

# MHD hypersonic flow control for aerospace applications

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**The heat barrier, resulting from shock waves, is the main problem to overcome in hypersonic flight. Shock waves start from the intersection of Mach waves, but it is shown that a suitable electromagnetic force field can modify the pattern. Computational and experimental studies involving magnetohydrodynamics are presented, allowing for shock wave cancellation and active aerodynamic control of an ionized flow through Lorentz force action. Further solutions are also considered for advanced aerospace applications of MHD converters using magnetized non-equilibrium plasmas.**

## Nomenclature

$J$	=	current density
$B$	=	magnetic field
$F$	=	Lorentz force
$V$	=	flow velocity
$V_s$	=	surface wave speed
$\rho$	=	fluid density
$L$	=	interaction length
$\eta$	=	interaction parameter
$a$	=	speed of sound
$M$	=	Mach number
$E$	=	electric field
$\sigma$	=	electrical conductivity
$R_m$	=	magnetic Reynolds number
$P$	=	fluid pressure
$P_m$	=	magnetic pressure
$\mu_0$	=	vacuum permeability
$T_g$	=	gas temperature
$T_e$	=	electron temperature

## I. Introduction

IT has been sixty years since various methods have been investigated in view of lowering heat transfer to high-speed flying bodies. Hypersonic magnetized plasmas have been initially studied for space capsules equipped with electromagnetic shields, around which air is naturally ionized due to subsequent heat behind shock waves.<sup>1,2</sup> Later work focused on detaching shock waves from leading edges of blunt bodies with an upstream *non-magnetized* plasma “air-spike” acting like a protective cushion for the materials. Ionization is then obtained through many means, including applying high voltage discharges, high frequency electromagnetic waves, or lasers.<sup>3,4,5</sup> Moreover,

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the modification of gas-dynamic through microwave radiation heats up the plasma and modifies the local value of the sound velocity, which attenuates the recompression behind a soft shock wave. But none of these methods really acts on the flow to truly impose one way or another to it.

A first category of plasma-aerodynamic devices *actively* acting upon the flow uses electrohydrodynamics. Those EHD accelerators are generally known as plasma actuators. They use properties of electric fields only (polarization body force, DC ion mobility drift or RF peristaltic waves) to carry the ions and the neutral gas through Lorentzian collisions upon a thin layer. Peristaltic EHD devices can theoretically accelerate air in the boundary layer up to Mach 1.0 (neglecting heating and viscous effects which lower the real effect).<sup>6,7,8</sup> But magnetohydrodynamics, involving both applied electric and magnetic fields combined into Lorentz forces  $J \times B$ , is preferred to control airflows up to hypersonic regimes.

Next-generation aircrafts of a new kind are described which, if supplied by a powerful energy source, could flight silently at high Mach numbers in dense air without shock wave nor turbulence, fully driven by MHD force fields controlling the flow around their whole body. In relation with such devices, original solutions to classical problems raised by plasma instabilities in the presence of powerful magnetic fields are proposed.

Among applications of MHD converters described in this paper: wave drag and wake turbulence cancellation, flow laminarization, engine inlet control, combination of accelerators and generators into MHD-bypass systems, HV plasma protection of leading edges, electromagnetic braking for atmospheric reentry. The association of all these techniques leads to a unique device combining a space launcher, a plane and an atmospheric reentry capsule into one fully reusable vehicle taking-off and landing on its own steam, successor of conventional rockets.

## II. Hydraulic analogy experiments

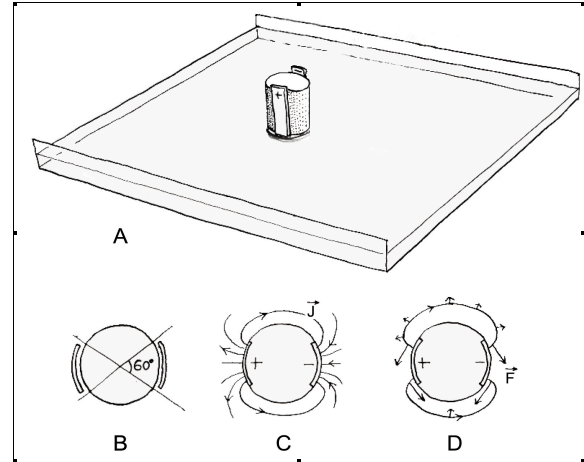
As early as 1976, preliminary experiments have shown, through hydraulic analogies, the effectiveness of Lorentz forces on wave front in immersed profiles at flows where  $V > V_s$  with subsequent elimination of bow and stern waves, suggesting for the first time the possibility of completely cancelling wave drag, as well as controlling the flow around a body travelling at supersonic speed.<sup>9</sup>

The principle was the following: acidic water (hence conducting electricity) flows in a channel on a slightly inclined plane. The low thickness of this liquid layer slows down surfaces waves  $V_s$  which means that in this experiment a flow speed of 8 cm/s could simulate an equivalent air speed of Mach 1.4. An 8 mm diameter cylindrical obstacle is introduced as indicated on Fig. 1A. This model is made of insulating material, and has 2 lengthwise electrodes 180° apart as indicated in Fig. 1B, so an electric current flows within the fluid as in Fig. 1C. The model is placed in between the poles of an electromagnet shown in Fig. 3, able to produce a 1T axial magnetic field. Model's electrodes are connected to a low voltage DC generator. The fluid is subjected to a Lorentz force field given in Fig. 1D.

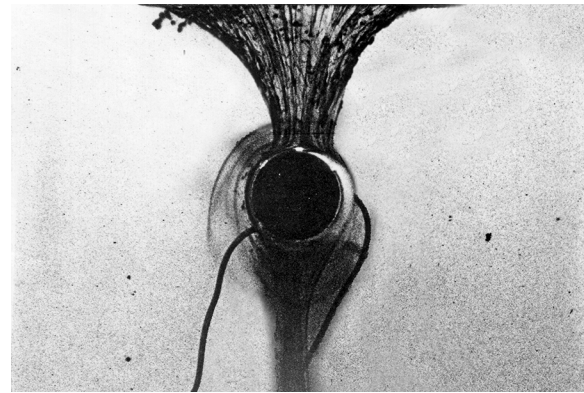
Experiment conditions are dimensioned in such way that the interaction parameter is greater than unity:

$$\eta = \frac{JBL}{\frac{1}{2}\rho V^2} \quad (1)$$

In order to minimize electrolysis phenomena, the current density  $J$  must be limited, which, in returns, leads to strong magnetic field  $B$  in the order of one tesla.



**Figure 1. Hydraulic MHD experiment.** Cylindrical model with electrodes partially imbedded in an electrically conducting liquid.



**Figure 2. Sucking effect by Lorentz force field  $J \times B$  and induced flow around a cylindrical MHD accelerator.**

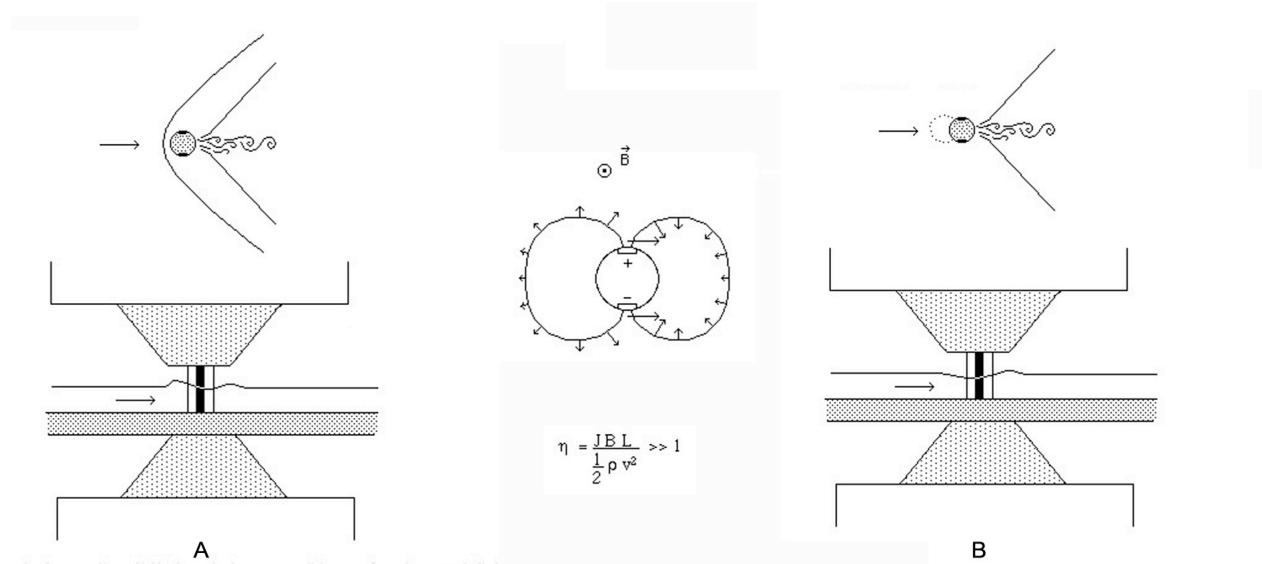
Before conducting the experiment in a moving fluid, the Lorentz field's effect was demonstrated in a stationary fluid, and produced the flow photographed in Fig. 2, visualized with a dye.

The model generates in its front part a clearly visible sucking effect, as well as a laminar flow and wake without any apparent turbulence. Figure 2 also shows two electrical wires carrying the current to electrodes, and a parasitic gaseous emission on right electrode due to anodic oxidation of electrolysis.

The same experiment carried out in a moving liquid without applying any power to the model shows a highly turbulent wake around the cylinder, and clearly demonstrates how MHD can eliminate wake turbulence. We were the first showing this effect as early as 1976.<sup>9</sup>

This shockwave cancelation experiment, not only demonstrated front wave elimination, but has also shown the effectiveness of Lorentz field in generating a depression at the model's stagnation point, as depicted in Fig. 3.

### III. MHD action on Mach waves

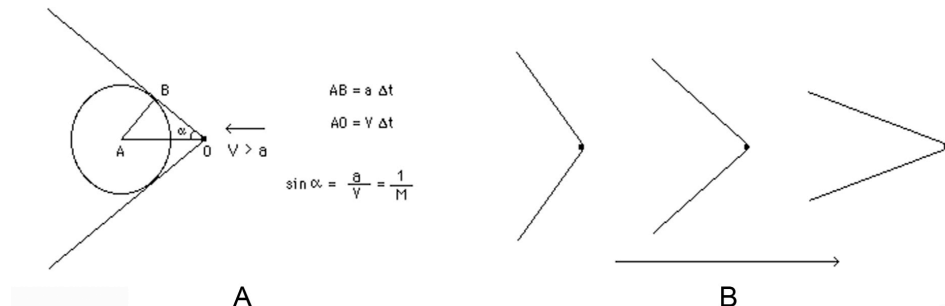


**Figure 3. Bow wave cancellation by Lorentz force field around a cylindrical model.** *Magnetic field created by 1T electromagnet. A) Passive model with zero  $J \times B$  forces: bow and stern waves, turbulent slipstream. B) MHD field applied: front wave annihilated and depression created at stagnation point.*

This lead us thinking that the effect of Lorentz forces field could cancel out wake turbulence on one hand, and on another hand prevent shockwave formation, hence eliminating wake turbulence, which, in effect would notably reduce thermal effects linked to the position of shockwave on the front part of a moving body.

