Drag Reduction and Propulsive Power by Electric Field Actuation

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1. Introduction to Micro Aerial Vehicles

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- Micro Aerial Vehicles (MAV) operate at chord Reynolds numbers below 200000
- Flow pattern dominated by laminar separation at the leading edge
- Compact geometry (low aspect-ratio below 2) gives rise to strong 3D effects
- Thus nonlinear lift characteristics and low aerodynamic efficiency
- MAVs are „hanging“ on the thrust vector - overdimensioned propulsion

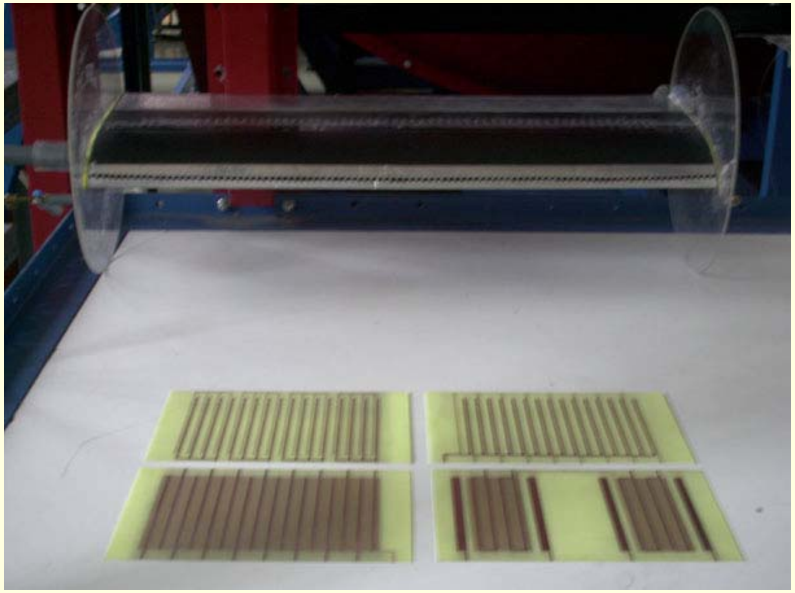
→ Need for <u>active flow control</u> systems to increase aerodynamic efficiency

→ Need for <u>alternative propulsive systems</u> (mechanically or electronically flapping wings) to increase aerodynamic and propulsive efficiency

2. Experiments to Drag Reduction

Experiments to <u>flow control on airfoils and cylinders</u> are based on acceleration of weakly ionized air - thus nontraditionally mimicking the technique of blowing out.

<u>Used Atmospheric Air Ionisation Methods:</u>

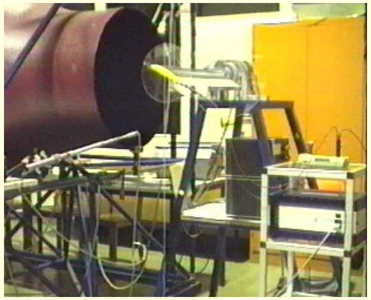


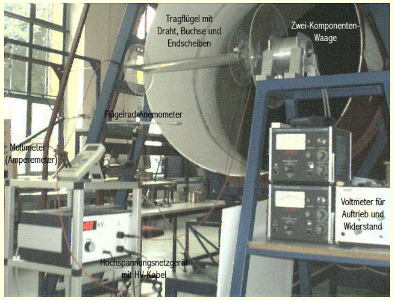
- *<u>Corona Discharges</u>* from DC high voltage charged thin metal wires (diameters = 0.10 - 0.15 mm)

- *<u>Dielectric Barrier Discharges</u>* from AC high voltage charged flexible printed circuit boards (thickness = 0.5 mm, electrode width = 1 mm)

Velocity Range of Free-Stream Wind-Tunnels at the Institute of Bionics:

0	-	6 m/s	(Small Wind-Tunnel)
5	-	15 m/s	(Grand Wind-Tunnel)





