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Electrodynamic Tethering: An Energy Source for Satellite

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Abstract: There is a tremendous force interest for the satellites which the nations have been utilizing over a long time for correspondence, spying, tests, analysis, etc; and tracking down an elective energy hotspots for satellite has been a major undertaking that must be settled as quickly as time permits and electrodynamic tie situation can be the ideal decision for the force supplanting framework. The current existing strategies are somewhat more established, fusy and should be changed for expanded use office of a satellite. Electrodynamic ties are long, dainty conductive wires which are conveyed in space appended to the plasma bend generator of the satellite framework and can be utilized to create power by eliminating the motor energy from their orbital movement, or to deliver push while adding energy from an on board source. regardless , the frictional or push power is created electrodynamically , through the communication between the moving charges only the electrons of the ionospheric plasma and the attractive field of earth. Electrodynamic ties work by temperance of the power an attractive field applies on a current conveying wire which is only the lorentz power. Generally, it is a shrewd method of getting an electric flow to stream in a long directing wire that is circling Earth, so that world's attractive field will apply a power on and speed up the wire and thus any payload appended to it. By switching the bearing of current in it, a similar tie can be utilized to de-circle old satellite and once again circle them if necessary under the fundamental circumstances. Electrodynamic ties have solid potential for giving propellant less impetus to rocket in low-Earth orbit(LEO) for applications, for example, satellite deorbit circle boosting, and station keeping. The tie, in any case, is anything but an unbending pole held above or beneath the rocket.
Keywords: Electrodynamic, Ionospheric plasma, LEO, Tethers, Deorbit, Reorbit, plasma arc generator.

I. INTRODUCTION

Satellites play a major role in the present communication system. These satellites are launched with the help of rockets. Typically a payload will be placed by a rocket into Low Earth Orbit or LEO (around 500 km) and then boosted higher by rocket thrusters. But just transporting a satellite from the lower orbit to its eventual destination can lead to several thousand dollars per kilogram of payload. inorder to cut the expenses the researchers have come up with a wide range of ideas and are working on them.

There are over eight thousand satellites and other large objects in orbit around the Earth, and there are countless smaller pieces of debris generated by spacecraft explosions between satellites. Until recently it has been standard practice to put a satellite into and leave it there. However the number of satellites has grown quickly, and as a result, the amount of orbital debris is growing rapidly. Because these debris are traveling at orbital speed (78km/s), it poses a significant threat to the space shuttle, the International Space Station and the many satellites in Earth orbit.

Electrodynamic tether provides a simple and reliable alternative to the conventional rocket thrusters. Functionally, electrons flow from the space ionospheric plasma into the conductive tether, are passed through a resistive load in a control unit and are emitted into the space ionospheric plasma by an electron emitter as free electrons. In principle, compact high-current tether power generators are possible and, with basic hardware an amount equivalent to kilowatts of energy can be attained . It is a very long, thin cable, and has little or no flexural rigidity. The transverse electrodynamic forces therefore cause the tether to bow and to swing away from the local vertical. Gravity gradient forces produce a restoring force that pulls the tether back towards the local vertical, but this results in a pendulum-like motion which is typically an oscillation . Because the direction of the geomagnetic field varies as the tether orbits the Earth, the direction and magnitude of the electrodynamic forces also varies, and so this pendulum motion develops into complex librations in both the in-plane and out-of-plane directions. Due to coupling between the in plane motion and longitudinal elastic oscillations, as well as coupling between in-plane and out-of-plane motions, an electrodynamic tether operated at a constant current will continually add energy to the oscillatory motions, causing the libration amplitudes to build until the tether begins rotating or oscillating wildly. In addition, orbital variations in the strength and magnitude of the electrodynamic force will drive transverse, higher-order oscillations in the tether which can lead to the unstable growth of "skip-rope" modes which can even be used for faster travelling of the satellite system which indeed has its own threats to the conductive tether.

II. COMPARISON OF EDT WITH PRESENT PROPULSION SYSTEM

The current rocket impetus instrument drives energy from rocket powers. Hydrogen peroxide(H_2O_2) is one of the generally utilized rocket powers. The drawback of these rocket powers is that it delivers low push. The fluid force requires the cryogenic frameworks for their execution. Thermal power can be utilized as a force. Yet, it produces radiations, which are extremely hurtful. There are a few burdens in managing fluid impetus frameworks. Spills or releases or a few dangerous issues happen in it. Typically requires more volume because of low normal fuel thickness contrasted with the others and the somewhat they are wasteful. A couple of forces likewise part with the poisonous fumes or exhaust. Indeed, even in strong force framework there are many detriments, for example, these charges are generally inclined to blast and debilitate gases are most likely harmful. A few fuels or force fixings can even disintegrate which diminishes the existence of the entire framework and conveying it an intimidation to turn out to be dead and inclined mishaps by slamming into the other satellite framework. An electrodynamic tie is a superior forward choice which can preclude every one of the plausible hindrances that are inclined by the present existing frameworks and can be given as an energy source and engine which inturn likewise gives an increment in the productivity in working and push to the satellite framework

III. PRINCIPLE

The fundamental guideline of an electrodynamic tie is Lorentz power. It is the power that an attractive field applies on a current conveying wire toward a path opposite to both the course of current stream and the attractive field vector.

A. Lorentz Force Law

The Lorentz Force Law can be utilized to depict the impact of a charged molecule moving in a consistent attractive field.

The Dutch physicist Hendrik Androon Lorentz showed that a moving electric charge encounters a power in an attractive field. (on the off chance that the charge is very still, there won't be any power on it because of attractive field) Hence obviously the power experienced by a current conductor in an attractive field is because of the floating of electrons in it. In the event that a current I courses through a conductor of cross-area A, I = neAv where v is the float speed of hardware n is number thickness in the conductor and e is the electronic charge.

For a component dI of the conductor Id = nAdIev But Adi is the volume of the current component. In this manner, nAdI addresses the number (N) of electrons in the component. Henceforth,

$$nAdIe = Ne = q(\text{charge}).$$

Consequently in above condition addresses q is the absolute charge in the component. Thusly, IdI=qv But, the power dF on a current conveying component dI in an attractive field B is given by dF=IdIB i.e.,dF=qvB This major power on an accuse q moving of a speed v in an attractive field B is known as the Magnetic Lorentz Force. The easiest type of this law given by the scalar condition,

$$F = QvB$$

'F' is the power following up on the molecule (vector) 'V' is the speed of the molecule (vector) 'Q' is charge of molecule (scalar) 'B' is attractive field (vector).

<u>*NOTE*</u>: For this situation is intended for v and B opposite to one another in any case use F = QvB (sin (X)) where X is the point among v and B, when v and B are opposite X =90 deg. So sin (x) =1. Fleming's left hand preclude comes in to play here to figure what direction the power is acting.

B. Fleming's Left Hand Rule

For a charged molecule moving (speed v) in an attractive (field B) the course of the resultant (power F) can be found by: center finger of the left hand in heading of current forefinger of the left hand in bearing of field B, thumb presently focuses toward the power or movement F. The power will consistently be opposite to the plane of vector v and B without thought of the point among B and V

IV. WORKING AND THEORETICAL ANALYSIS

Electrodynamic ties (EDTs) are long leading wires, for example, one sent from a tie satellite, which can work on electromagnetic standards, by changing their dynamic energy over to electrical energy(as generators), as well as the other way around (as engines). Electric potential is produced across a conductive tie by its movement through the Earth's attractive field. As a feature of a tie impetus framework, artworks can utilize long, solid conductors (however not all ties are conductive) to change the circles of shuttle.