As early as 1970, a theory backing up the experiment started to emerge. It was necessary to consider what phenomena caused the formation of shockwaves in a flow. The later obeys to Navier-Stokes law which possesses its associated characteristics system. In subsonic flow, characteristics surfaces are imaginary, whereas in supersonic flow those surfaces are real, corresponding to what is called Mach waves. Refer to Fig. 4.

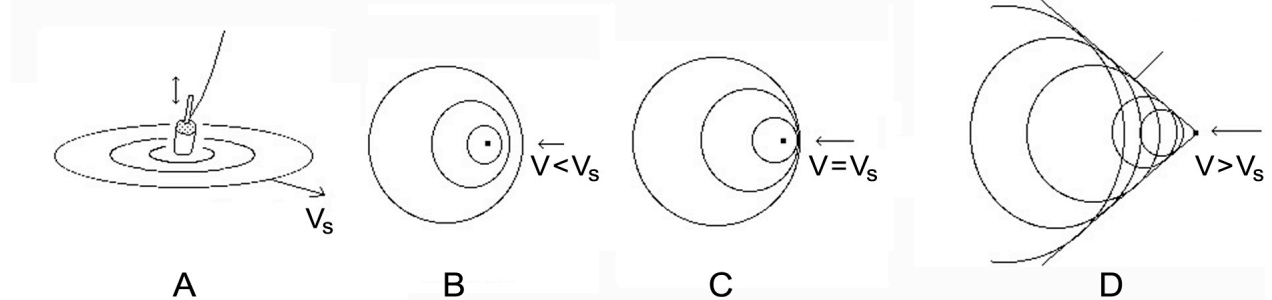
It is common knowledge that one can simulate supersonic flows through hydraulic analogy, by using channels where water flows, with one free surface. Such technique was used in aeronautical universities until mid 60's, when computerized analysis became readily available.



**Figure 4. Mach waves. A) Geometrical relations. B) Increasing speed.**

By the same token, the analogue of the speed of sound becomes the propagation speed of surface waves  $V_s$  and Mach waves can easily be materialized as seen in Fig. 5.

Figure 6 depicts a hull in liquid, flowing at a speed  $V$  greater than surface waves  $V_s$ . A system of waves appears: some waves starting from the bow, and some from the stern. Those waves are similar to oblique shockwaves that would appear on a lenticular airfoil of constant section as seen on Fig. 7.



**Figure 5. Mach waves in hydraulics.** A) Propagating surface waves. B) "Subsonic" flow. C) "Transonic" flow. D) "Supersonic" flow.

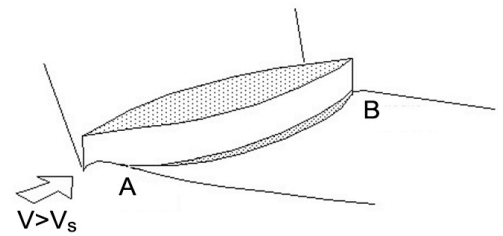
In a gas, the propagation of shockwaves produces a sharp variation of gasodynamic parameters over a distance equivalent to the mean free path: pressure, density, as well as a reduction of speed, and a change of direction, so the later becomes tangent to the wall.

Behind frontal shockwaves, the fluid undergoes a reacceleration following a Prandtl-Meyer expansion fan pattern. A second wave system might appear when the acceleration is too high, and also due to the fact that the direction of fluid's speed does not match ambient air's. Consequently, two new oblique shockwaves are formed. This system modifies the pressure distribution around the airfoil; therefore one should add wave drag to frictional drag. Wave drag increases very rapidly when the number of Mach increases. Shockwaves materialize this energy dissipation.

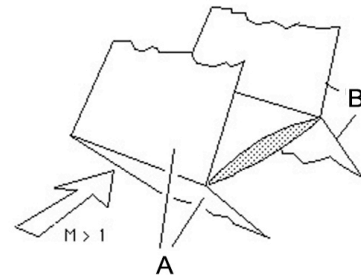
In *hydraulic analogy*, the water level will simulate density and pressure increases. Behind the front wave, the water level rises abruptly, and immediately behind, water is accelerated along the hull to a speed higher than the ambient flow. At the same time the water level drops below the plane of flotation. Hence, two stern waves make the emerging flow compatible with the ambient environment. Apart the turbulence resulting from friction, one can say that those two waves bring the water level back to where it was before the ship penetrated in the fluid.

Although water is far more viscous than air, all sailors know that when bow and stern wave are fully developed, a lot more power is necessary in order to maintain the same speed. This is due to the modification of the pressure field along the hull.

If one resolves the characteristic system of Navier-Stokes equations relative to a supersonic flow around a lenticular airfoil, one would obtain what is seen on Fig. 8, which is extracted from Bertrand Lebrun's thesis I directed, as well as from publications in peer reviewed journals, and communications during international MHD symposiums which we have taken part to.<sup>10,11,12,13,14,15</sup>

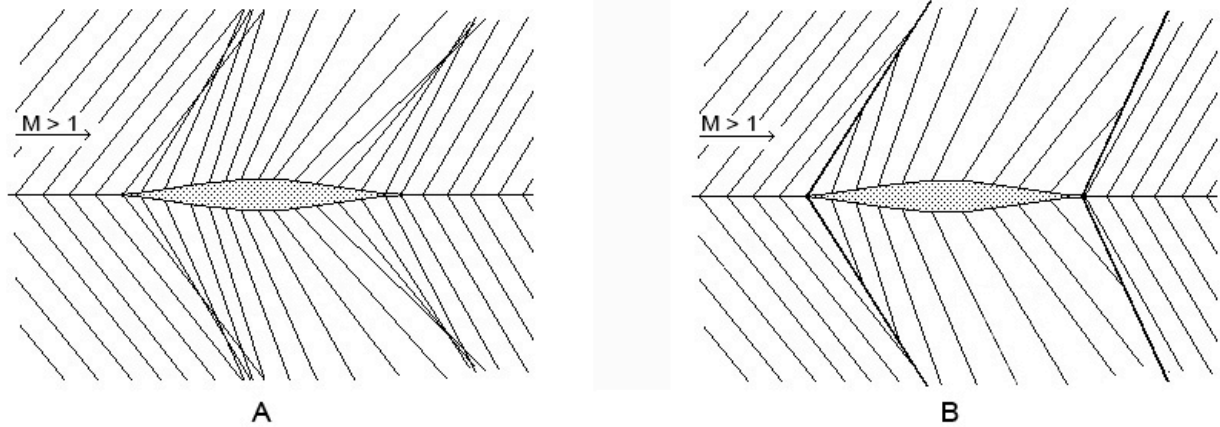


**Figure 6. Liquid around hull.** A) Bow wave. B) Stern wave.



**Figure 7. Shockwaves around lenticular airfoil at supersonic speed.** A) Front shockwave. B) "Stern" shockwave.

Shockwaves originate where pressure disturbances, materialized by Mach waves, accumulate. Taking into account the presence of Mach waves (that can be calculated in such way that those break the speed allowing for it to



**Figure 8.** Two dimensional drawing of crossing characteristics for a supersonic flow around a lenticular airfoil. A) Mach waves converge in front and back, and diverge in expansion fan. B) Front and stern waves illustrated where Mach waves cross.

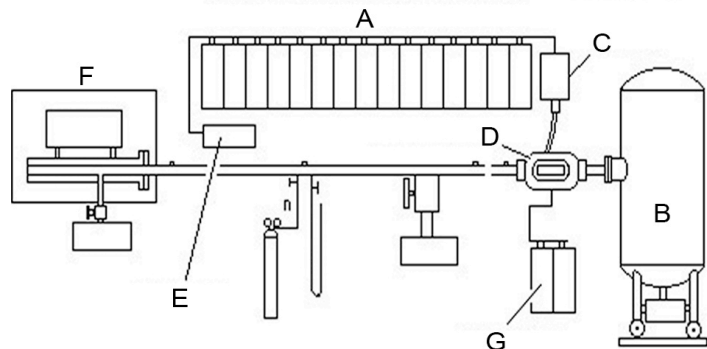
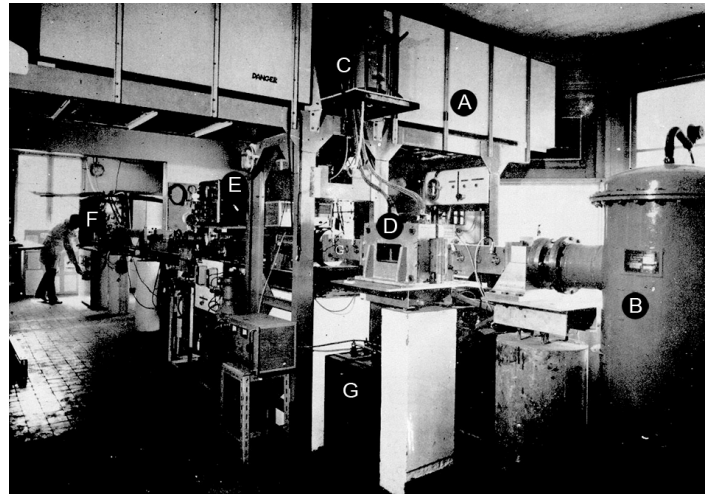
become tangent to the wall, upstream; and then take the general direction of the flow, downstream), one can establish a complete tables of shockwave characteristics. In between two waves (front and stern), those characteristics lay down in an expansion fan pattern, indicating gas acceleration in this section.

Using Lorentz forces, it is possible to accelerate or slow down a fluid flowing at supersonic speed in a constant section Faraday nozzle. In doing so, one slows down or accelerates Mach waves. Back to 1965, I was carrying out supersonic flow MHD experiments on hot argon in shock tubes. The parameters for the MHD generator mode were the following:

Flow burst duration:  $50 \times 10^{-6}$  s  
 $P = 1$  bar  
 $V = 2,750$  m/s  
 $B = 2$  T  
 $\sigma = 3,000$  S/m

Figure 9 shows the setup. Since the squall (burst of gas) was only fifty microseconds long, the magnetic field was generated by the discharge of capacitors bank located on the top, and driven by an ignitron. We set the timing of the gas burst in such way that the squall flowed in the MHD channel when the magnetic field was in a quasi-stationary state.

We used a Faraday type MHD nozzle made of Plexiglas, and the electrodes were made of red copper. All of this was not affected by the gas burst temperature (10,000 K) thanks to the very short duration of the experiments that kept the thermal stresses in the materials at low levels.