2.1 Flow Control on Airfoils

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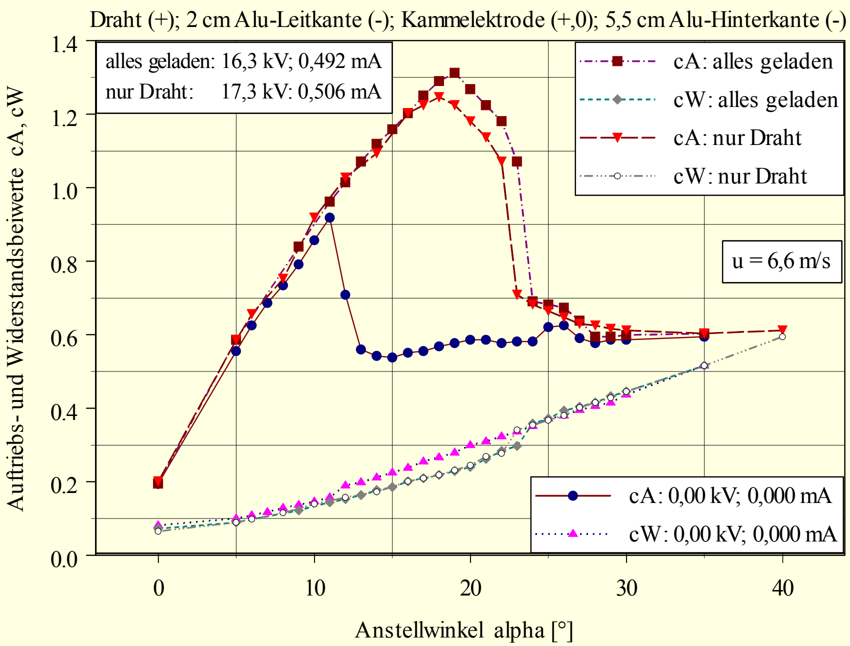
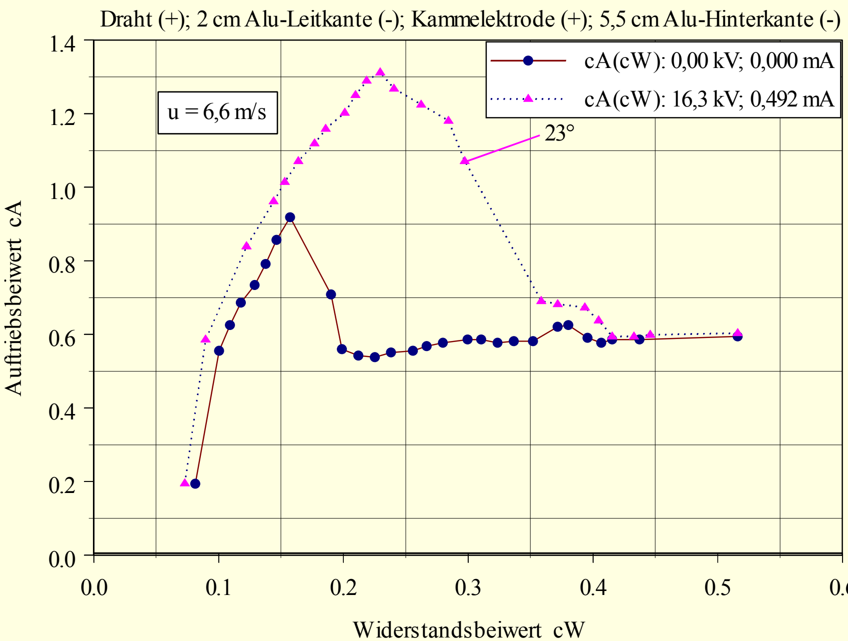
Separation Delay and Lift Enhancement at u=6.6 m/s

- Lift enhancement at alpha = 19° is 127%
- Drag coefficient decreases by 18%

  → Increase of aerodynamic efficiency by 177%
- At alpha = 0° drag reduction by 10.1 % with electric field actuation





Additional electrode pair at trailing edge has effect of jet flap.