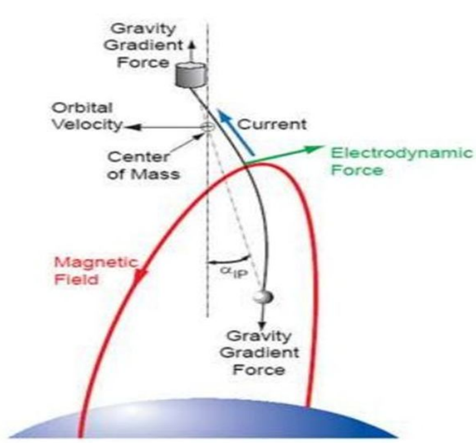
The electrodynamic tie is produced using aluminum compound and normally somewhere in the range of 5 and 20 kilometers in length. It expands downwards from a circling stage. Aluminum compound is utilized since it is solid, lightweight, cheap and effortlessly machined. It tends to be utilized either to speed up or brake a circling rocket.

At the point when direct current is siphoned through the tie, it applies a power against the attractive field, and the tie speeds up the shuttle. The gravity angle field (otherwise called flowing power) will in general arrange the tie in an upward position. In the event that the tie is circling around the Earth, it will cross the world's attractive field lines orbital speed (7-8 km/s). The movement of the conductor across the attractive field initiates a voltage along the length of the tie. The voltage accordingly made along its length can be up to a few hundred volts for each kilometer.

In an electrodynamic tie drag framework, for example, the eliminator Tether, the tie can be utilized to diminish the circle of the rocket to which it is appended. On the off chance that the framework has a method for gathering electrons from the ionospheric plasma toward one side of the tie and ousting them back in to the plasma at the opposite finish of the tie, the voltage can drive a current along the tie. This current bill, thusly, communicates with the Earth's attractive field to cause a Lorentz JXB power, which will go against the movement of the tie and whatever it is connected to. This electrodynamics drag power will diminish the circle of the tie and its host shuttle. Basically, the tie changes over the orbital energy of the host rocket in to electrical force, which is disseminated as ohmic warming in the tie.

In an electrodynamic drive framework, the tie can be utilized to help the circle of the shuttle. In the event that a force supply is added to the tie framework and used to drive current toward a path inverse to that which it ordinarily needs to stream, the tie can push against the Earth's attractive field to raise the rocket's circle. The significant benefit of this procedure contrasted with the other space drive framework is that it doesn't need any force. It utilizes Earth's attractive field as its response mass. By disposing of the need to dispatch a lot of charge in to circle, electrodynamic ties can incredibly diminish the expense of in-space drive. The tie is hauled through the climate ionospheric plasma. The tenuous mechanism of electrons through which the entire set up is going at a speed of 7-8km/s. In this manner, the 5km. long aluminum wire removes electrons from the plasma toward the end farthest from the payload and conveys them to the close to end (plasma chamber tests have checked that slim exposed wires can gather current from plasma). There an exceptionally planned gadget known as an empty cathode producer removes the electrons, to guarantee their re-visitation of room flows in the circuit. Normally, a uniform attractive field following up on a current-bearing circle of wire yields a net power of nothing, since that drops the power on one side of the circle on the opposite side, wherein the current is streaming in the other way However, since the fastened framework isn't precisely connected to the plasma. The attractive power on the plasma current in the space doesn't drop the powers on the tie. Thus the tie encounters a net power.

As the tie cuts across the attractive field, its predisposition voltage is positive toward the end farthest from Earth and negative at the close to end. This polarization is because of the activity of Lorentz power on the electrons in the tie. Along these lines the regular vertical current stream due to the (adversely charged) electrons in the ionosphere being drawn to the ties far and afterward got back to the plasma at the close to end. Helped by, the empty cathode producer. The empty cathode is crucial without it, the wire's charge dissemination would rapidly arrive at harmony and no current would stream. Turning on the empty cathode causes a little tungsten cylinder to warm up and load up with xenon gas from little tank. Electrons from the tie cooperated with the warmed gas to make particle plasma. At the furthest finish of the cylinder a 'guardian terminal' is available, which is emphatically accused of regard to the cylinder. Draw the electrons and ousts them to space. (the xenon particles, in the interim are gathered by the empty cathode and used to give extra warming). The quick release of electrons welcomes new electrons to follow from the tie and out through the empty cathode. Earth's attractive field applies a drag power on a current conveying tie, decelerating it and the payload and quickly bringing down their circle. In the long run they reemerge Earth's climate.



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V. MATHEMATICS BEHIND EDT

A motional electromotive force (EMF) is generated across a tether element as it moves relative to a magnetic field. The force is given by faraday's law of induction,

$$\mathrm{V}(\boldsymbol{emf}) = \int (\boldsymbol{\vartheta}^{\rightarrow} \times \boldsymbol{B}^{\rightarrow})\boldsymbol{dL}^{\rightarrow}$$

$$\boldsymbol{L}\ \mathbf{0}$$

Without loss of consensus, it is expected the tie framework is in Earth circle and it moves comparative with Earth's attractive field. Likewise, if current streams in the tie component, a power can be created as per the Lorentz Force Equation,

$$\boldsymbol{F}^{\rightarrow} = \int \boldsymbol{I}(\boldsymbol{L})\mathrm{m}\ \mathrm{d}\boldsymbol{L}^{\rightarrow}$$

$$\boldsymbol{L}\ \mathbf{0}$$

$$\times\ \boldsymbol{B}^{\rightarrow\rightarrow}$$

In self-fueled mode (de-circle mode), this EMF can be utilized by the tie framework to drive the flow through the tie and other electrical burdens (for example resistors, batteries), discharge electrons at the emanating end, or gather electrons at the inverse. In help mode, on-board power supplies should beat this motional EMF to drive current the other way, subsequently making a power the other way, as seen in underneath figure, and boosting the framework.

A. Model

At 300-km height, the Earth's attractive field, in the north-south course, is roughly 0.18 – 0.32 Gauss up to ~40º tendency, and the orbital speed concerning the nearby plasma is around 7500 m/s. This outcomes in a Vemf scope of 35 – 250 V/km along the 5km length of tie. This EMF directs the possible contrast across the uncovered tie which controls where electrons are gathered and/or repulsed. Here, the ProSEDS de-help tie framework is arranged to empower electron assortment to the emphatically one-sided higher elevation part of the uncovered tie, and got back to the ionosphere at the lower height end. This progression of electrons through the length of the tie within the sight of the Earth's attractive field makes a power that creates a drag push that helps de-circle the framework, as given by the above condition. The lift mode is like the de-circle mode, aside from the way that a High Voltage Power Supply(HVPS) is additionally embedded in series with the tie framework between the tie and the higher positive possible end. The force supply voltage should be more prominent than the EMF and the total inverse. This drives the current the other way, which thusly causes the higher elevation end to be adversely charged, while the lower height end is emphatically charged(Assuming a standard east to west circle around Earth).

With a long leading wire of length L, an electric field E is created in the wire. It creates a voltage V between the far edges of the wire. This can be communicated as:

$$\mathrm{V{=}E\ .\ L{=}EL}\boldsymbol{\cos\tau} = \boldsymbol{\vartheta B L}\boldsymbol{\cos\tau}$$

where the point τ is between the length vector (L) of the tie and the electric field vector (E), thought to be the upward way at right points to the speed vector (v) in a plane and the attractive field vector (B) is out of the plane.