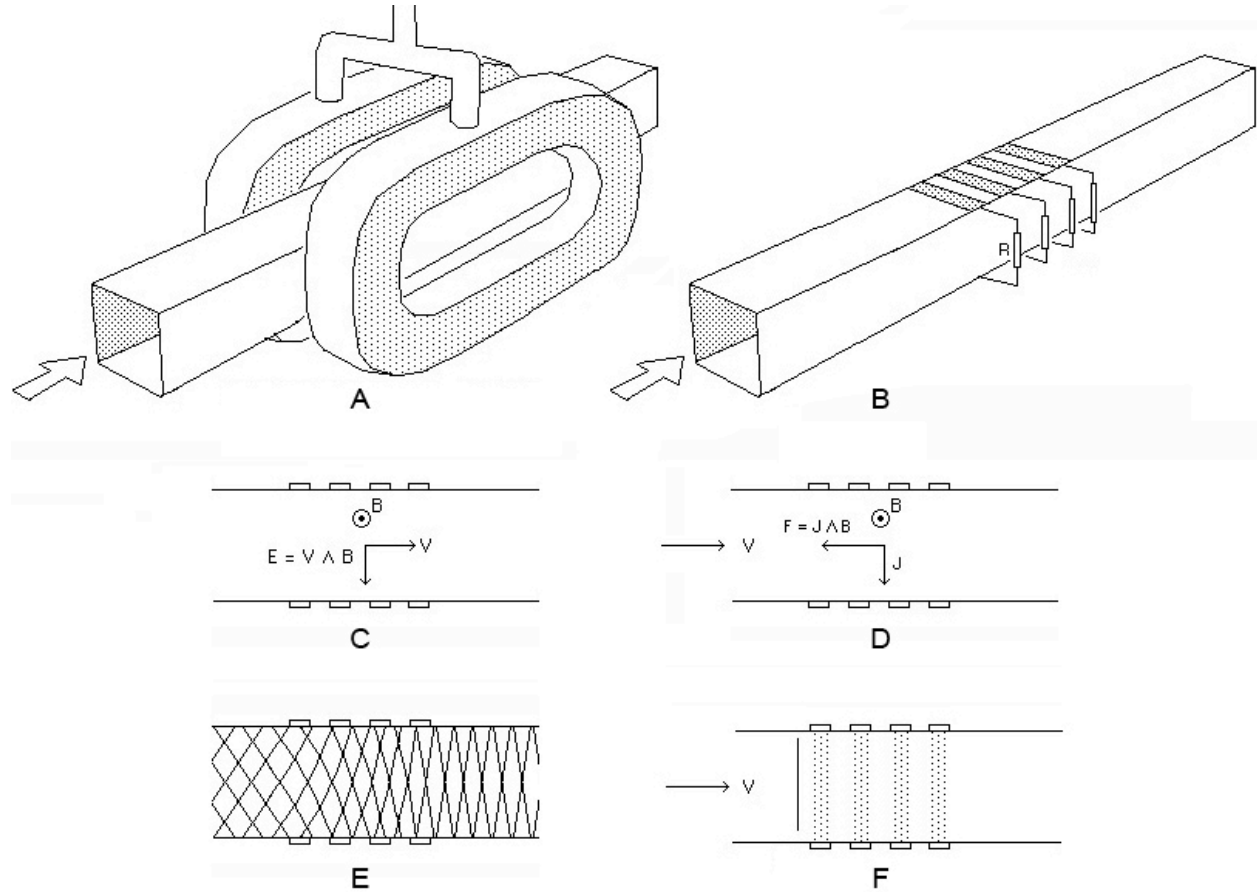


**Figure 9.** The TC8 setup at the Marseille Institute of Fluid Mechanics, France (1965). A) Capacitors bank. B) Vacuum "dumb pot" C) Ignitron. D) Electromagnet and MHD channel. E) 5kV capacitor charger. F) Combustion chamber. G) Generator for converter's electrodes.

Back then, those experiments were part of a project in view of producing electricity using MHD converters, and this apparatus was amazingly simple and cheap, as opposed to the numerous installations in use, that used exotic and expensive materials able to withstand intense thermal stresses. We were able to obtain pulses in the range of several megawatts peak, from a generator not larger than a beer can.

The reason why we are mentioning those experiments from the 60's is because they were the starting point of all the research exposed in the present report. When the MHD converter was used as a power generator, the strong current  $J$  flowing transversally, combined to the magnetic field  $B$ , was slowing down the gas flow.

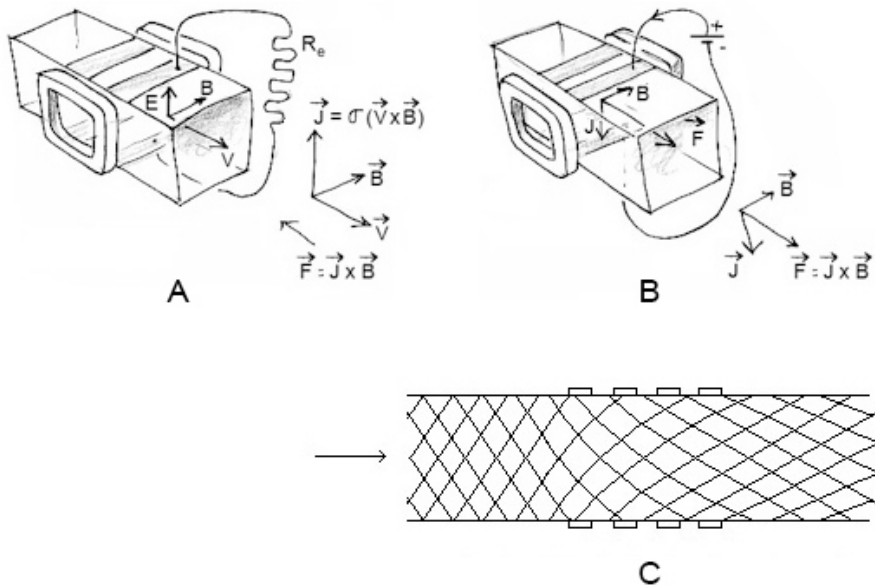
Considering the strong interactions parameters that could be achieved in those experiments, the slowing down effect could be very intense. The lower the external load resistance, the higher the current was. When the electrodes were shortened the current was reaching its highest value, and in that case the intense slowing effect was creating a clearly visible straight shockwave, with the associated density step, measured through laser interferometry, as shown in Fig 10.



**Figure 10. Faraday MHD generator.** A) Electromagnetic coils. B) Segmented electrodes and load resistors. C) Induced electromotive force. D) Lorentz force. E) Flow slowing down shown by Mach waves. F) Plane straight shockwave established at nozzle intake (1965).

Then came the following thinking: If it is possible, using a certain amount of energy, to produce a shockwave in a gas flowing inside a constant section duct, then it may be possible to effectively act upon, or even cancel out shockwave around an object immersed in a supersonic gas flow, by acting on the gas, using the suitable Lorentz force field.

Back to the 60's, we were also able to demonstrate the effectiveness of Lorentz forces, by accelerating an argon squall to the same parameters: It was possible to create an increase of speed over 5000 m/s along a distance as short as 10 cm.<sup>17</sup> In that case the direction of current was reversed, thanks to a capacitor bank, producing an electric field higher than the electromotor  $V \times B$  relative to the fluid flow. See Fig. 11.

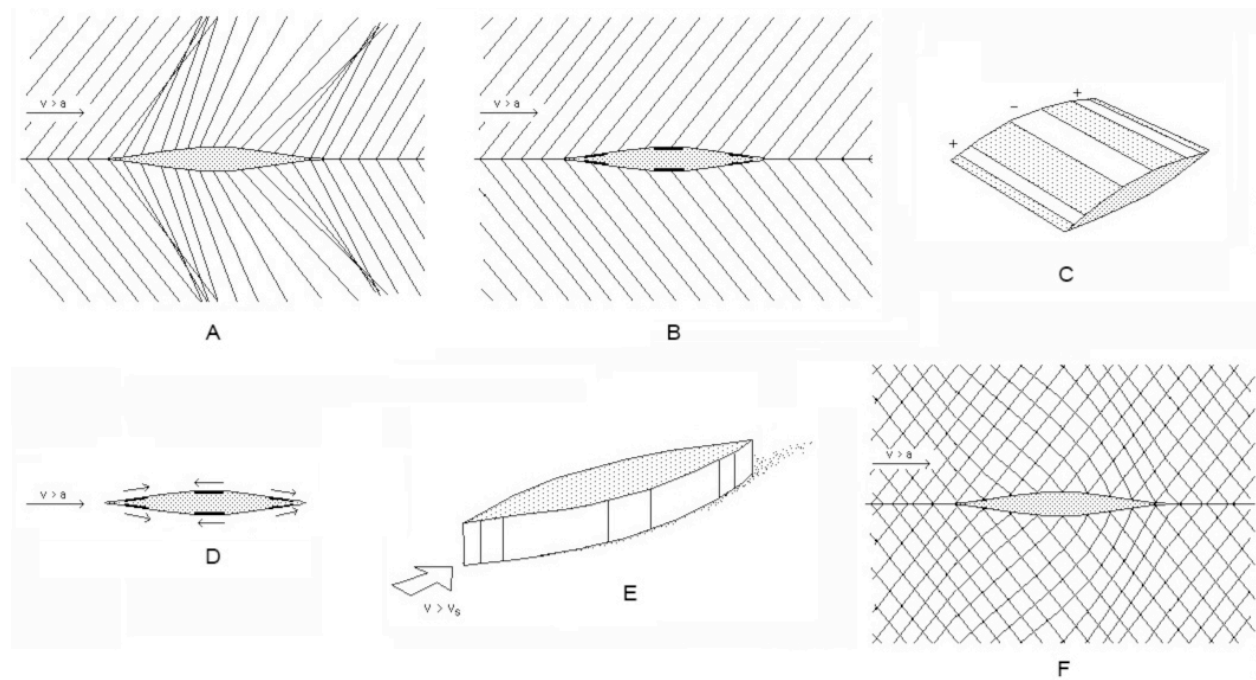


**Figure 11.** Faraday MHD converter. A) Generator mode. B) Accelerator mode. C) Diverging Mach waves in accelerator mode.

#### IV. Shock wave cancellation in gases

Everything was ready in 1976 to set up an experiment in view of cancelling the shockwave around a lenticular airfoil immersed in a conducting supersonic gaseous flow, and still working at low magnetic Reynolds number.

The first step was to carry out computer simulations.<sup>11</sup> Meanwhile, we had established a system of characteristic Navier-Stokes equations, taking into account the presence of an external field. This modeling work had never been done before. The equations were solved using finite element analysis methods.



