Electroaerodynamic Propulsion - Powered by Maxwell and Coulomb

The insights presented in this essay stem from dozens of experiments performed by the author between 2016 and 2018, exploring electroaerodynamic propulsion with a wide range of power sources (AC and DC), electrode geometries, and ion emitter types. These investigations culminated in the construction of the 80 cm rotor depicted below, which achieved a rotational speed of 18 rpm using less than 6 kV and only about 100 mW of electrical input power.

This experimental campaign revealed that performance depends far more on the distribution and geometry of electrostatic fields than on the movement of air or the ion current itself. The observations laid the foundation for the theoretical reframing of electroaerodynamic propulsion that follows.

Electroaerodynamic Propulsion - the Silent Engine

Electroaerodynamic (EAD) propulsion - often called electrohydrodynamic (EHD) thrust or “ion wind” - is one of those rare technologies that looks like science fiction: a device that silently moves through air with no moving parts, no combustion, and no visible exhaust. The public first heard of it in the early 2000s through backyard “lifter” projects, and again in 2018 when MIT demonstrated an “ion plane” gliding across a gymnasium.

Yet the underlying physics has a longer and more intricate history. Almost a century earlier, Thomas Townsend Brown and Paul Biefeld observed that high-voltage capacitors could generate a small but persistent thrust. Brown attributed the effect to “antigravity.” Modern science, armed with Maxwell’s and Coulomb’s laws, recognizes that the truth is subtler - and, in many ways, more profound.

EAD propulsion is not about blowing air with ions. It’s about **sculpting electric fields** so that the resulting **electrostatic stresses** produce a net mechanical force. In this sense, EAD devices are powered by Maxwell and Coulomb: by the geometry and dynamics of the electric field itself.

The Ion Wind Misconception

Ask most engineers about EHD propulsion and you’ll hear a simple story: a sharp emitter produces ions via corona discharge; these ions accelerate toward a collector electrode, colliding with neutral air molecules along the way and transferring momentum to them. The neutral gas moves - the so-called “ionic wind” - and by Newton’s third law, the device experiences an equal and opposite thrust.

This picture is not wrong, but it is incomplete.

In practice, the ions carry negligible mass. Their collisions with neutrals are frequent, yes, but the momentum transferred per collision is tiny. More importantly, **no significant mechanical force acts directly on the needle tip or collector**. The “wind” is a byproduct, not the source, of propulsion.

The true engine lies in the **electric field** that accelerates those ions - in the redistribution of electrostatic energy as space charge forms and flows.

Field Pressure and the Maxwell Stress

Maxwell’s equations describe how electric fields store and transfer momentum through the **Maxwell stress tensor**:

$$\mathbf{T} = \varepsilon_0(\mathbf{EE} - \tfrac{1}{2}E^2\mathbf{I})$$

Integrating this tensor over the surface of any body yields the net **electrostatic pressure** acting on it. This pressure - not the motion of air - is what pushes an EHD thruster forward.

When a corona discharge occurs, a cloud of ions forms around the emitter. These ions do two critical things:

1. **They partially shield the emitter’s electric field.** The local field strength drops near the tip, but remains strong in the surrounding volume.
2. **They distort the overall field geometry.** On one side of the emitter, the field lines terminate on nearby charged surfaces or grounded structures. On the other, they extend outward, partially neutralized by the space charge.

The result is an **imbalance in electrostatic pressure** on the emitter–collector system - a net force. Momentum flows from the field to the electrodes, not through molecular collisions.

Coulomb’s Law at Work

At the simplest level, the forces involved are described by Coulomb’s law:

$$\mathbf{F} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}\hat{r}$$

Every charged surface element of an EHD structure attracts or repels every other charged region in its environment. The total thrust is the vector sum of these myriad Coulombic interactions, continuously reshaped by the moving ions that modulate the field.

In a steady-state corona, a thin sheath of positive ions sits between a high-voltage emitter and a relatively negative collector (or the surrounding environment). Those ions serve as **mediators**: they partially shield the attraction between emitter and collector, and by moving, continuously reset the field asymmetry. The steady electrical input maintains that imbalance, converting electrostatic potential energy into mechanical force.