2.1 Flow Control on Airfoils

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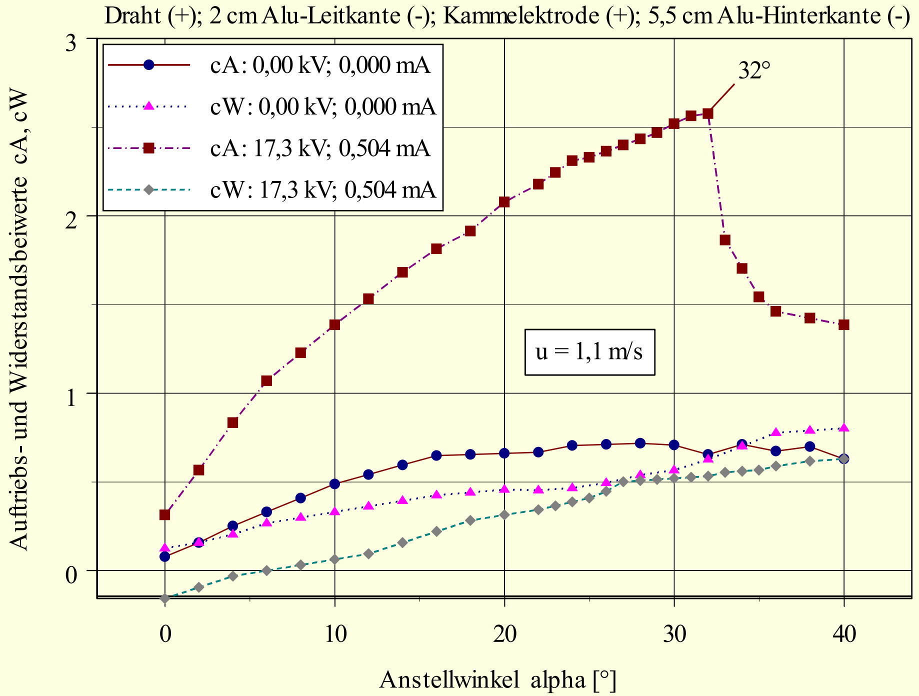
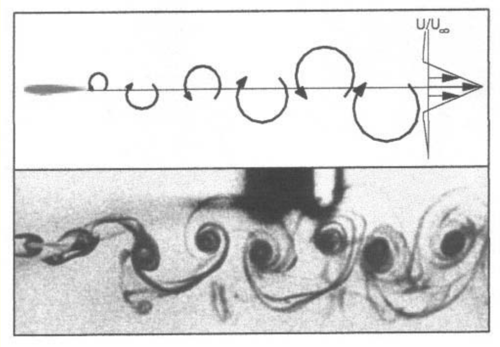
Separation Delay and Lift Enhancement at u=1.1 m/s

<u>Ionic Wind Velocity > Wind Tunnel Air Velocity</u>

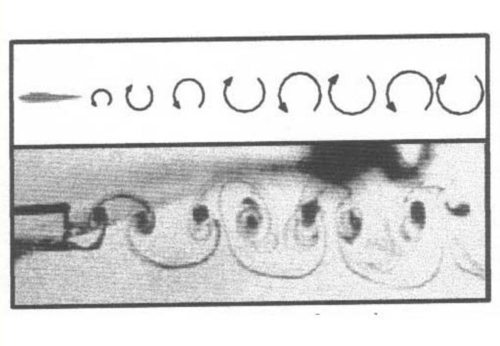
- at alpha = 0° drag coefficient reduced by 113%
  thus wing generates thrust up to alpha = 6° !!!

- at alpha = 32° lift coefficient enhancement by 293%,
  maximum lift coefficient of 2.57





Vortex Street for Thrust
(Source: Jones, K. D.)