B. Current in Conductor

An electrodynamic tie can be depicted as a kind of thermodynamically "open framework". Electrodynamic tie circuits can't be finished by just utilizing another wire, since another tie will foster a comparative voltage. Luckily, the Earth's magnetosphere isn't "vacant", and, in close Earth districts (particularly close to the Earth's environment) there exist exceptionally electrically conductive plasmas which are kept somewhat ionized by sunlight based radiation or other brilliant energy. The electron and particle thickness fluctuates as indicated by different variables, like the area, height, season, sunspot cycle, and tainting levels. It is realized that a decidedly charged exposed conductor can promptly eliminate free electrons out of the plasma. In this manner, to finish the electrical circuit, an adequately enormous space of uninsulated channel is required at the upper, emphatically charged finish of the tie, along these lines allowing flow to course through the tie.

Be that as it may, it is more hard for the inverse (negative) finish of the tie to launch free electrons or to gather positive particles from the plasma. It is conceivable that, by utilizing an exceptionally enormous assortment region toward one side of the tie, enough particles can be gathered to allow huge current through the plasma. This was exhibited during the Shuttle orbiter's TSS-1R mission, when the actual bus was utilized as an enormous plasma contactor to give over an ampere of current.

Further developed techniques incorporate making an electron producer, like a thermionic cathode, plasma cathode, plasma contactor, or field electron outflow gadget. Since the two closures of the tie are "open" to the encompassing plasma, electrons can stream out of one finish of the tie while a comparing stream of electrons enters the opposite end. In this design, the voltage that is electromagnetically incited inside the tie can make flow course through the encompassing space climate, finishing an electrical circuit through what gives off an impression of being, from the beginning, an open circuit.

VI. TETHER CURRENT

The amount of current (I) flowing through a tether depends on various factors. One of these is the circuit's total resistance (R). The circuit's resistance consists of three components:

A. The effective resistance of the plasma
B. The resistance of the tether
C. A control variable resistor

In addition, a parasitic load is needed. The load on the current may take the form of a charging device which, in turn, charges reserve power sources such as batteries. The batteries in return will be used to control power and communication circuits, as well as drive the electron emitting devices at the negative end of the tether. As such the tether can be completely self-powered, besides the initial charge in the batteries to provide electrical power for the deployment and startup procedure. The charging battery load can be viewed as a resistor which absorbs power, but stores this for later use (instead of immediately dissipating heat). It is included as part of the "control resistor". The charging battery load is not treated as a "base resistance" though, as the charging circuit can be turned off at anytime. When off, the operations can be continued without interruption using the power stored in the batteries.

The below figure describes a typical EDT system in a series bias grounded gate configuration (further description of the various types of configurations analyzed have been presented) with a blow-up of an infinitesimal section of bare tether. This figure is symmetrically set up so either end can be used as the anode.

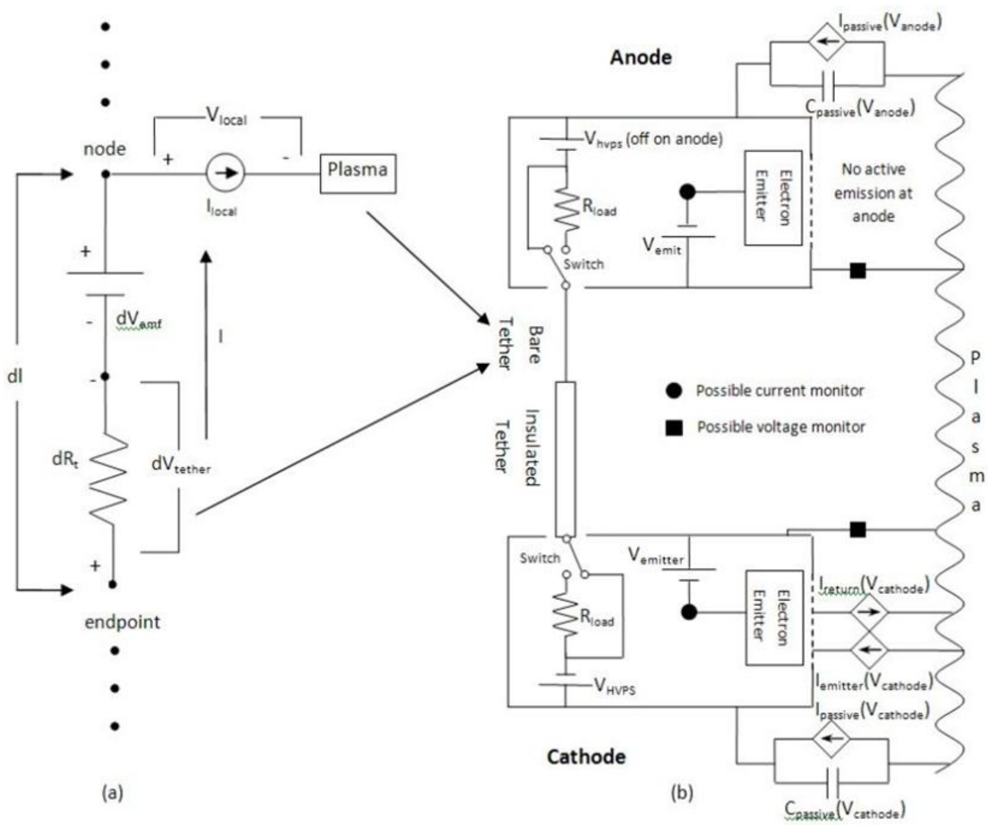

Fig. 5.4(a) A circuit diagram of a bare tether segment (b) An equivalent EDT system circuit model showing the series bias grounded gate configuration.