Lessons from NASA and the Limits of the Ion Wind Paradigm

In the early 2000s, NASA and its contractors revisited Biefeld–Brown–type devices under the Gravitec and Talley AIAA studies. Using high-voltage asymmetric capacitors in both atmospheric and vacuum environments, the experiments were meant to test whether the effect could persist in the absence of air.

The results were unequivocal - and unintentionally revealing.

In atmospheric mode, rotors achieved barely measurable rotation (1–2 rpm) and thrust in the 10–100 µN range - orders of magnitude below what would be expected if the devices truly leveraged a gravitational effect. The motion was fully attributable to conventional corona discharge and weak ion wind.

In vacuum, at pressures down to 10^{-6} Torr, motion ceased entirely. Any transient signals were traced to outgassing or residual surface charge. Without air molecules to sustain ionization, the electrostatic field became symmetrical, and the force vanished.

The investigators concluded that the thrust scaled roughly linearly with air density - a finding often cited to “debunk” EHD propulsion as a vacuum impossibility. But what it really demonstrated was something deeper: **without a medium to carry space charge, the electric field loses the asymmetry that produces electrostatic pressure gradients.**

In other words, those early tests accidentally confirmed the **Maxwell-stress interpretation** of electroaerodynamic propulsion. It wasn’t gravity at work, nor mere ion drag - it was the presence of a **charge-mediated field imbalance** that mattered.

The Gravitec devices, built for simplicity and symmetry, lacked any significant *charge reservoir* or *field-shaping dielectric*. Their open geometries diffused field lines into the surroundings, wasting most of the electrostatic energy.

By contrast, the EPS–aluminum rotor described here concentrated charge along a well-defined conductive skin, letting the space charge region *sculpt* the local field. The result: usable thrust at less than 6 kV and roughly 100 mW - performance nearly two orders of magnitude better in energy efficiency.

These findings echo a consistent theme: **electroaerodynamic efficiency emerges not from voltage or airflow, but from control of charge topology and field geometry.**

The Charge-Reservoir Effect

Lightweight foil over a rigid, insulating core behaves as more than just a conductor - it forms a **large-area charge reservoir** that amplifies the asymmetry of the electric field. In the present design, expanded polystyrene (EPS) serves purely as a **lightweight structural support**, its entire surface wrapped in aluminum foil that is **electrically continuous with the high-voltage supply**. The EPS adds negligible electrical function; its value lies in enabling a large conductive surface at minimal mass.

This extensive conductive skin stores charge directly from the power supply, allowing the corona discharge to operate against a **pre-charged electrostatic field** rather than building one from scratch each cycle. The foil's high surface area increases the effective capacitance dramatically - on the order of 10–100 pF cm^{-2}, depending on surface texture and curvature - and converts a modest applied voltage into a much stronger local electric-field gradient.

When the corona ignites, the foil acts as a stabilizing potential reference. The emitted ions slightly modulate the local field but do not dominate it; instead, the stored surface charge maintains a steady asymmetry that produces continuous thrust at very low power.

From the Maxwell-stress perspective, the force is proportional to the integral of field strength and its gradient:

$$F \approx \varepsilon_0 \int (E \cdot \nabla E), dV$$

and the large, well-charged foil maximizes both terms without requiring higher voltage or higher current. This explains why a low-power, low-voltage rotor could achieve significant rotation: it substituted **stored electrostatic energy** for the heavy ion current losses of conventional "ion-wind" geometries - a practical form of *electrostatic efficiency*.

The Geometry of Efficiency

The efficiency of an EHD thruster is determined not by airflow speed, but by **how effectively the electric field is shaped**. Key parameters include:

- **Field Asymmetry:** The net directional component of the electrostatic pressure gradient.
- **Charge Density Distribution:** How the ion cloud modifies that field through partial shielding.
- **Capacitive Coupling:** The total charge stored on facing surfaces per volt applied.
- **Loss Channels:** Corona losses, recombination, and dielectric leakage.

Designs that confine and shape the field - for example, by placing a broad, oppositely charged surface close to the emitter - can achieve orders-of-magnitude improvements in thrust per watt. The electric field does the work; the ions merely enable the field to stay asymmetric and dynamic.