Vortex Street for Zero Drag
(Source: Jones, K. D.)

2.1 Flow Control on Airfoils

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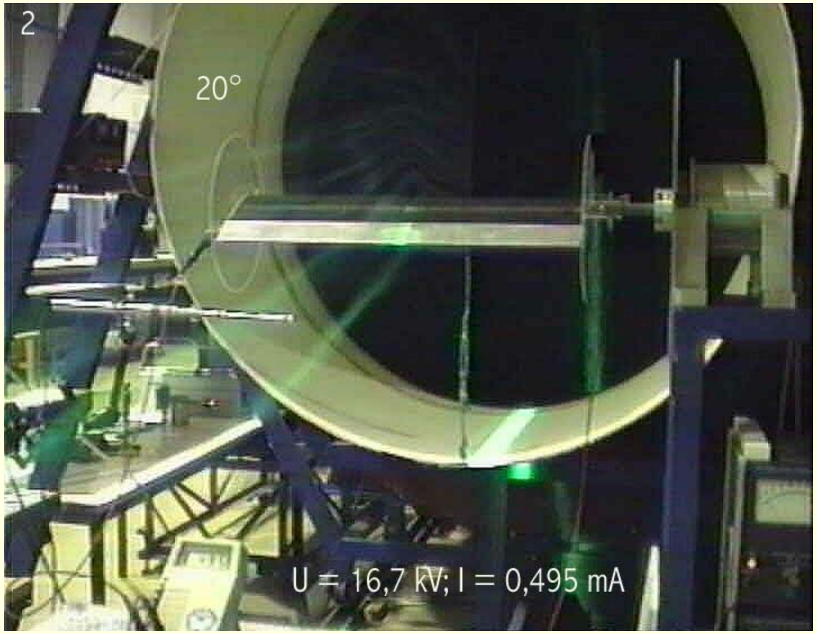
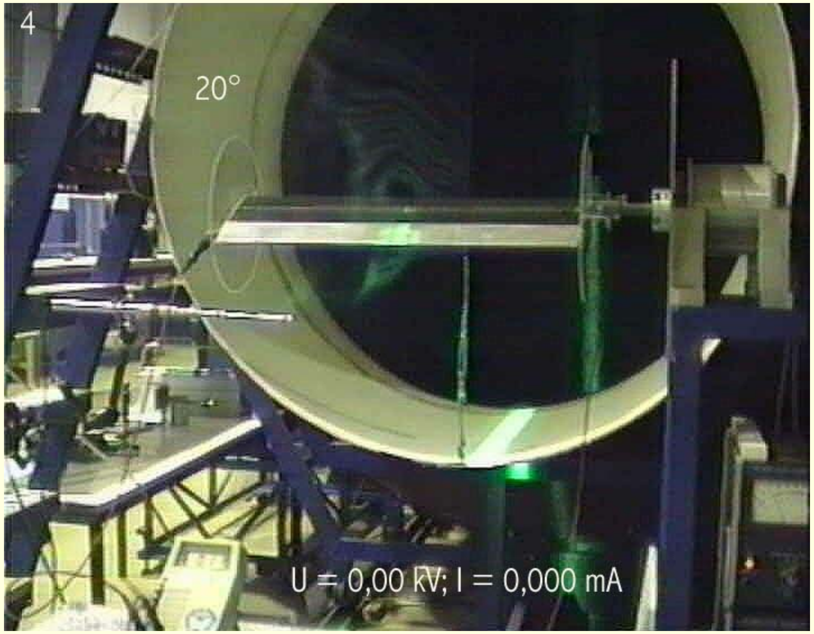
Laser-Light-Sheet Smoke Wire Visualisation





Up to alpha = 15° the flow can be separated, reattached and again separated like in a fluidic flip-flop-switch.