**Figure 12.** Bidimensional shockwave cancellation around an airfoil. A) Birthplace of shockwaves. B) Desired action upon Mach waves. C) Place of electrodes. D) Lorentz forces. E) Hydraulic experiment. F) Computational 2D simulation of supersonic plasma flow control eliminating shockwaves.

The main idea was quite simple: if shockwaves are created due to the accumulation of characteristics that are crossing, then a Lorentz force field would surely maintain or rectify them, restoring parallelism.

Taking this concept back to the hydraulic world would command that one keeps constant the speed of water all the way around the ship's hull. By the same token, one should maintain the water height to a constant level all the way along the flotation line. Achieving this goal would imply that one would accelerate the fluid at the bow, and at the stern, and at the same time stop it from over-accelerating on the hull sides, as seen on Fig. 12E.

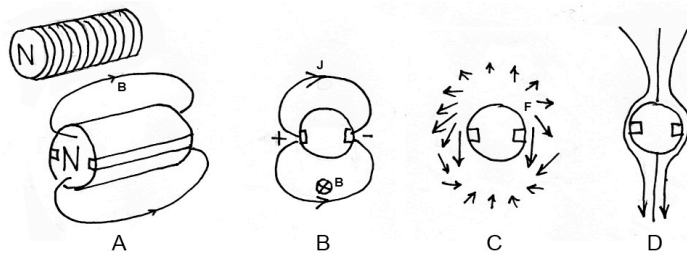
The reader will find this concept exposed in more details in a scientific comic book published in 1983.<sup>17</sup>

When a flow is slowing down, it gives up energy. This is when the MHD bypass concept emerged. Quite rapidly we could obtain significant results that were presented in many publications.<sup>9,10,11,12,13,14,15</sup>

From an energy point of view, the MHD bypass concept is extremely interesting. The overall power budget shows that the energy corresponding to the wave drag disappears. Will only remain: the energy dissipated through Joule effect, and spent to overcome friction forces.

In the early 80's, those results were the basis of an interesting experiment, using a shock tube, and technologies from the 50's-60's. Unfortunately, due to the lack support from the French government, this experiment could not be carried out.

MHD is a very rich field. From the experiment carried out on a cylindrical model subjected to an external magnetic field shown in Fig. 1-3, one could imagine an MHD aircraft of a new kind like the one depicted in Fig. 13,



**Figure 13. Cylindrical MHD aerodyne.** A) Magnetic field. B) Electric field lines and current density. C) Lorentz forces field. D) Airflow.

creating its own magnetic field and ionizing the ambient air. This craft would be able to sustain itself and move.

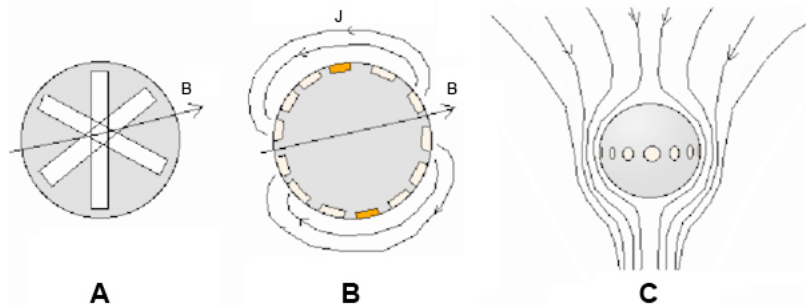
From this geometry, we evolved towards others models that could be spherical, or spheroidal. A spherical MHD craft would be fitted with a ring of electrodes. Inside, a system of three solenoids would be mounted 120 degrees apart, and would be powered by AC current of the right phasing allowing for the creation of a rotating dipole, as shown in Fig. 14A. If at all time one pair of diametrically opposed electrodes is energized (Fig. 14B), then one obtains the same force field as in Fig. 13C.

If the revolution period of the couple 'rotating magnetic field + power on a pair of diametrically opposed electrodes' is low compared to the fluid's transit time around the object, then this fluid will behave as if it was subjected to a constant axisymmetrical forces field.

This apparatus can also be tested in acidic water. A ring of electrodes is located on the periphery of a tennis-table ball. Inside the ball, the three AC solenoids are replaced by a rotating permanent magnet rigidly connected to a set of slip rings sequentially powers in a pair of diametrically opposed electrodes.

If we could have been in a position of completing our research program on shockwave cancellation around a lenticular airfoil, we would have achieved a milestone in the sense that the detached frontal wave could have been cancelled in a supersonic gaseous flow (unlike the stern wave).

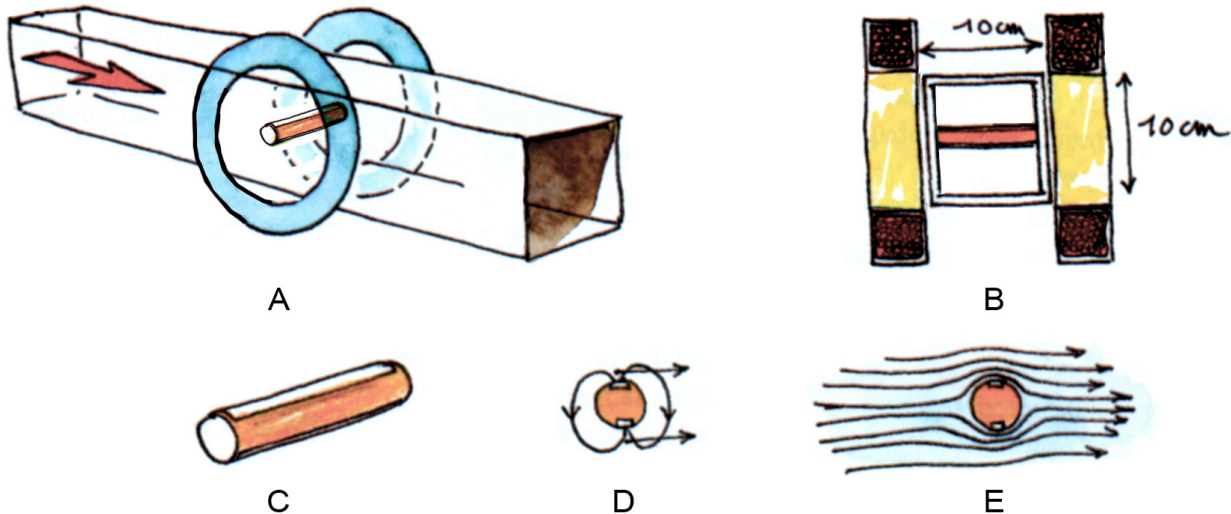
One can see how the force field acts upon the upstream fluid and prevents the establishment of a detached shockwave on the front part of the craft. Far ahead of the craft, away from any contact, Lorentz forces progressively slow down the fluid, push the molecules asides, and accelerate them around the profile, whereas downstream those forces will reattach the fluid.



**Figure 14. Spheroidal MHD aerodyne.** A) Top view. Three solenoids 120° apart with AC currents act like a rotating dipole. B) Top view. Two diametrically opposed electrodes are energized. C) Side view. Electrodes commutation quickly rotates with the magnetic field and an airflow appears.

## V. Cold gas, wake cancellation experiment

We had planned to demonstrate turbulent wake cancellation in subsonic flow with the apparatus shown in Fig. 15 (gaseous equivalent of the hydraulic experiment described in Fig. 1-3). We would have used cold gas, equivalent to a high altitude subsonic flow, and we would have introduced an obstacle perpendicular to the flow. A set of external electromagnets would have generated a continuous magnetic field of several thousand Gauss, in line with the cylinder's axis.



**Figure 15.** Turbulent wave cancellation experiment in cold subsonic airflow around a cylindrical model.

A) Variable-pressure subsonic wind tunnel with two solenoids creating an homogeneous magnetic field around the cylindrical model. B) Cut view of the apparatus. C) Cylindrical model with two lengthwise electrodes 180° apart. D) Electric discharges and Lorentz forces. E) Airflow with laminar wake.

Experiment parameters:

Flow speed: 60 m/s  
 Static pressure:  $60 \times 10^{-3}$  bar  
 Microwave frequency: 2.45 GHz  
 Microwave power (crest value during  $10^{-6}$  s): 750 kW pulsed in 500 Hz  
 Magnetic field (static): 0.3 T  
 Magnetic Reynolds number  $< 1$

Diametrically opposed electrodes would be mounted along the main axis of a hollow cylinder made of insulating material. A simple microphone located on the wall would record the turbulence reduction. The next step was to make the air slightly conducting.

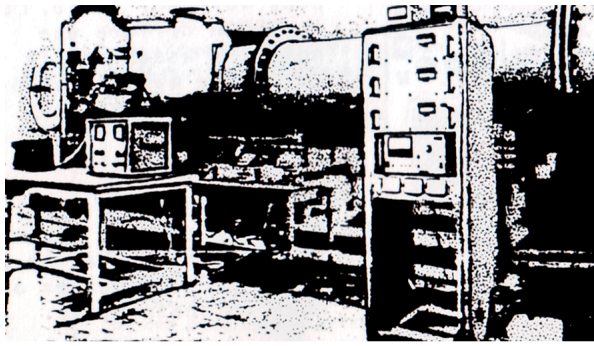
This experiment was tried in 1980 at CERT<sup>§</sup> (under the supervision of the engineer Bernard Zappoli, phd in fluid mechanics, in an experiment setup shown on Fig. 16. This work was subsequent to a research contract granted by GEPAN,<sup>\*\*</sup> a division of CNES,<sup>††</sup> and was following a project report I had submitted to CNES in 1979,<sup>18</sup> where I was recommending the use of a pulsed microwave source transmitting at 2.45 GHz (best frequency to ionize the air at atmospheric pressure).

But the project managers in charge of this experiment did not feel appropriate to ask for my help, and they made one mistake: transmitting the microwaves through a Teflon window located next to the wall.

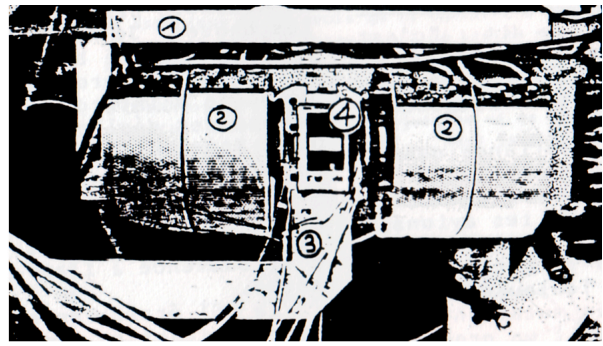
<sup>§</sup> Centre d'Etudes et de Recherches Techniques (tr. *Technical studies and research center*, the aerospace French laboratory, Toulouse, France).

<sup>\*\*</sup> Groupe d'Etude des Phénomènes Aérospatiaux Non-identifiés (tr. *Group for study on unidentified aerospace phenomena*) managed at that time by engineer Alain Esterle.

<sup>††</sup> Centre National d'Etudes Spatiales, the French government space agency.