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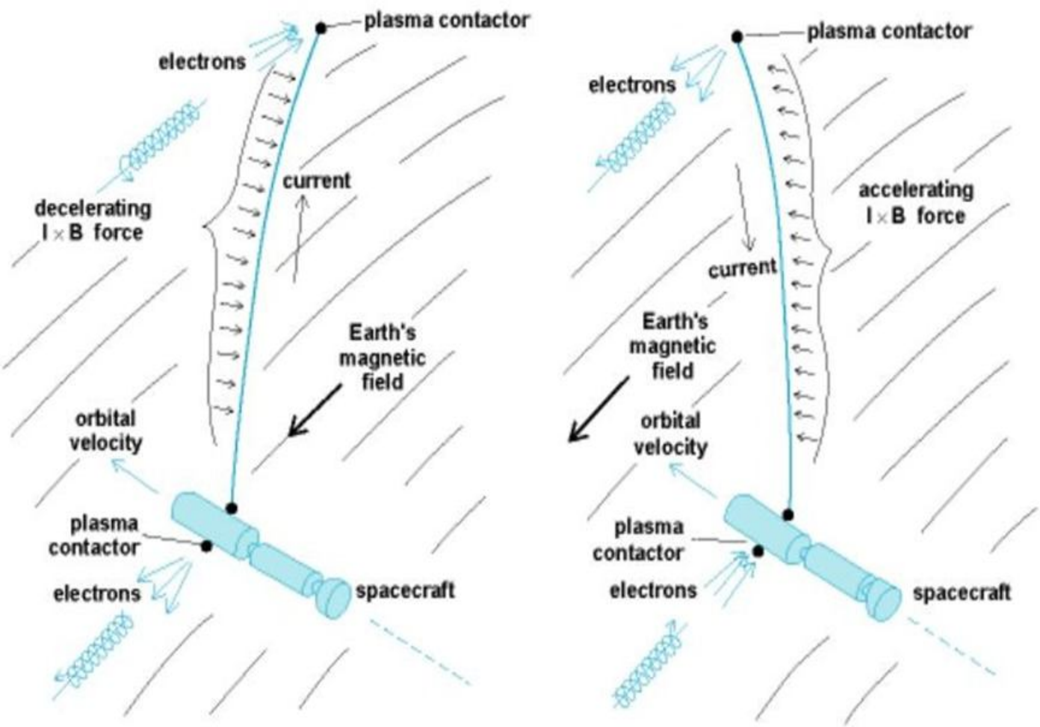
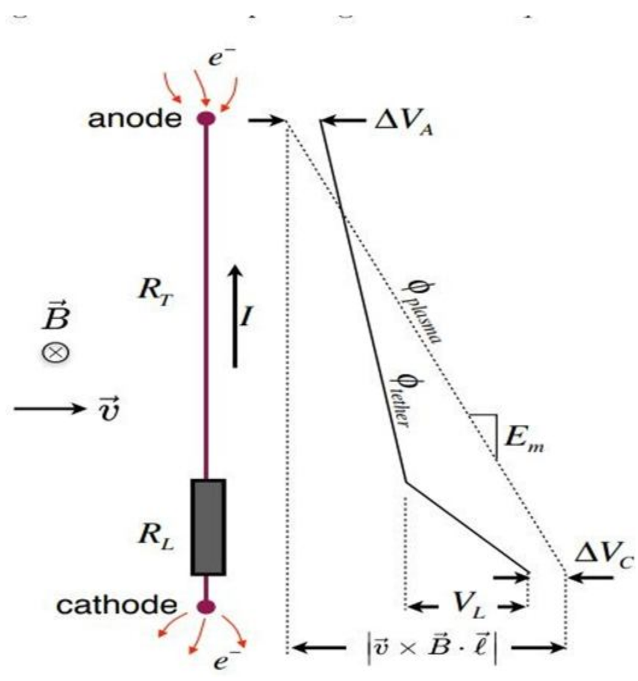
This tie framework is balanced in light of the fact that turning tie frameworks should utilize the two closures as anodes and cathodes eventually in its pivot. The V_hvps may be utilized in the cathode end of the EDT framework, and is wound down in anycase.



VII. TETHERS AS POWER GENERATORS

In this case, we have a spacecraft deploying an insulated tether "upwards" as shown in the figure below. we assume that the tether moves with a velocity v under a perpendicular magnetic field B. the tether has length l and a corresponding resistance RT.



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As the tie moves, we have a □eld Em = vB that will produce an "open circuit" voltage Voc = vBe. In case there is a heap opposition RL in series, the a (positive) current will □ow, as ionospheric electrons are gathered on an uncovered anode at the highest point of the tie,

$$I = Voc - \Delta V/RT + RL$$

where ΔV is the (somewhat little) all out possible drop because of plasma sheaths at the anode and cathode. To finish the circuit, a cathode delivers the electrons at the lower part of the tie. Given this flow □ow, electrical force will be produced at the heap,

$$P = I*IRL = (Voc - \Delta V/(RT + RL))*(Voc - \Delta V/(RT + RL))*RL$$

We see that the produced power is both zero when the heap opposition is either zero or ∞. This implies there is an ideal opposition that will yield greatest force. To □nd this, we differentiate the above condition and set it to nothing, hence,

$$P\ max = (Voc - \Delta V)/4RT$$

which happens when RL = RT The efficiency of this force producing tie can be de□ned as,

$$\eta g = RL/RT + RL*(1-\Delta V/Voc)$$

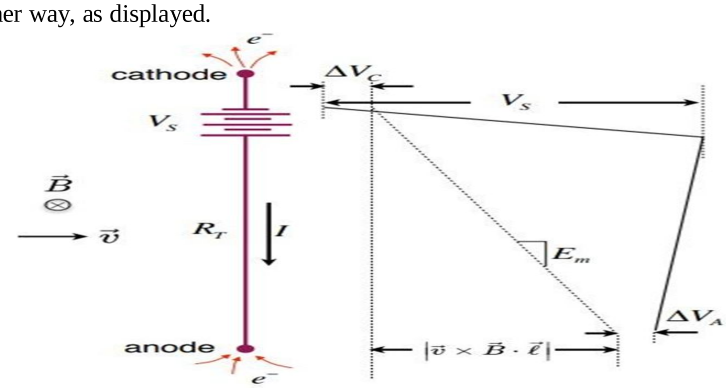
We can undoubtedly confirm that for greatest force age, the efficiency is $\eta g \approx 0.5$. Preferably, we might want RL » RT for most extreme efficiency, however at that point we get lower power. We can likewise check that the info power IVoc is indistinguishable from the pace of progress of the electrodynamic drag work (power E, power thickness E),

$$W = \text{fundamental of}(j \times B \cdot v\, dV) = IBlv = IEml = IVoc$$

Ties as Thrusters Now, we have a space apparatus that conveys the tie "downwards". For this situation, the anode at the base gathers electrons from the ionosphere. The Em □eld will point likewise upwards, notwithstanding, we presently have an on-board power supply that powers the net (positive) current the other way

VIII. TETHERS AS THRUSTERS

Presently, we have a rocket that conveys the tie "downwards". For this situation, the anode at the base gathers electrons from the ionosphere. The Em □eld will point likewise upwards, in any case, we presently have an on-board power supply that powers the net (positive) current the other way, as displayed.



Rather than eliminating energy from the circle, this con□guration will add energy, as the power thickness f = j × B focuses toward the speed vector Ev. With the current given by,

$$F = IBL*v/v \quad I = V(s) - \Delta V - Eml/RT$$

Hence, the pace of work added to the circle is, The efficiency of the tie as an engine is,

$$W = Fv$$

$$\eta t = Voc/v(s)$$

It is then conceivable to utilize a tie both as a generator and a propellantless engine. Truth be told, since the tie can be utilized as a generator, a fascinating inquiry would be: what is the tie efficiency thought about against an energy component? Energy components utilize some consumable (like fuel) to deliver electric force. As an activity, work out the efficiency of a tie delivering power when its drag is repaid by an engine devouring charge. This is a tie functioning as an energy unit. presently as per the earlier numerical evidences obviously the gravity angle power gives a force that heads the other way to the tie from the vertical and along these lines it will in general settle the tie toward the path positive for its utilization as electrodynamic actuator.