→ Principal demonstration of fast flight mechnical forcing without moving parts (see video: http://www.bionik.tu-berlin.de/user/goeksel/electrofluid1.AVI).

2.2 Flow Control on Cylinder

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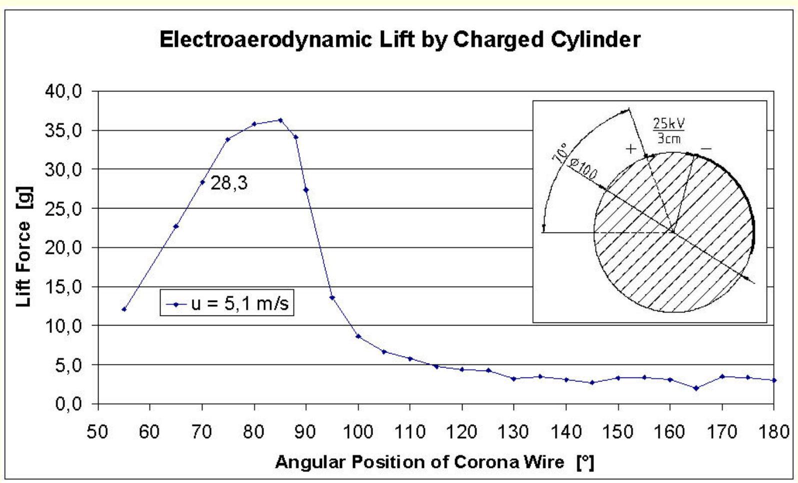
A corona wire on the cylinder surface is charged with 25000 Volt. The weakly ionized air streams down to the grounded aluminium sheet electrode. The maximum current is limited to 0.5 mA. The tangential ion wind velocity is about 1.5 m/s.

Experiments to study the electroaerodynamic Coanda-effect on a stationary cylinder.



Depending on the angular position of the corona discharge wire, the laminar flow separation can be more or less effectively controlled on the cylinder surface.

Lift mass forces up to 36 g at incoming velocity of 5.1 m/s

3. New Concept for Propulsion System

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Electrostatic Wave Propulsion by Polyphase Plasma Actuators

Flapping Wing Model
University of Toronto
(Source: DeLaurier).

Objectives for atmospheric ion propulsion system:

- Fixed-wing simulation (bionic transformation) of flapping wing (mechanical wave propulsion) of birds and Insects through pulsating („flapping“) travelling electrostatic soliton-fields (electronical wave propulsion).

- Like in natural example air acceleration over the whole spanwidth

- Development of all electrokinetically propelled MAVs.

Advantages: - no fast, narrow downstreams behind the wing

- better maneuverability without moving parts.

Project *Electrostatic Wave Propulsion by Polyphase Plasma Actuators* was recently recommended for funding as outcome of the German Research Ministry (BMBF) Concept Contest *“Bionics – Innovations from Nature“*

3.1 Theory for Polyphase Actuation

The first successfull generation of electrostatic traveling waves for aerodynamic applications were done by H. Sin in his M.S. thesis at the University of Tennessee:

H. Sin (2002) *A Polyphase Power Supply and Peristaltic Flow Accelerator Using a One Atmospheric Uniform Glow Discharge Plasma*. M. S. in Electrical Engineering Thesis, Department of Electrical and Computer Engineering, University of Tennessee, Knoxville.