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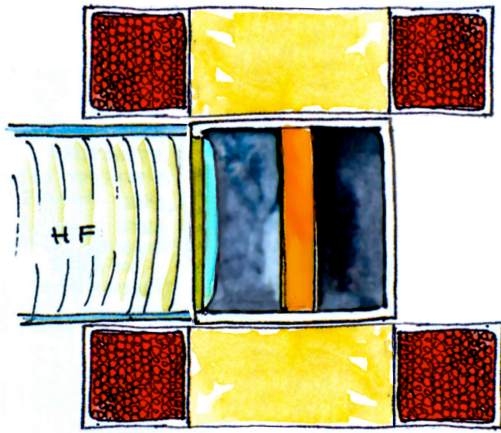


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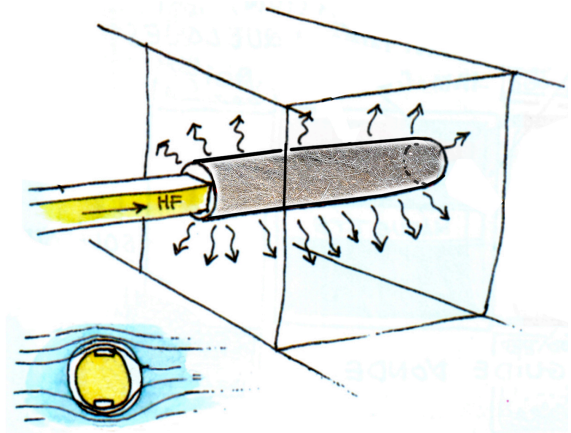
**Figure 16.** CNES experiment (1980). A) Subsonic wind tunnel. B) The heart of the experiment. 1: frame. 2: electromagnetic coils. 3: microwave guide with 90° elbow. 4: nozzle section with cylindrical model.

If Teflon is indeed virtually transparent at microwave frequencies, air isn't. A thin plasma layer formed at the contact of the window located next to the wall, and prevented any ionization around the model, as shown on Fig. 17. CNES' team was unable to fix this problem out, just trying to increase power of microwaves, which only led to unstable arc regimes. They eventually cancelled the whole research project.

I heard about these issues several years later, and would personally have suggested the configuration depicted in Fig. 18 as a solution to this problem.



**Figure 17.** Cut view of CNES' problem (1980). Waveguide on left. HF goes through the Teflon window (green) but ionization stays confined inside a thin plasma layer next to wall and does not embed the model.

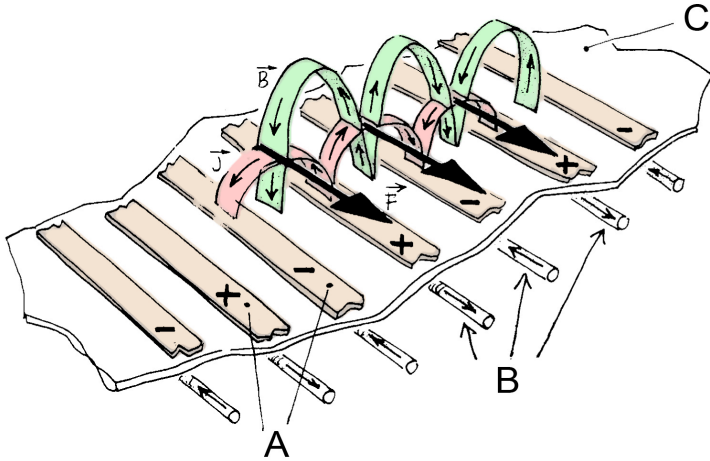


**Figure 18.** How things should have been done. A smaller waveguide brings HF directly inside the model made of Teflon, filled with scattering steel wool. The cylinder is embedded in a thin plasma layer around its whole hull.

Instead of bringing the microwave beam through a Teflon window, it would be advisable to inject the HF energy directly inside the body of a hollow model, made of Teflon. Inside the later, some steel wool will insure optimum radiation scattering, hence homogenous ionization in the vicinity of the whole model's surface, where it is precisely needed.

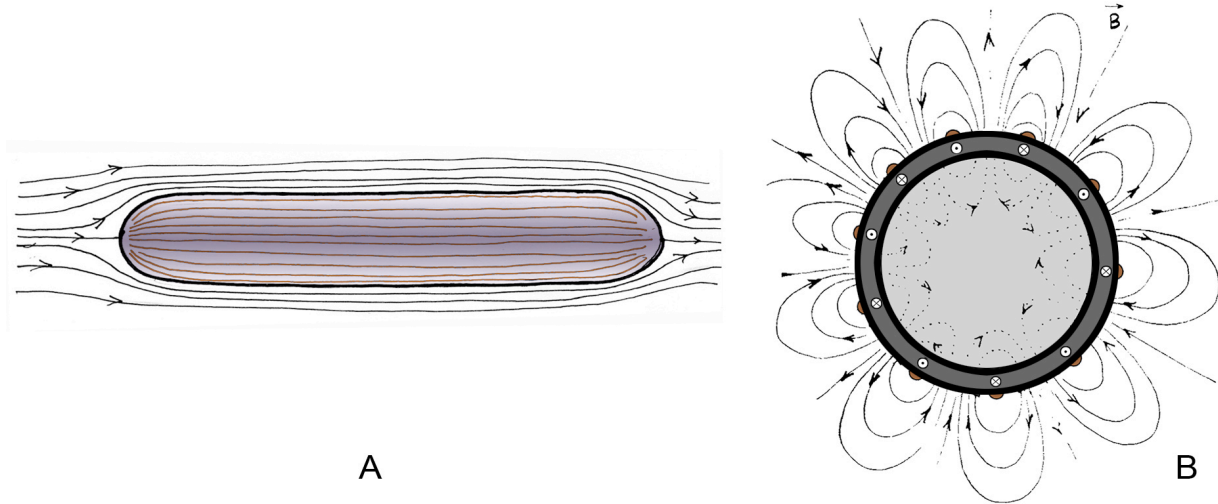
## VI. Wall MHD converter

The concept of the wall converter applied to MHD is quite old, and finds its origins in the early experiments made on MHD applied to maritime propulsion.<sup>19,20</sup> The principle is to set many electrodes, alternating polarities while magnetic field direction is also reversed between each consecutive pair of electrodes. Used as a thruster, the cross products  $J \times B$  then give parallel Lorentz forces of the same direction everywhere on the device. See Fig. 19.



**Figure 19. Wall converter layout.** A) Electrodes with alternated polarities. B) Electric wires or hollow superconductor pipes for cryogenic coolant, with alternated current directions. C) Wall made of insulating material.

This concept was reused in 1975 for hydraulic experiments. This geometry offers several advantages. The MHD interaction is concentrated over a relatively thin layer, but is spread out over a large area, allowing for interaction on the whole wetted area (that is, the area in contact with the fluid). The volume to be magnetized is kept down, hence the energy required, which is proportional. The short distance between electrodes allows working at lower voltages. In a gaseous environment, this layout enables local acceleration or deceleration of the fluid, according to the MHD bypass principle, and will control the flow at all points in such way that shockwaves are cancelled out (no wave drag) and as a consequence, turbulence will be eliminated. As long as those two issues are addressed and dealt with, then it would be desirable to give to the cylindrical aerodyne an elongated shape as shown in Fig. 20.



**Figure 20. Cylindrical MHD aerodyne with wall accelerator.** A) Side view with airflow. B) Axial cut view of a simplified, 10 electrodes cylinder: magnetic pattern.

Research work based on this concept should be undertaken both theoretically and experimentally.

One should note that a scientific team from the Rensselaer Polytechnic Institute, lead by Leik N. Myrabo is carrying out in depth researches on MHD aircrafts called 'Lightcrafts'. Those disk shaped aircrafts have their bodies fitted with electrodes and are allegedly aimed to intra-atmospheric flight, for civil and military applications.<sup>21,22,23,24,25</sup>

However, if their thematic appears to be the same as ours, the technical solutions used on the MHD *Lightcraft* are very different from what we are suggesting. Leik Myrabo uses MHD accelerators in 'snow plow' mode where highly localized electric discharges slide between electrodes, literally pushing the air on their way. Due to the simple magnetic geometry developed in his project, the pairs of electrodes are confined to the periphery of the disk, and air

ionization can only be reached in front of half of them. To the contrary, we suggest a non-thermal ionization without thermal blockage, a glow-discharge plasma covering the whole area of the disk (in the same token, electrodes with alternate polarity according to the regular inversion of the magnetic field, make the use of all available pairs as shown of Fig. 19-20).

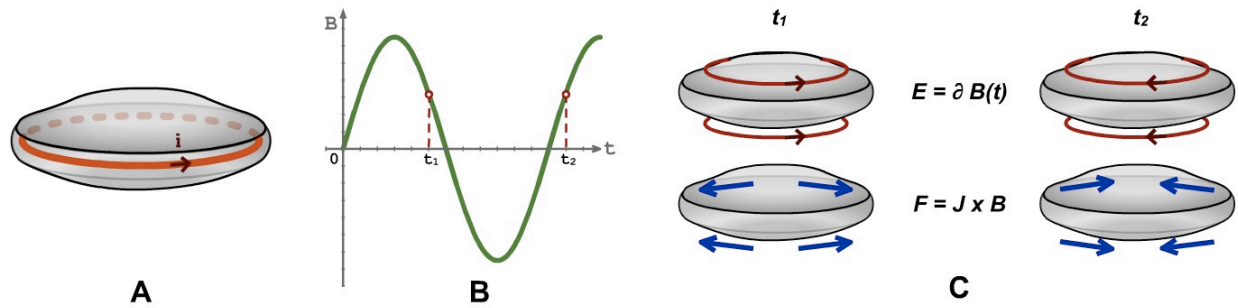
Beside, Leik Myrabo has to fight against the intense thermal flux subsequent to hypersonic speeds and affecting a blunt body, by detaching the frontal shockwave upstream through the use of a microwave generated plasma air spike, of which slipstream is accelerated by peripheral accelerators. This is forgetting that MHD can prevent the formation of shockwaves. But one needs to control the flow in all points of the wall by extending the MHD interaction to the whole body as well as using strong magnetic fields (10 teslas or above). However the magnetic fields used on the *Lightcraft* is limited to 2 teslas, despite the fact that the solution proposed in this project could use much higher values. We believe that this choice is dictated by the intention of limiting the Hall parameter in the plasma, since the geometry of the *Lightcraft* accelerator is incompatible with a strong Hall effect. Besides, there is no mention of the problematic electrothermal instability occurring in weakly ionized gases, and well known to be almost not solvable, despite the fact that we have experimentally demonstrated that it could be kept under control.<sup>26,27,28</sup>

## VII. Induction MHD aerodynes

In 1975, I have suggested the design of a disk-shaped MHD aerodyne with electrodes, using spiral currents with high Hall effect.<sup>29</sup> The year after I imagined a better solution: a disk-shaped but electrodeless MHD aerodyne, using induction, that is to say a variable magnetic field.<sup>30</sup> The working principle of this induction MHD aerodyne is described thereafter.

