(\tilde{s}_{B*} - \tilde{s}_B) < |\Delta V_{B*}|/E_m L \quad (9)$$

where $\tilde{s} = s/L$. The above bias ratio at tether point B* is very small under a broad range of conditions. Analysis of **just** full RD-emission can give a corresponding ratio $e\Delta V/kT$ at SCL current onset.

Asymptotic analysis of the Vlasov-Poisson system for cylindrical emissive Langmuir probes in the high bias limit and probe radius $R = R_{max}$ to collect ions within the OML regime showed that, for ion, electron and probe temperatures satisfying $T_i = T_e \equiv T = 4\,T_p = 0.1$ eV, the full RD emission to SCL regime takes place at $e|\Delta V_{B*}|/\mathrm{kT}$ equal to 26.2, 89.7, 143.0, 238.8 for ν = 20, 50, 70, 100, or roughly [6],

$$e|\Delta V_{B*}|/kT \approx 0.38\, \nu^{1.4} \qquad (10)$$

Equation (10) shows that, for the range of υ values considered above, such a ratio is much less than characteristic values for eE_mL/kT, such as 4500 for E_mL = 450V and kT = 0.1 eV, say. Small B* bias ratio thus requires not too low E_m or too high $\nu \propto T_p^{\frac{3}{2}}\exp(-W/kT_p)/N_\infty$ (i.e. low N_∞, and/or low W/kT_p). The LHS of Eq. (9) is then very small, and thus, for $1 - i_B$ of order unity (moderate ohmic effects, see below), Eq (9) proves the BB* segment short.

Consider now current exchange in the segment from B to C. Full RD emission applies from B* to C. The integration of Eq. (2) with the boundary condition I_C = 0 then yields

$$I_{B*} = p_t \nu e N_\infty \sqrt{\frac{2kT_p}{\pi m_e}}\,(L - s_{B*}) \qquad (11)$$

whereas from B to B*, emission is reduced by space-charge, leading to

$$I_B - I_{B*} = \int_{s_B}^{s_{B*}} \left|\frac{dI}{ds}\right| ds < p_t \nu e N_\infty \sqrt{\frac{2kT_p}{\pi m_e}}\,(s_{B*} - s_B)(12)$$

Use of Eqs (11) and (12) then yields

$$\frac{i_B - i_{B*}}{i_{B*}} < \frac{\tilde{s}_{B*} - \tilde{s}_B}{1 - \tilde{s}_{B*}} \qquad (13)$$

showing that current varies little in the mid-segment and thus requires no SCL emission modelling [7], if sub-segment B*C is not similarly short (see below).

Analysis of the anodic segment and use of $\tilde{s}_{B*} \approx \tilde{s}_B$, and $i_{B*} \approx i_B$, , as they followed from the moderate ohmic effects and not too short sub-segment B*C conditions, confirms those conditions for $\nu\sqrt{kT_p/eE_mL}$ small, in agreement with the regime, considered following Eq.(10), for negligible SCL emission.

4. SHORT TETHER REGIME

Again integrating for bias in Eq. (1) allows writing

$$|\Delta V_{B*}|/E_mL = [1 - <i>_{BB*}](\tilde{s}_{B*} - \tilde{s}_B) \quad (14)$$

where $<>_{BB*}$ stands for avering over the segment BB*. As the ratio in the left-hand side of Eq. (14) increases with ν, at given eE_mL/kT_p, the B*C segment collapses and i_{B*} decreases to zero along with $L - s_{B*}$. Assuming Eq. (10) still valid, Eq. (14) takes the form

$$\frac{0.38\nu^{1.4}}{eE_mL/kT} \approx [1 - <i>_{BB*}](1 - \tilde{s}_B) \qquad (15)$$

A second equation for $\tilde{s}_B$ follows from equating i_B from an anodic segment analysis to its value as following from Eqs.(11) and (12), this last one corrected by using (6) with the unknown factor f yet to be determined.

To determine *f*, we model *SCL* emission in the cathodic sub-segment BB* as a double layer involving emitted electrons and attracted ambient ions (neglecting ion current and ambient electrons). This is simplified by using the *sheath* radius in OML ion collection as the *anodic* radius in the classical analysis for emission in vacuum from an inner cylinder to a coaxial anodic one [7]. In the weak ohmic-effects limit this yields *f* = 0.5.

The resulting equation together with Eq. (15) allows to determine a short-tether parametric domain condition involving the dimensionless parameters kT_p/eE_mL and ν.

5. CONCLUSIONS

The analysis shows that, even without knowing the law of the emitted current within the SCL regime, it is possible to find the parametric conditions that separate two limit operation regimes of a TBT: (i) negligible SCL segment and (ii) short-tether with no full RD emission segment. The model proposed just involves the value of the tether bias at which the transition from SCL to full RD happens, a result that can be taken from asymptotic kinetic analysis of just cylindrical emissive Langmuir probes.

6. ACKNOWLEDGMENTS

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