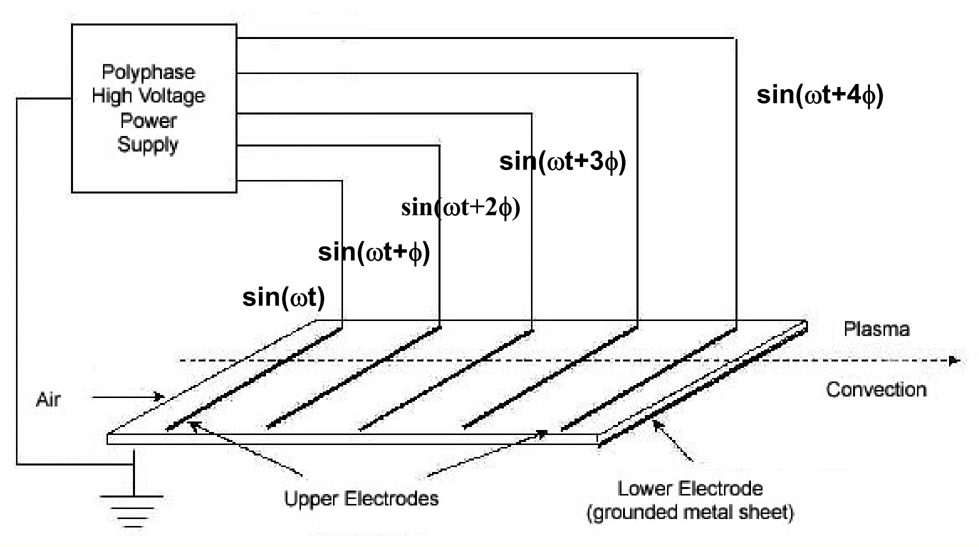
The following two <u>Methods for Plasma Flow Acceleration</u> will be used in the atmospheric ion propulsion:

<u>Paraelectric Flow Acceleration:</u>

Plasma is accelerated in the direction of increasing electric field gradient.

<u>Peristaltic Flow Acceleration:</u>

Plasma is accelerated by electrostatic traveling waves. This method requires a polyphase high voltage power supply.



$$Ø = \frac{360^\circ}{N}$$ N = Number of phases per period

3.1 Theory for Polyphase Actuation

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The potential of the electrostatic traveling wave is defined as

$V = V_0 \sin(\omega t + k x)$ with the wave number k as

$k = \frac{2\pi}{\lambda} = \frac{2\pi}{N L}$; N is the number of phases per period and L is the distance between electrode stripes.

The phase velocity (acting on net charge velocity) is

$v_p = \frac{\omega}{k} = v_o N L$ with $v_o = \frac{\omega}{2\pi}$ as the driving RF-frequency (e.g. range of 5 - 50 kHz).

The phase velocity can be several hundred meters per second, whereby the ion induced neutral gas velocity in atmosphere air is

$v_{oi} = \frac{e V_o}{m_i v_{in}} \frac{2\pi}{NL}$ with v_{in} as ion-neutral collision frequency, m_i as ion mass and V_o as voltage.

With the following parameters, the ion induced neutral gas velocity is about 100 m/s :

$V_0 = 3000$ volts

$N = 8$ phases

$L = 1$ cm

$M_o = 28.5$ AMU, ion-neutral mass

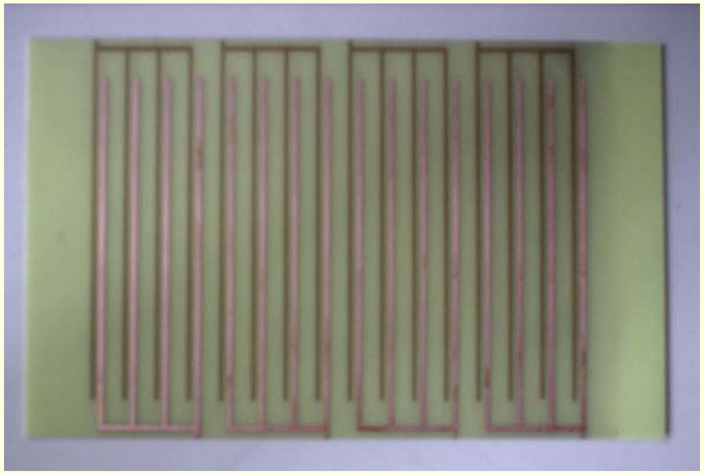
$v_{in} = 7 \times 10^9$ collisions / sec