### A. Principle

Let's consider an alternating dipolar magnetic field, generated by an electromagnetic coil placed inside a thick disk made of an insulating material. Maxwell laws dictate that this magnetic field will generate an induced electric field. If the surrounding gas conducts the electricity well enough, eddy currents will appear in it, and will combine with the field  $B(t)$  to produce radial Lorentz forces  $J \times B$  alternatively centrifugal then centripetal, as indicated in Fig. 21. But this would only shake the gas around the disk with no propulsion effect, the integral of momentum being equal to zero over a period.

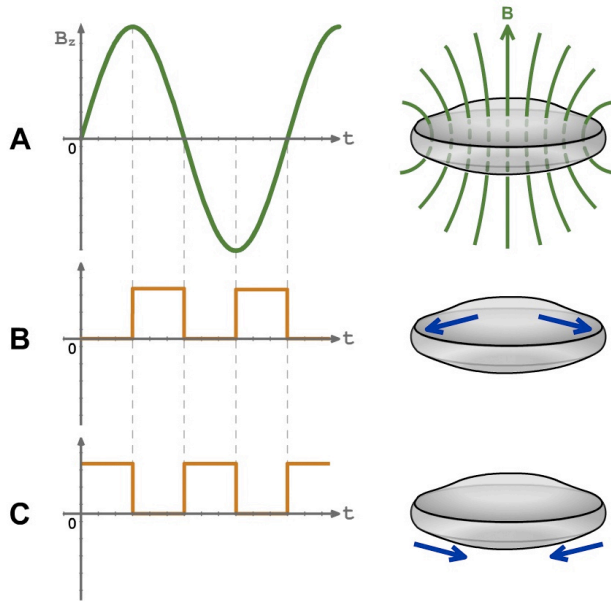


**Figure 21.** Induction effects in an electrically conductive fluid. A) Solenoid within a disk-shaped insulator enclosure. B) Evolution of magnetic field through time for an AC-powered solenoid. C) Induced electric field and eddy currents in the fluid; resulting radial Lorentz forces.  $t_1$ : Centrifugal forces.  $t_2$ : Centripetal forces.

### B. Wall ionization control

Assuming that one could alternatively modulate the air's electrical conductivity locally from one side of this disk to another, an adequate propulsive force field can be obtained as explained in Fig. 22.

This local ionization can be achieved through different manners. For example thanks to microwaves, or by using miniaturized wall HV ionizers covering the hull. Those would have the shape of a wolf trap. An axial cathode protudes from the bottom of a small conical cavity. A ring anode completes the whole device, seen in Fig. 23.



**Figure 22. Suitable force field by local modulation of air ionization.** A) Varying magnetic field. B) Top ionization current and centrifugal forces. C) Bottom ionization current and centripetal forces.

possibly short lived negative ions, through fugitive attachment of the electrons to the surrounding atoms. If the number of cycles of the alternating electrical conductivity between upper and lower surfaces of the disk is low with respect to the gas transit time around the object, then the fluid will behave as if it was subjected to an axisymmetrical force field, and one could imagine using this phenomenon as the basis for the propulsion of a disk-shaped MHD aerodyne.

### C. Plasma confinement and hull shape

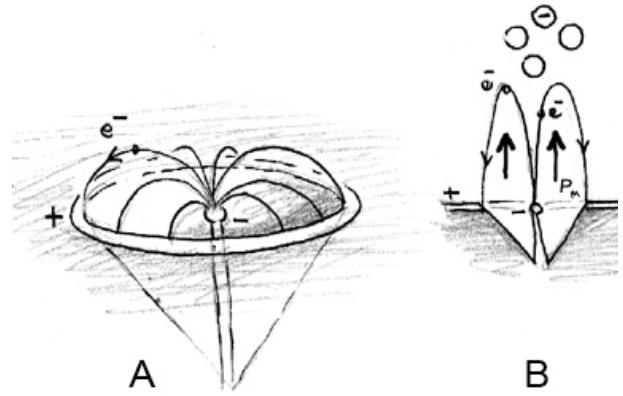
However, in 1976, during low air density experiments made to test those devices, we faced a problem: the blowing of the plasma far from the wall, subsequent to magnetic pressure gradient effect, as described in Fig. 24.

The magnetic pressure is given by:

$$P_m = \frac{B^2}{2\mu_0} \quad (2)$$

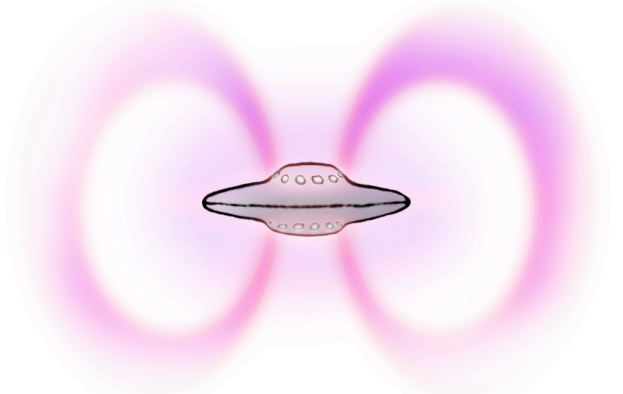
Those experiments were performed in view of testing another configuration of disk-shaped aerodyne using electrodes and working in strong Hall effect regime with circular currents. To keep the present report to acceptable size, we would suggest referring to related publications.<sup>29,34</sup> But the same phenomenon would also disturb the behavior of an induction-based aerodyne. The solution consists in reversing the magnetic field gradient, not by using only one coil, but three, as shown in Fig. 25.

Confinement effectiveness was recently demonstrated, after having drafted in 1976 through low density air experiments.<sup>28</sup> Figure 26 depicts an electrode-based system, but this confinement effect also applies for electrodeless devices. The effect of the pressure gradient, measured in Fig. 27B, literally squeezes the plasma against the wall. This wall is drawn perpendicularly to the field lines, and the craft hull, initially designed to be convex, becomes necessarily concave, in order to confine the plasma under the zone of strongest magnetic field, as shown in Fig. 25-26.

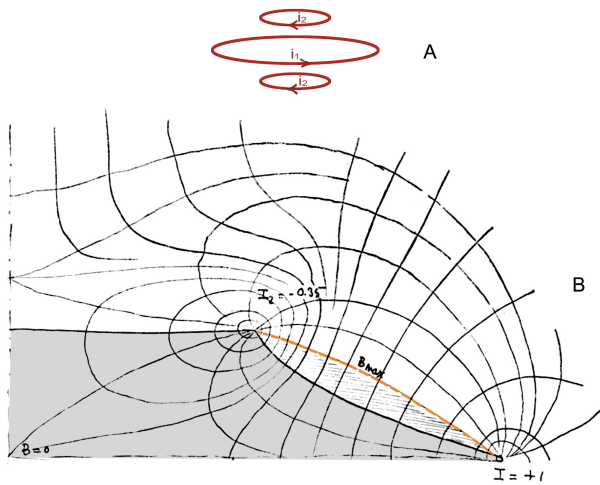


**Figure 23. Wall ionizer.** A) Umbrella-shaped electric discharge between spike cathode and ring anode. B) Cut view.

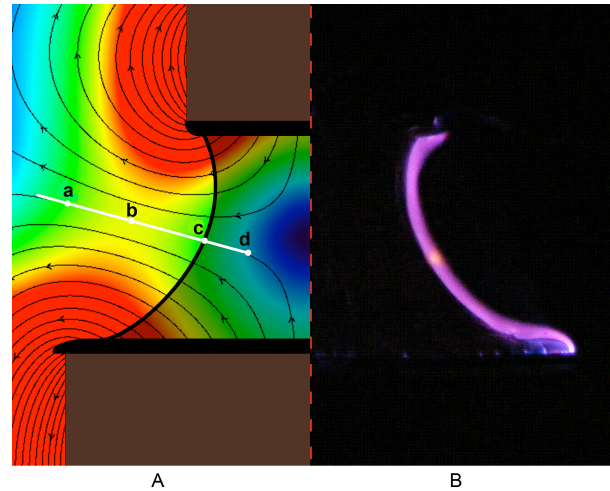
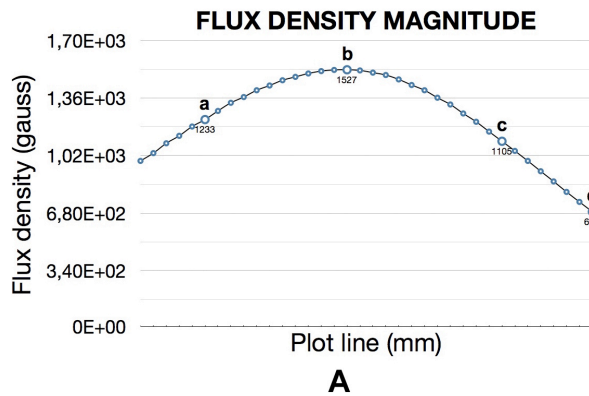
When a high voltage discharge is generated in between two electrodes, an umbrella-shaped current flow appears. The magnetic pressure under this plasma umbrella will tend to 'expel' this current domain outwards. This miniature apparatus bears some similarities with the Dense Plasma Focus experiments.<sup>31,32</sup> MHD instabilities enhance the capacity of the system to create free electrons, and



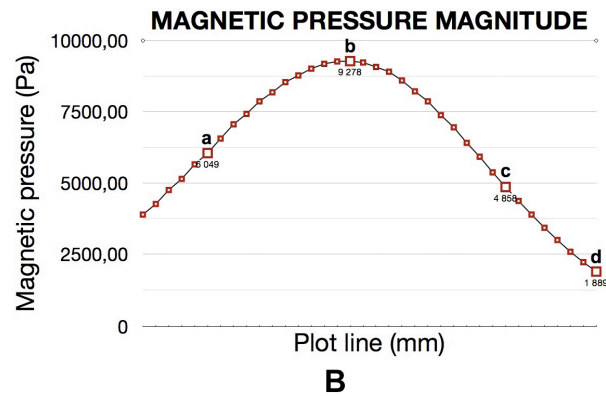
**Figure 24. Electric discharge blown by magnetic pressure, maximum near wall.**



**Figure 25. Plasma confinement system by magnetic gradient inversion.** A) Currents in three solenoids. B) Quarter cut view of the MHD aerodyne. Max B-field is approximately a truncated conical surface linking the solenoids.