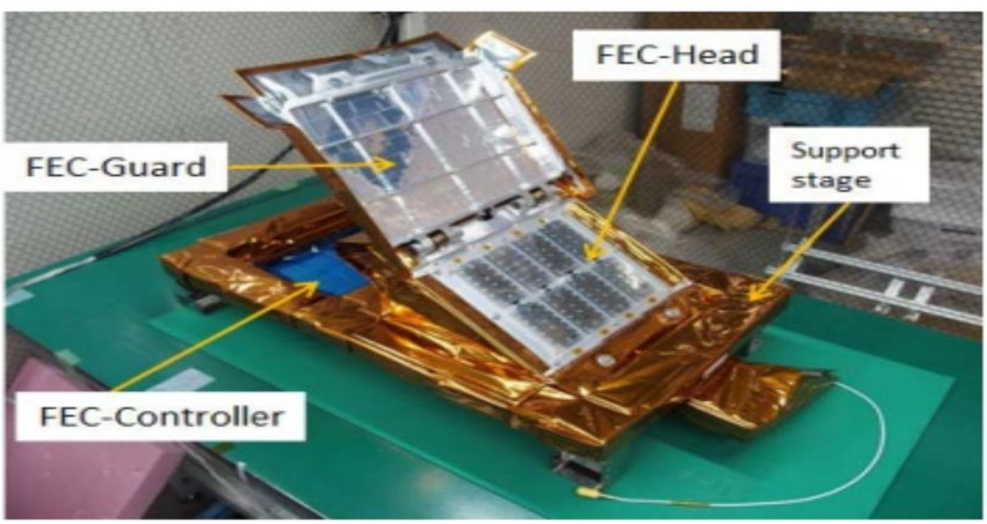
IX.EXPERIMENTAL RESULTS (MISSION KITE)

The essential goals of KITE are to show the key EDT advances, for example, a net-formed uncovered tie having high resistance to little trash sway and a field emanation cathode (FEC) as a little and straightforward electron source and to expand innovation preparation levels to plan and foster the EDT framework for ADR. The 700-m-length exposed tie gathers electrons from the surrounding space plasma, and the FEC on the HTV radiates 10-mA-level electrons into the plasma. This mix of the plasma contactors can give total fuel free deorbit drive.

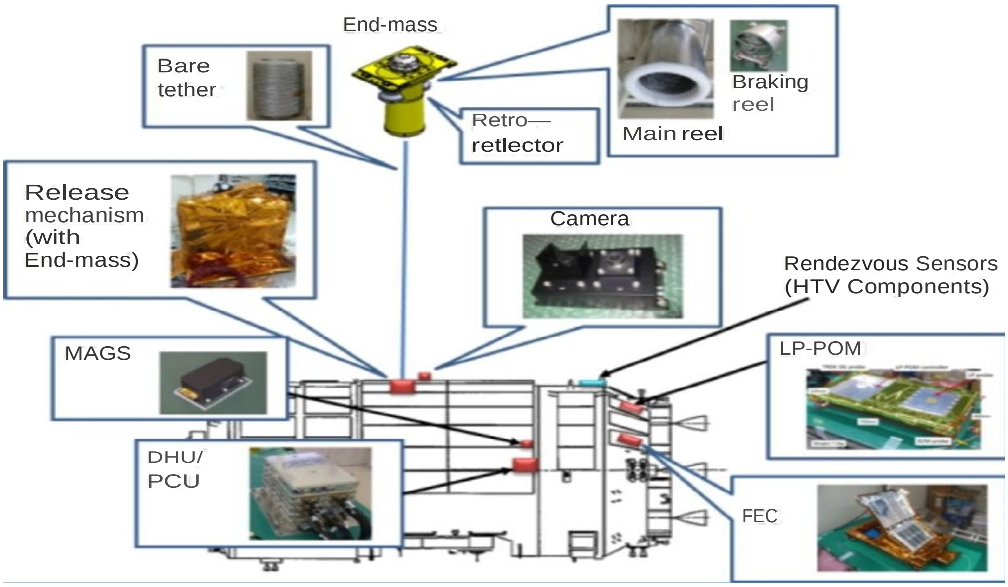
Table 1. Major mission specifications of KITE (planned).

Platform	H-II Transfer Vehicle 6 (HTV-6)
Mission duration	7 days
Orbit	20 km (or more) below ISS orbit (Altitude: 300 – 400 km, Inclination: 52 deg.)
Tether deployment direction	Zenith
Tether length	700 m (approx.)
Tether current	10 mA (approx.)
Electron collector	Bare tether
Electron emitter	Field emission cathode

The above table shows the arranged significant missions details of KITE which were determined to achieve the mission objectives under some restrictions. Deorbiting of the HTV is beyond the scope because the expected EDT thrust is low. The planned sequence of event of KITE is summarized in Fig. 3. Following events were planned in the 7-day mission. On Day 1, the tether is deployed after the checkout of KITE components and the tether vibration amplitude is alleviated using HTV thrusters. On Day 2, the tether vibration behavior, the tether voltage induced by the self induced electromotive force, and the tether current due to the transfer of charged particles from/to the ambient plasma are measured. On Day 3, the initial characteristics measurement of the FEC is done, following the HTV potential measurement with and without electron emission. On Day 4, changes in the tether current and voltage are measured during the repetition of the on/off operation of the FEC. On Day 5, the FEC is operated in an autonomous mode and the autonomous operation of the EDT system is demonstrated. On Day 6, EDT thrust measurement is to be attempted by monitoring the tether vibration amplitude. On Day 7, the tether is severed to avoid causing troubles for the re-entry operation of the HTV.



1) *KITE Components:* The major components for KITE are the bare tether, reels for housing and braking, end-mass, releasing mechanism of the end-mass, camera for tether dynamics observation, FEC, electrical potential monitor (LP-POM), magnetic sensor (MAGS), and data handling unit/power control unit (DHU/PCU). This gives shows the locations of the components on the HTV.



Day	Event	Image
Day 1	①Checkout of KITE Components	② ③ Deployment =3
	②End-mass Ejection (Tether Deployment)	
	③Tether Motion Alleviation by HTV Maneuver	
Day 2	④Observation of Tether Dynamics & ⑤Measurement of Electromotive Force	④ Vibration ⑤ EMF
Day 3	⑥Checkout & Characteristics Measurement of Field Emission Cathode	⑥⑦ Electron emission
	⑦Measurement of HTV Electric Potential with and without Electron Emission	
Day 4	⑧Repetitive Measurement of Tether Electric Potential & Current	⑧ Electron collection Current Electron emission
Day 5	⑨Tether Motion Alleviation by HTV Maneuver (If required)	⑩ Electron collection Current Electron emission
	⑩Autonomous EDT Operation at Several Settings	
Day 6	⑪Autonomous EDT Operation at Maximum Electron Emission for EDT Thrust Measurement by Monitoring Tether Libration	⑪ Thrust
Day 7	⑫Extra Time for Additional Tests	⑬ Cutting
	⑬Cutting of Tether from HTV	

Figure 3. Planned sequence of event in KITE.

2) *Results Overview:* The flight components of KITE have been installed to the HTV-6 until July 2016 and the freight was launched in December 2016. The HTV-6 left the ISS after the successful transportation operation, and the KITE mission was conducted from January 28 to February 5, 2017. Table 2 summarizes the daily events in the KITE mission. On Day 1, following the initial checkout of the KITE instruments, the end-mass ejection process for tether deployment was pursued, however, release of the end-mass was not detected. On Day 2, investigation on the malfunction and plans for retrieval were discussed. After Day 2, both the re-attempts to deploy the tether and the operation of FEC were conducted in parallel or serial. Despite various efforts and attempts to recover the malfunction, the end mass could not be released at the end. The KITE mission was terminated just before HTV-6 began re-entry maneuver. Although the tether deployment was unsuccessful, the FEC operated well without any critical trouble throughout the mission period. Some additional tests on FEC, such as the electron emission operation at various HTV attitude, which was not planned in original, were conducted using an extra mission time. Other KITE components were also functioning well without fatal problems. LPPOM was continuously operated from the HTV launch to the re-entry. The electrical potential of the HTV body and the plasma current were obtained at the all HTV operation phases; solo-flight, docking to the ISS, berthing at the ISS, releasing from the ISS, and the KITE mission. MAGS also worked well during the KITE mission acquiring three-axis magnetic flux density. The camera could not be used for monitoring the end-mass and tether, however, images of the ISS, which are effective for developing visual guidance and navigation systems for ADR, were acquired during the rendezvous phase.15 DHU/PCU performed its roll perfectly. In the following section, results of FEC operation were described in detail. B. Results of FEC Operation The FEC operation was started on Day 3 by opening the FECG and ended on Day 8 by obtaining the final I-V characteristics. All eight cathode units operated throughout the mission period without any critical failure, such as a short-circuit between the electrodes. Table 3 shows the summary of FEC operation results.