$\frac{e}{m_p} = 9.50 \times 10^7$ Coulombs/kg

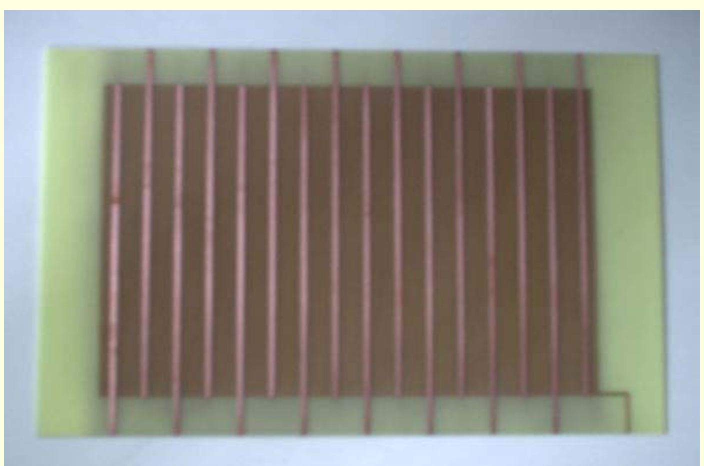
→ Also useful as flow control method for applications at transsonic and hypersonic speeds.

3.2 Polyphase Plasma Actuators

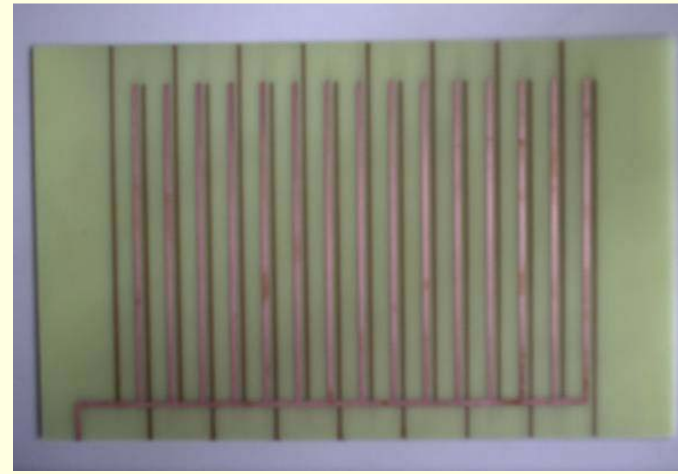
Dielectric Panels for Plasma Generation with Dimension 160mm x 100mm x 0.5mm



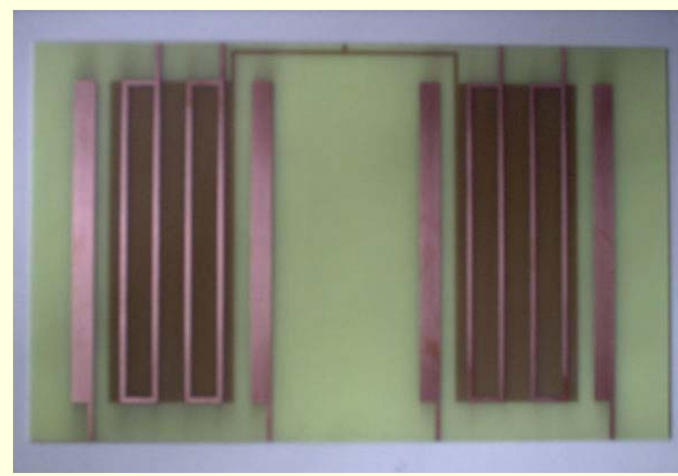
1. Paraelectric (Single Phase Actuator).