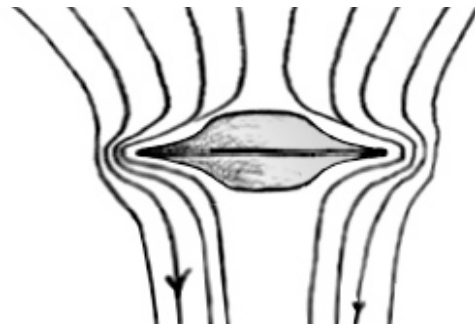


**Figure 26. Wall confinement experiment.** A) Magnetic field lines and magnetic pressure gradient. B) Actual picture of plasma confined near the wall of a model fitted with two bucking permanent magnets in a low air density experiment.



**Figure 27. Evolution of magnetic field near wall (plotted from Fig. 25).** A) Magnetic flux density. B) Corresponding magnetic pressure. The peak value in 'b' and strong magnetic gradient confines the plasma to the wall located in 'c' (approximately 50 % difference between those pressures)

Consequently, the aerodyne takes a counterintuitive shape, with respect to traditional fluid mechanics, as shown in Fig. 28. Not only its edge implies extremely abrupt flow line changes, but also the top and bottom walls present concavities. To this, one may add that Lorentz forces can be extremely powerful, and vastly superior to inertia forces in the gas. A quick calculation can demonstrate this point, by showing which value of accelerations one can apply to a mass of air with rather modest density of current, and magnetic field, bearing in mind that  $J \times B$  is a force of volume, expressed in newtons per cubic meter.



**Figure 28. Flow and hull shape of a disk-shaped MHD aerodyne.** Strong radial  $J \times B$  forces applied in a thin layer of plasma confined next to wall suck the surrounding air by Coandă effect. A lower air pressure appears above the disk and an over-pressure underneath, generating lift.

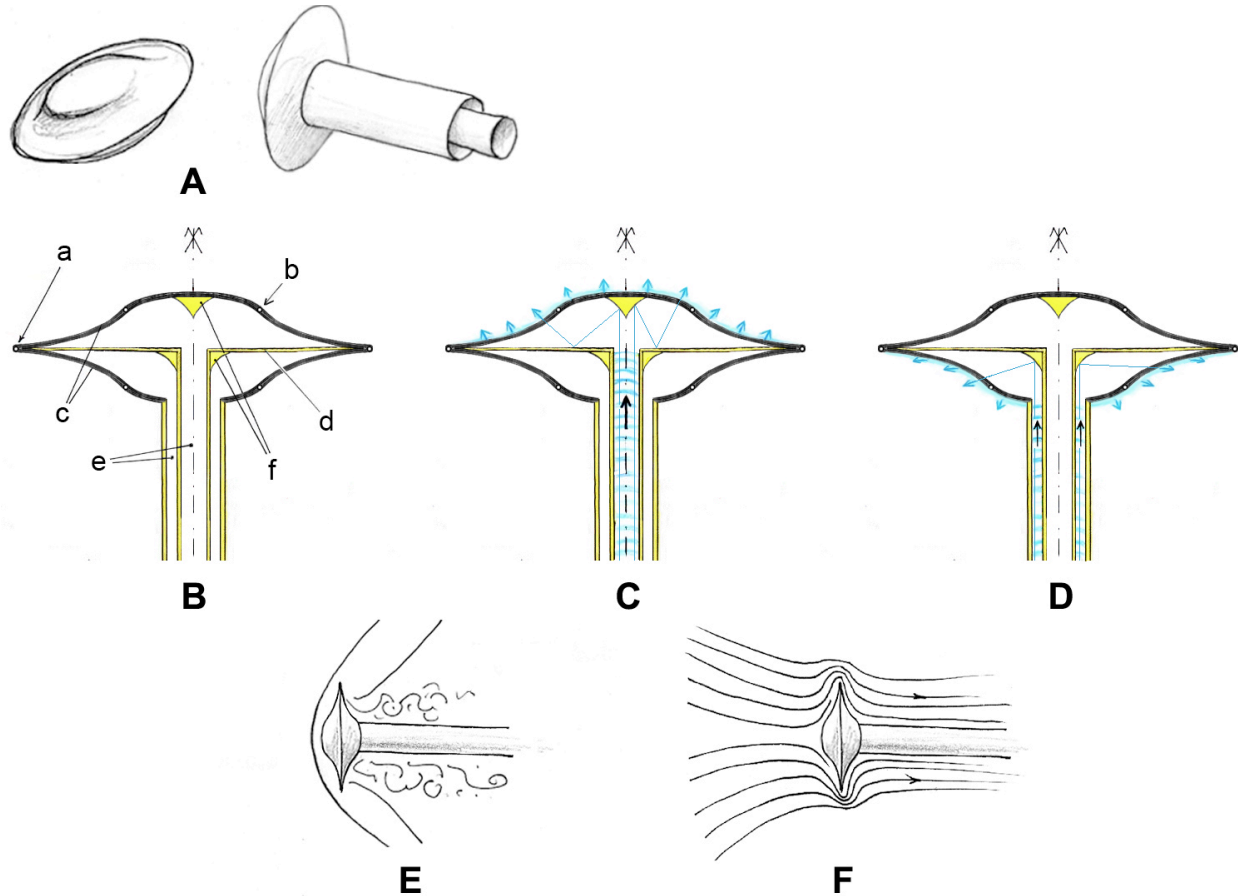
#### D. Induction MHD experiment in cold gas

An alternative solution to locally ionize air around a disk-shaped MHD aerodyne would consist of generating a plasma by using a high frequency HV generator, and by alternatively energizing the top and bottom part of the hull. But one would most certainly create HF discharges, as seen on the picture shown in Fig. 29, corresponding to low air density experiments.

A better solution depicted in Fig. 30, recently published,<sup>34</sup> would consist in a supersonic MHD flow control experiment, where two microwave beams would act (each of them being fed through coaxial circular-waveguides, and reflected by metallic mirrors and brass plates that would ionize the surrounding 1-bar air through Teflon walls).



**Figure 29.** Picture of HF discharges. The sharp edge of this disk-shaped model made of an electrically conducting material makes radial HF discharges looking like “truncated light rays”.



**Figure 30.** Supersonic MHD flow control experiment in wind tunnel, combining magnetic confinement, non-thermal microwave ionization, and induction acceleration around a disk-shaped model. A) Shape of the model and its incoming coaxial waveguides. B) Cut view. a: equatorial solenoid, b: confinement solenoid, c: Teflon walls, d: brass plate, e: coaxial waveguides. f: silver-plated brass mirrors. C) Air ionization on top by 2.45 GHz microwaves fed through inner waveguide. D) Air ionization below the model by microwaves fed through outer waveguide. E) Airflow around passive model: detached front shockwave and turbulent wake. F) Expected flow control with induction coils powered in phase with high frequency sequential ionization of air.

## VIII. MHD bypass applied to hypersonic space planes

A conventional turbojet can be viewed as a machine operating a mechanical bypass system, with an energy transfer from downstream to upstream, transferring this energy through a shaft carrying compressor blades. In fact, some energy is taken away from the combustion chambers located downstream by blades assemblies, and used to rotate the upstream compressor.

In what follows, one part of the incident kinetic energy of a fluid sticking an object at hypersonic speed is converted into electric energy through the use of wall generators; the recovered electrical energy is reused to accelerate and add an extra speed to the ejection gas flowing out from the nozzle. Here is a general drawing of a hypersonic plane that could represent the aircraft operated by the USA since the 90's, as a replacement for the trisonic Lockheed SR-71 'Blackbird' spy plane, as well as the concept of the Russian Ayaks hypersonic plane.

Figure 31 is one of the rare pictures of the latter in a hypersonic wind tunnel, showing the location of its engines, on the bottom side, the semi-guided nozzle, and its completely flat top. The idea is quite simple, and was unveiled by a Russian designer in 1996.<sup>35</sup> The aircraft has a significantly accentuated fleche, a truncated leading edge. Its top part is parallel to the main airflow. It takes off thanks to conventional turbojets, located on the bottom part of the body. Ejection nozzles have a constant section, i.e. no variable system that usually adapts the flow to different altitudes.

The semi-guided nozzle has an important expansion rate given the fact that the aircraft operates at high altitude, between 130,000 and 250,000 ft. (approximately 40 and 80 km). During takeoff, this highly raised 'ducktail' makes the jet very unstable, and while on the ground, the aircraft may generate infrasound. The supersonic flow behind the nozzle presents a succession of small and large sections peculiar to any over-expanded nozzle in supersonic mode. See Fig. 32.

During the climb, and until operational altitude is reached, the contrail looks like a dotted line, as shown in Fig. 33. When the reached altitude offers the best air electrical conductivity, the aircraft changes its geometric configuration, depicted in Fig. 34. An MHD wall converter is located on the top side, operating in generator mode, hence slowing the fluid down, and rectifying Mach waves. It is then possible to use the top inlet as the main air

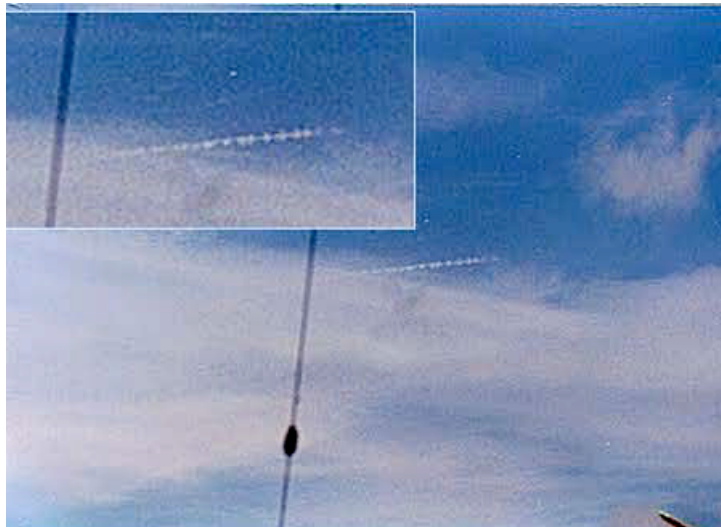


Figure 33. Alleged contrail of "Aurora" spy plane.

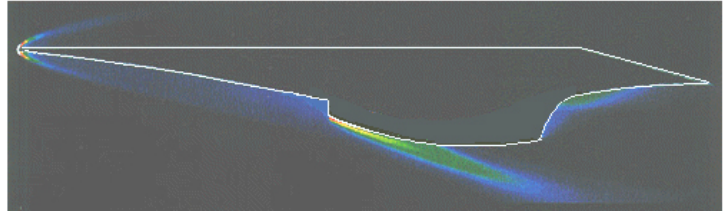


Figure 31. Russian Ayaks in supersonic wind tunnel test. *Waverider* profile with sharp leading edges, semi-guided "ducktail" nozzle and flat top.