Table 2. t3verview of daily events in KITE

Day	Event
Day 1	Checkout of KITE components
	Tether deployment attempt. Resulted in unsuccessful.
Day 2	Discussion on tether deployment malfunction.
Day 3	Opening of FECG.
	Measurement of I-V charactetist›cs of FEC.
Day 4	Successive FEC operation at low current level.
Day 5	Tether deployment re-attempt. Unsuccessful.
	Measurement of I-V characteristics ol FEC.
Day 6	Tether deployment e-attempt. Unsuccessful.
	Successive FEC operation at high current Jevel.
Day 7	Successive FEC operation at three different current levels.
	Successive FEC operation at three different HTV Yaw attitude .
Day 8	Measurement of I-V characte ist›cs of FEC.
	Shutdown of KITE components.

Table 3. Summary of FEC operation.

Accumulated operation time	50 h
Accumulated exposure time	130 h
Number of I-V measurement operation	84
Number of autonomous consecutive operat on	22
Maximum emitter current (sum of 8 cathode units)	10.2 mA

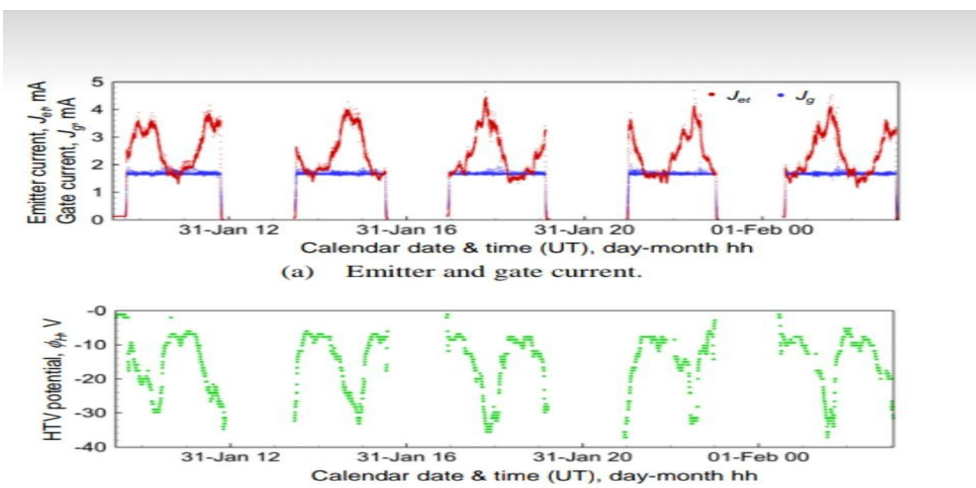
The accumulated operation time reached 50 hours in the total exposure time of 130 hours. The total maximum emitter current and emission current were approximately 10 and 6 mA, respectively. “Emitter current” indicates the electron current emitted from the CNT emitter and “emission current” means the electron current extracted to outside the cathode units. The emission current is calculated by subtracting the gate current from the emitter current.

a) Electron emission to plasma without tether the first point to be discussed on the FEC operation in KITE is whether the electrons were really emitted to the ambient plasma in this experiment, in which a bare tether did not exist. In the EDT fundamentals, the tether generates the potential difference between the tether ends, and thus the electron current loop via the electron emitter, ambient plasma and bare tether is formed in a steady state. We infer that the voltage generated by the HTV's solar cells plays a role of the tether voltage, and the exposed anodic potential area of the solar cells collects electrons from the ambient plasma. Figure 11 illustrates the conceptual image of the current loop formation via space plasma in this experiment. Figure 12 shows supporting evidence of the inference above. This figure shows the trends in electrical potential of the HTV and in emission current from the FEC at the initial current-voltage characteristics measurement on Day 3. The potential and current were obtained by LP-POM and FECC, respectively. There is a correlation between the HTV potential and emission current, that is, the negative potential of the HTV was mitigated by the electron emission from the FEC. This relation indicates that the potential balance between the HTV and the space plasma in the nominal condition was violated by the electron emission from FEC, thus establishing a new potential equilibrium. These data also indicate that FEC can be applied to control or mitigate spacecraft charging for preventing malfunction caused by unintended discharges.

b) Current-voltage characteristics of FEC on-orbit An example of current-voltage (I-V) characteristics of a single cathode unit is shown in Fig. 13. This figure shows the relationship between the emitter current and gate voltage of the No. 4 cathode unit obtained at the initial I-V measurement on Day 3. Measurement results at several times of voltage-sweep are plotted here. Typical characteristics in field emission phenomena were observed from this figure.

c) Trend in electron emission in accordance with HTV potential variation Figure 14 shows an example of the trend in total emitter and gate current when the eight cathode units operated simultaneously. Results of five successive autonomous operations on Day 4 were shown in this figure. The electrical potential of the HTV with reference to ambient plasma at the same time range is also shown in the figure

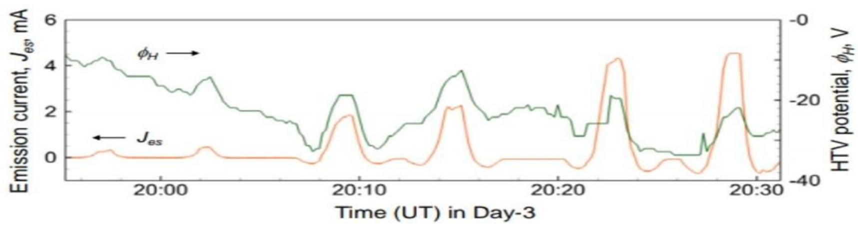
The intermissions between the operations are attributable to recording and downlinking of the data. The gate current was kept almost constant and the emitter current widely varied in magnitude. These results show that the gate voltage of each cathode unit was adjusted to maintain constant gate current as intended, and the emitter current varied depending on the HTV potential. The trend in HTV potential largely depends on the voltage generation by the HTV's solar cells, that is, the solar irradiation conditions. The emitter current is larger when the HTV potential is lower. This tendency is reasonable because the space charge limit is mitigated when the potential difference between the FEC and the plasma becomes larger. 4. Electron emission efficiency One of the essential indicators to characterize the FEC performance is the electron emission efficiency against the anode (or plasma on-orbit) potential. Note that "electron emission efficiency" indicates the ratio of emission current to emitter current. This indicator is important for estimating the tether current in the EDT system under various potential conditions.



(a) Emitter and gate current.

(b) Electrical potential of HTV with reference to ambient plasma.