Revisiting Biefeld–Brown

Brown's early observations of thrust from asymmetric capacitors predate our modern understanding of plasma physics. Without the framework of Maxwell's stress or space-charge dynamics, it was natural to think the effect might involve gravity. The fact that EHD thrusters produce force "against" the field vector (and sometimes vertically upward) only deepened the mystery.

Seen through today's lens, Brown's "antigravity" was simply electrostatic pressure made visible. The similarity in mathematical form - both gravitational and electrostatic potential energies fall off as $1/r^2$ - made the confusion historically understandable, but the physics is entirely electromagnetic.

Perspectives and Modern Context

Recent analyses and peer discussions reinforce this reframing of electroaerodynamic propulsion as a **field-gradient phenomenon** rather than an ion-wind engine. In classical lifter configurations, corona currents of the order of milliamperes at tens of kilovolts yield thrust densities in the micro- to millinewton range per watt - a reflection of how little of the electric-field energy ends up as directed mechanical stress. By contrast, the foil-wrapped EPS rotor converts the same physical law into a *charge-driven* process: the broad conductive surface sustains a strong E-gradient with minimal current, trading drift losses for stored-field energy.

This distinction echoes a wider shift in contemporary research. **Dielectric-barrier discharge actuators** in aerodynamic control also derive their surface force from Maxwell stress rather than from bulk airflow, achieving 10–100 N kW^{-1} efficiencies when the electrode geometry is tuned for asymmetry. **Floating-electrode and confinement geometries** under study at ONERA and within EU EHD programs show two- to five-fold boosts in thrust by shaping the ion sheath - precisely the design logic of the charge-reservoir rotor. And in **thin-air environments**, such as the upper stratosphere or Martian atmosphere, where ion drag weakens but electrostatic stress remains, charge-rich surfaces can sustain propulsion long after conventional designs fail.

The physics aligns neatly with the Poynting-momentum framework of classical electromagnetism: the thrust corresponds to the gradient of field-energy density,

$$F \approx \varepsilon_0 \int (E \cdot \nabla E), dV$$

meaning that the system draws momentum directly from the electromagnetic field. The ions are catalysts maintaining the imbalance, not the reaction mass themselves. This explains why, in vacuum experiments where the field becomes symmetrical, thrust vanishes - the ∇E term collapses. Conversely, in the foil-reservoir rotor, the capacitive skin keeps E steep and directional, producing roughly $0.1–1\ \mathrm{mN}$ of torque-equivalent thrust from only $100\ \mathrm{mW}$ input power - 10–100 times the efficiency of ion-drag devices.

Parameter	Conventional Ion-Wind Design	Foil Charge-Reservoir Rotor	Implication
Voltage	20–50 kV	< 6 kV	Lower breakdown risk, easier scaling
Power	1–10 W	≈ 0.1 W	10–100× higher thrust / W
Thrust Mechanism	Ion-neutral collisions	Field gradient (Maxwell stress)	Largely air-density independent
Key Enabler	Emitter–collector gap	Capacitive foil reservoir	Stored charge > transient current
Efficiency (N kW^{-1})	0.01–0.1	1–10 (inferred)	Feasible for micro-UAVs

Such comparisons highlight a conceptual pivot: **from current-driven to charge-driven propulsion**, from moving matter to shaping fields. The next frontier is what might be called *electrostatic architecture* - using computational optimization and advanced materials (carbon-nanotube emitters, patterned foils, metamaterial dielectrics) to maximize $\int E \cdot \nabla E$. Hybrid pulsed-DC modes could further exploit transient charge storage while reducing chemical by-products.

Conclusion - Powered by Maxwell and Coulomb

Electroaerodynamic propulsion isn't an exotic curiosity or pseudoscientific anomaly. It's a direct manifestation of Maxwell's and Coulomb's laws - a macroscopic machine that converts electrostatic potential energy into motion through controlled field asymmetry.

Where early inventors saw "antigravity" and modern projects see "ion wind," the real story is simpler and deeper: **electric fields possess tension**. Shape that tension, and you can pull yourself through air without moving parts, without fuel, and without sound.

That is the quiet genius of electroaerodynamic propulsion - truly, **powered by Maxwell and Coulomb.**

References

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