2. Peristaltic with 8 Phases and 2 Periods.



3. Paraelectric und Peristaltic.



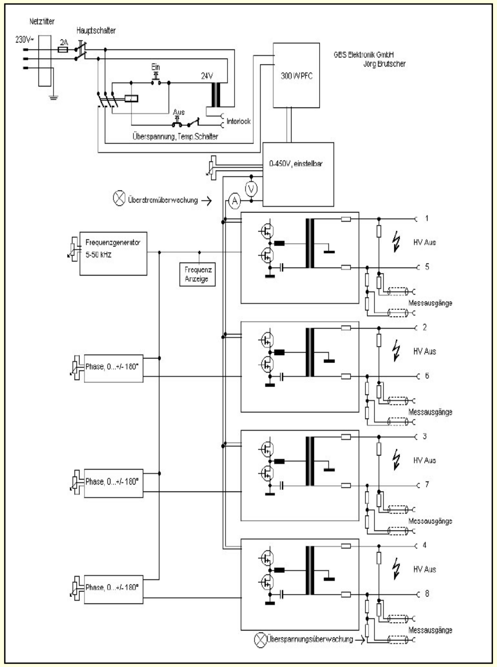
4. DC High Voltage Acceleration.

3.3 Polyphase High Voltage Power Supply

Polyphase high voltage power supply operating at kilohertz frequencies and RF voltages up to 6 kV are not available off-the-shelf.

GBS Elektronik (near Research Center Rossendorf) was specially ordered to develop a high voltage power supply providing 8 phases at 45° intervals at RF voltages up to 6 kVrms and a frequency range from 5 – 50 kHz.

Below is a picture of the draft circuit design.



<u>Characteristics of the Polyphase High Voltage Power Supply:</u>

- Maximum average power (for 8 outputs): 300 Watt
- Maximum output voltage: 3-6 kV
- Pulse frequency range: 5-50 kHz
- Variable phase angle vector for forward and backward traveling electrostatic waves
- power factor regulation and network filter to protect the electricity network
- fast current monitoring:
  output current restricted to maximum 20-30 mA

→ Contacting the outputs and the capacitive loads (plasma panels) is non-lethal, but should be avoided.

4. Conclusion

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- We already demonstrated the possibilities of active flow control by electric field actuation using corona discharges from thin metal wires
- We presented a new concept for an electrostatic wave propulsion system derived from the mechanically flapping wing propulsion – the concept was selected in the national wide contest “Bionics – Innovations from Nature”
- The simplified theory for poly phase plasma actuation was shown.
- We presented four plasma panels made of flexible printed circuits boards to test paraelectric and peristaltic flow accelerations.
- We presented the characteristics of an eight-phase power supply which was specially developed for the project “Electrostatic Wave Propulsion”
- For alternative propulsion applications on MAVs we envision ion induced neutral gas velocities up to 30 m/s – theoretically much more is possible.
- This will be studied in the Project “Electrostatic Wave Propulsion” from June 1st to November 30th, 2004.

5. Outlook

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1. Plasma panels can be covered by Teflon and other dielectric material thin layers (for instance made of high temperature ceramics) to protect the electrode stripes (for instance made of high temperature metals like Niobium):

   → Electrodes are invisible, nevertheless by switching on a high frequency high voltage field, a surface plasma can be generated by dielectric barrier discharges.

2. Such a surface plasma panel could be used for active flow control on hot vanes and blades in Low Pressure Turbines (LPTs):

   → Increasing efficiency at low Reynolds numbers, e.g. at high altitude operation

   See: J. List et al. (2003) Using a Plasma Actuator to Control Laminar Separation on a Linear Cascade Turbine Blade. AIAA 2003-1026, 41st AIAA Aerospace Sciences Meeting, Reno, NV.

3. <u>Electrostatic wave drives</u> to be used on manned and unmanned beamed energy propelled transatmospheric flight vehicles.

   See: B. Göksel, I. Rechenberg (2003) Surface Charged Smart Skin Technology for Heat Protection, Propulsion and Radiation Screening. DGLR-2003-257, German Aerospace Congress, Munich.