The electron discharge proficiency plotted against the plasma-to-HTV possible contrast during the independent procedure on Day 6. The outcomes at the last ground trial of the FECH are likewise displayed in this figure. The plate anode found 200 mm away from FECH was utilized for current assortment in the ground test. The on-circle information shows that discharge proficiency relies upon the plasmato-HTV likely distinction true to form, and that the qualities are superior to those got by the ground test utilizing the plate anode.



X. EXPERIMENTAL ANALYSIS

A. A Tesla coil is an electrical resonant transformer circuit designed by inventor Nikola Tesla in 1891. It is used to produce high-voltage, low-current, high frequency alternating-current electricity.

B. A Tesla coil is a radio frequency oscillator that drives an air-core double-tuned resonant transformer to produce high voltages at low currents. Tesla's original circuits as well as most modern coils use a simple spark gap to excite oscillations in the tuned transformer. More sophisticated designs use transistor or thyristor switches or vacuum tube electronic oscillator to drive the resonant transformer.

C. Tesla coils can produce output voltages from 50 kilovolts to several million volts for large coils. The alternating current output is in the low radio frequency range, usually between 50 kHz and 1 MHz. Although some oscillator-driven coils generate a continuous alternating current, most Tesla coils have a pulsed output;[15] the high voltage consists of a rapid string of pulses of radio frequency alternating current.

So, the tesla coil is used to represent the earth's magnetic field for our experimental analysis regarding the electrodynamic tether system. A high voltage supply transformer (T), to step the AC mains voltage up to a high enough voltage to jump the spark gap. Typical voltages are between 15v to 30v.

A capacitor that forms a tuned circuit with the primary winding of the Tesla transformer. A spark gap(SG) that acts as a switch in the primary circuit. The Tesla coil (L1, L2), an air-core double-tuned resonant transformer, which generates the high output voltage.

Optionally, a capacitive electrode (top load) (E) in the form of a smooth metal sphere or torus attached to the secondary terminal of the coil. Its large surface area suppresses premature air breakdown and arc discharges, increasing the Q factor and output voltage. A small CFL bulb attached to a coil of conducting wire which is brought near to the tesla coils magnetic field can make the CFL bulb glow. The same effect can be seen with a long conducting tether orbiting the magnetic field of a planet.

In here we are setting up a motor driven satellite (mechanical setup) and also this setup is aided with the help of rack and pinion and bevel gear systems to move around the tesla coil in order to represent the electrodynamic tether satellite around the earth in its magnetic field rotating in the ionospheric plasma of earth's atmosphere, this model of tesla coil and a motor driven satellite mechanical setup , is powered by the induction through the tesla coil field and this would be the proof of concept structure to my experimental analysis.

Now let us see the outcomes of this mechanical setup with regard to the characteristics;

Here I have constructed a 1800rpm motor(self-start) to test the running. the power required to run a small motor of this kind can be found by using the simple formula of

- energy=voltage *current/frequency

the properties are as follows;

- output voltage=250v
- input voltage =12-24v
- power consumption-=250w(max)
- timing chip=555
- max arc length= 25cm MMC 20kv
- spark gap=5-6mm
- primary turns=850
- secondary turns=850
- secondary height=40cm
- secondary width=5cm
- top load=10cm sphere

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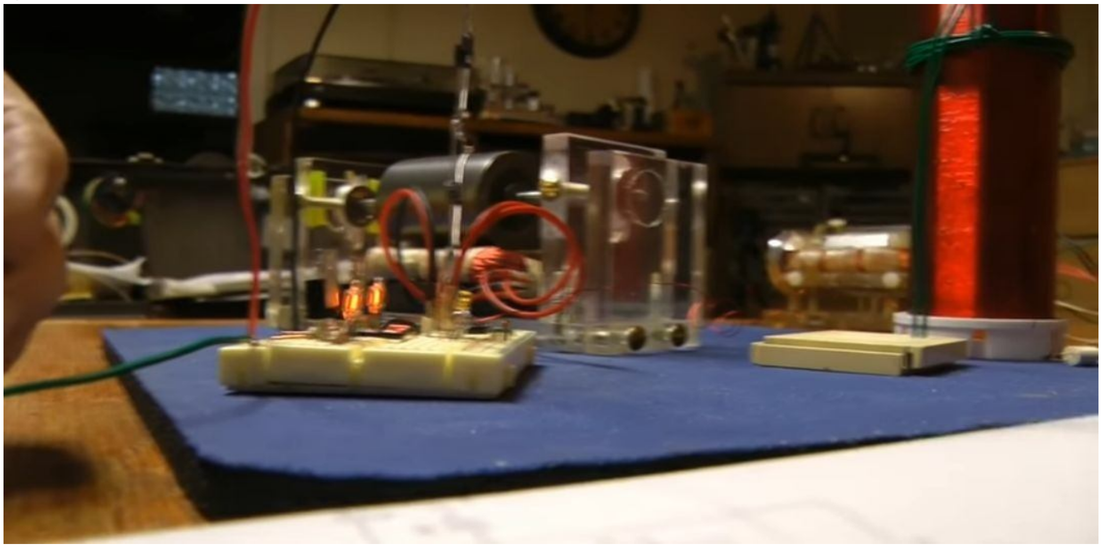
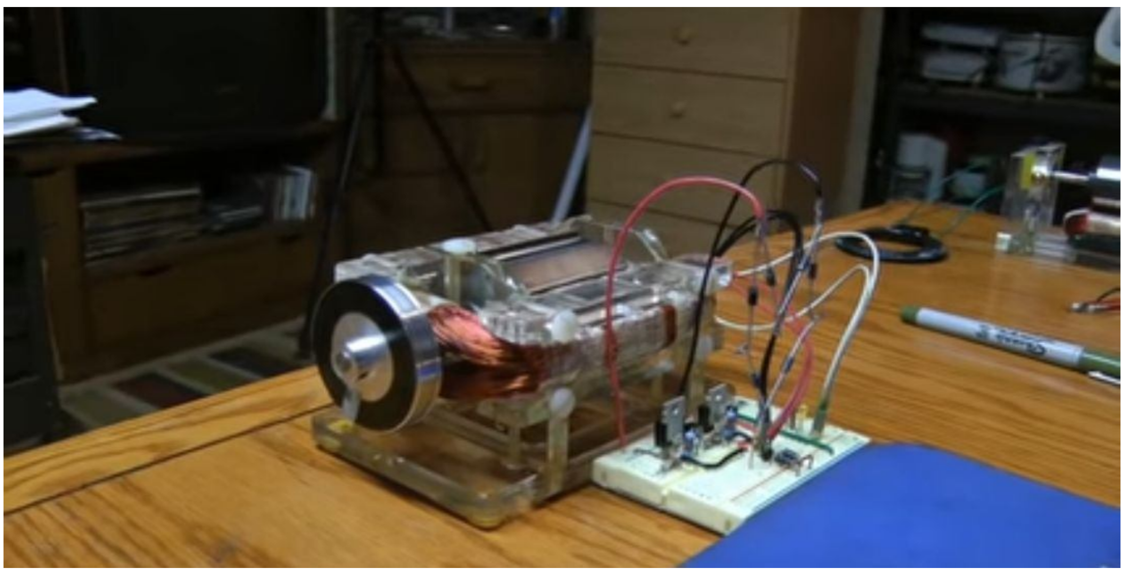
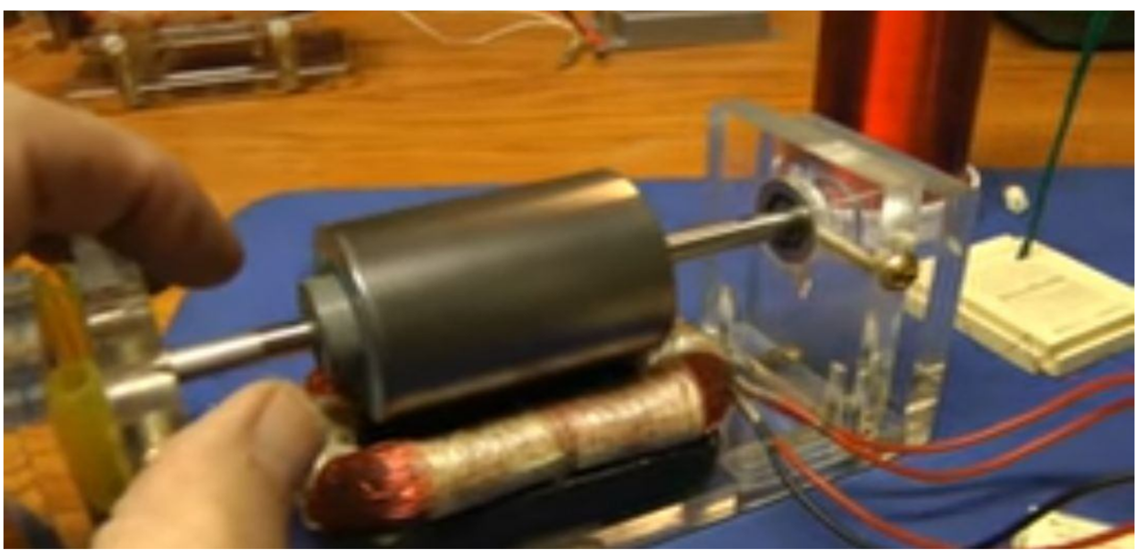
The following pictures shows the steps followed and experimental setup to show that the electrodynamic tether can be used for the power generation and this mechanical setup is used to run a motor using the tesla coil.







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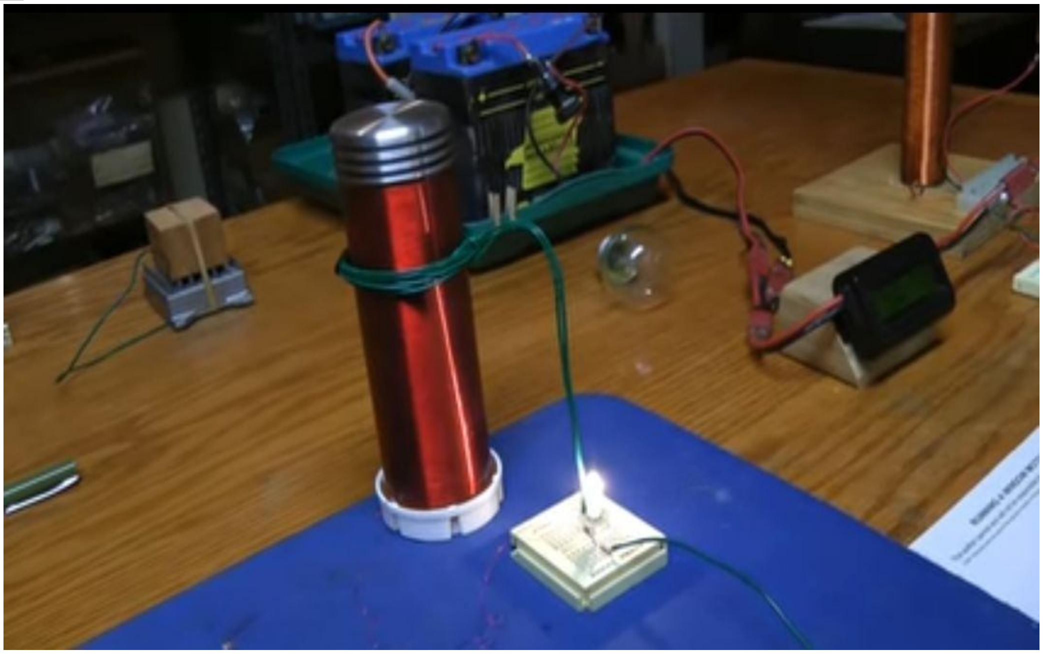

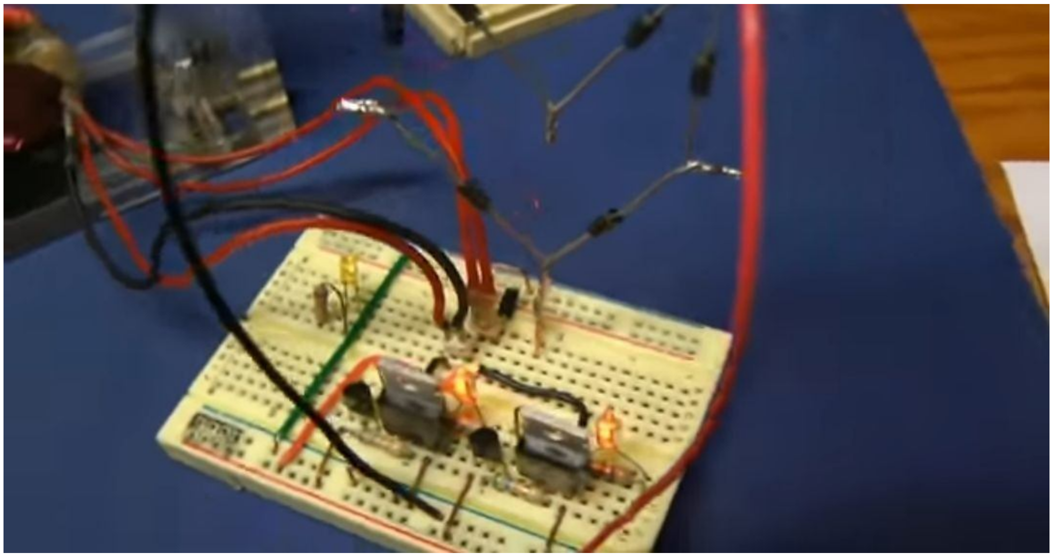

XI.CONCLUSIONS

Electrodynamic tie will be the most famous energy creation instead of engines for the satellite frameworks rockets. The utilization of room ties is the response to every one of the current issues as they don't need charges. ED ties can give long haul fuel less drive ability for orbital moving and station keeping of little satellites in low-Earth-circle. It lessens the deorbit time dissimilar to different satellites.

The mission idea, parts, and consequences of the electrodynamic tie probe the H-II exchange vehicle were investigated. Albeit the tie couldn't be conveyed because of the glitch of the end-mass delivery system, the field discharge cathode and other mission parts worked well all through the mission time frame. Acquired onorbit information on the field emanation cathode are successful to comprehend the electron discharge marvels in the ionosphere and to foster the cathode gadgets for future dynamic garbage evacuation frameworks.

Tie impetus requires no force and is totally reusable. It is likewise earth clean with minimal expense. It goes about as both promoter and braker for a space apparatus. Throughout the long term, various applications for electrodynamic ties have been distinguished for possible use in industry, government, and logical investigation. Electrodynamic ties may likewise give a conservative method for electrical force in circle. Past these, ETDs are opening new entryways in space investigation and drawing near to the universe. The space ties might even lead as a central issue for energy in the interstellar attack.

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