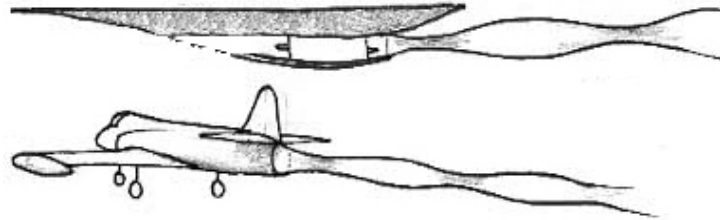
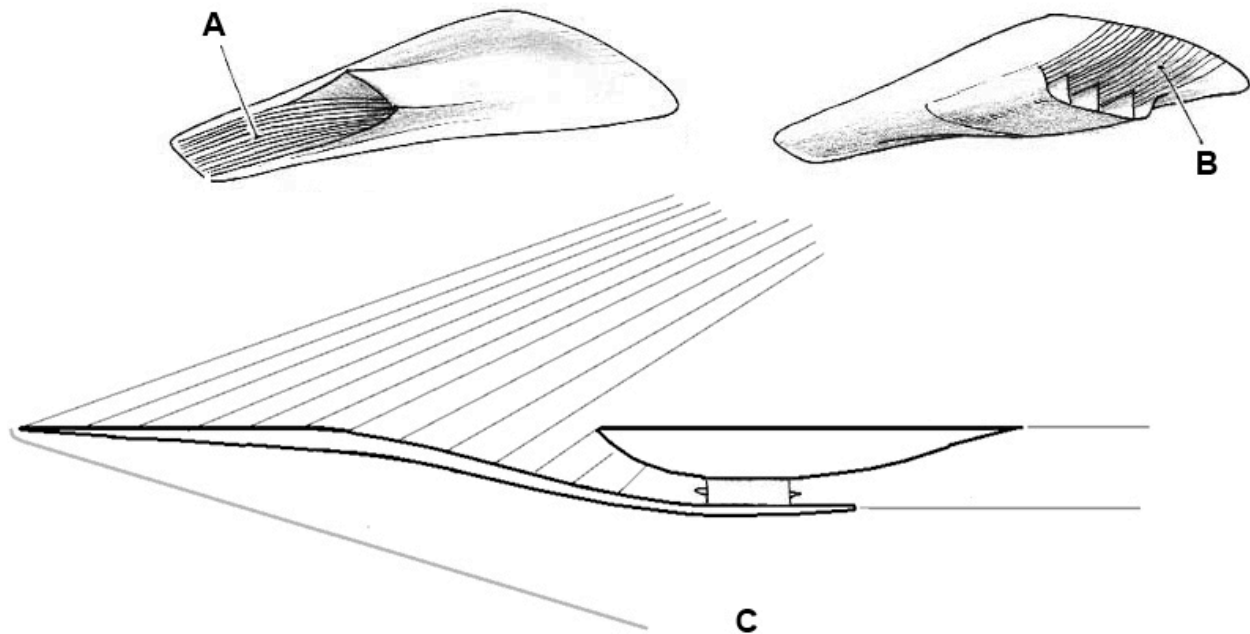


Figure 32. Examples of over-depressed jet contrails due to over-expanded nozzles at non-optimal altitude.

intake at Mach numbers and temperature low enough for the gases to feed the ramjets, hence taking over the turbojets. However, we are not excluding that the slowing process could be so effective that the gases might even be used to feed the turbojets used for takeoff. Some leaks from the engineer involved in Ayaks design,<sup>35</sup> were pointing in this direction, as well as recent declarations from NASA regarding MHD bypass hypersonic planes currently under active development.<sup>36</sup>

The temperature increase experienced by the gas is reduced, since some of the incident kinetic energy has been transformed, not in heat through a shockwave, but in electrical energy that is subsequently used to accelerate burnt gases behind the nozzle, thanks to a *ducks-arse* MHD wall accelerator.

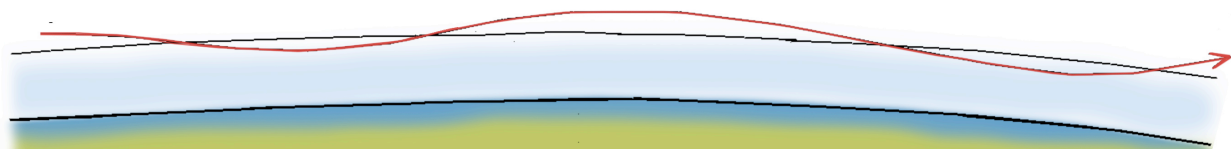
The fact that the top part of the craft is parallel to the main flow stream does not produce any shockwave in this area. However, an oblique shockwave starting from the leading edge will generate a pressure raise on the bottom part, hence a lift, according to the well-known waverider principle.



**Figure 34. Waverider with MHD wall converters.** A) MHD wall generator B) MHD wall accelerator after the engines. C) Profile cut view of the high-Mach number MHD-controlled inlet. Shockwave under leading edge. On top, air slows down along the long wall generator and Mach waves are progressively rectified with limited recompression and no shockwave until engine's intake.

In powered flight, the aircraft is embedded in plasma, which makes it a very poor observation platform. Used as a spy plane, this aircraft rebounds on the high atmosphere, and 'bounces' in ballistic flights between two propelled phases, more than several hundred kilometers apart, as illustrated in Fig. 35. During the ballistic phase, the craft is almost out of the atmosphere, much like a spacecraft, and then can carry spy work.

During its descent towards the high atmosphere, it can change of direction like a skier or a surfer. Considered under this aspect it is the *Silver Surfer*. But all problems are not solved. The craft's sharp leading edge still needs protection. To protect these leading edges, the generator works at a high Hall regime. The Hall field creates a discharge on the leading edge, a *plasma cushion* that detaches and softens the shockwave, minimizing its thermal effects.



**Figure 35. Atmospheric rebounds.**

## IX. Futuristic space launcher

In a version using a cryogenic assembly, the craft can use the oxygen from the air to burn the fuel, to start with, without having to burn onboard oxygen like a conventional rocket does. The cryogenic system gives a last push to reach the speed required for orbital injection. This system may replace conventional rockets to place payloads on orbit. Indeed it is not advisable:

- To not using the lift offered by the air, during the speed increase.
- To carry the comburant onboard when it is available outside.

Let's take a Boeing 747 for example. Clip its wings off, condemn it to carry in liquefied form all the oxygen necessary for its flight... Then what would be its payload?

When the MHD waverider reenters the atmosphere, all the wall converters are used as short generators. The air braking comes from the interaction of all the body and not an overpressure in the vicinity of the blunt part of the craft (which is possible on the blunt nose and blunt wing of the space shuttle, but not on waveriders' sharp profile). The energy is dissipated through Joule effect, by radiation, and the braking is progressive.

The work in non-equilibrium regime ( $T_e > T_g$ ) and at high Hall parameter regime renders the flow sensible to the effects of the electrothermal instability. But one can use a variant of the method cancelling this instability by magnetic pressure gradient, invented by the author.<sup>26,27,28</sup>

## X. Conclusion

This paper fills a void by giving a presentation of the various possibilities offered by magnetohydrodynamics in the field of propulsion applied to flying machines, named since our first publication *MHD aerodynes*. It also demonstrates that MHD, by locally accelerating or decelerating the flow, can prevent the birth of shockwaves at supersonic speed. After exceeding silently the sound barrier, MHD also allows control over the heat barrier, enabling atmospheric hypersonic cruise. Although the power source required to ionize the air, accelerate the plasma and sustain the whole craft was not defined in such futuristic systems, we should imply it is just a matter of time until some energy source with the adequate power-to-weight ratio is developed, perhaps with future compact controlled fusion reactors.

We then proposed a more classical aircraft using MHD bypass, where the primary source of energy to insure lift, and overcome drag, is easier to handle with today's technology: a chemical fuel, using the air available right up to the limit of high atmosphere. This craft uses wall converters, which contrary to heavy and cumbersome Faraday converters, can spread over large areas. The first set is located on the front part and works as a power generator. In doing so, it slows down the fluid with a minimum temperature rise, since an important part of the kinetic energy is converted into electricity. This system can feed either a ramjet, or a conventional turbojet, with compressed air at a temperature compatible with thermal limitations of today's engines. On the exit side, a second wall converter located behind the nozzle, on the lower side of the aircraft, accelerates the gases resulting from the combustion, giving back the energy collected in the front end. The lift is provided by the recovery of the high pressure resulting from the shockwave formed on a protective plasma cushion located on the vicinity of the leading edge, this type of flight being called the waverider technique. At high altitudes where it flies, the atmospheric pressure is low, therefore the craft does not require any particular system to ionize the air. This non-thermal ionization happens naturally thanks to the  $V \times B$  field. The low air density and the intensity of the magnetic field used in this design come along with an operation at high Hall effect. By using the Hall field, it is possible to generate an electric discharge on the sharp leading edge, that creates a protective cushion of plasma. Similar systems to those described by the author solve the Velikhov electrothermal instability.<sup>26,27,28</sup> As presented, this aircraft makes the ideal spy plane: able to cruise at Mach 12, bouncing on the high atmosphere. Given the fact that the USA have stopped operating the surveillance aircraft SR-71 in the beginning of the 90's, one question arises: does its successor exist as a project, or is it already operational under the nickname Aurora? In any case, this configuration could be the space launcher of the future, and will make all conventional cryogenic rockets obsolete. Small additional cryogenic stages will allow orbital work, whereas during the reentry phase, short-circuited wall generators will insure air braking on the whole fuselage allowing for optimum energy dissipation. There again, one part of the energy is used to maintain a protective cushion of plasma on the leading edges.

## References

- <sup>1</sup>Kantrowitz, A. R., "Flight Magnetohydrodynamics," *AVCO Research Report 51*, March 1959.
- <sup>2</sup>Jarvinen, P. O., "On the use of magnetohydrodynamics during high speed re-entry," *Avco Research Note 463*, July 1964.
- <sup>3</sup>Cahn, M. S., *and al.*, "Electroaerodynamics in supersonic flow," *AIAA Aerospace Sciences Meeting*, 6th, NY, 1968.

- <sup>4</sup>Myrabo, L. N., and Raizer, Y. P., "Laser-induced air spike for advanced transatmospheric vehicles," *Plasmadynamics and Lasers Conference*, 25th, Colorado Springs, CO, 1994.
- <sup>5</sup>Cain, T., and Boyd, D., "Electroaerodynamics and the effect of an electric discharge on cone/cylinder drag at Mach 5," *AIAA Aerospace Sciences Meeting and Exhibit*, 37th, Reno, NV, 1999.
- <sup>6</sup>Hill, G. A., "Ionized boundary layer fluid pumping system," U.S. Patent 3,095,163, filed 13 Oct. 1959.
- <sup>7</sup>Malik, M. R., Weinstein, L. M., and Hussaini, M. Y., "Ion wind drag reduction," *AIAA Aerospace Sciences Meeting*, 21st, Reno, NV, 1983.
- <sup>8</sup>Roth, J. R., Sherman, D. M., and Wilkinson, S. P., "Boundary Layer Flow Control with a One Atmosphere Uniform Glow Discharge Surface Plasma," *AIAA Aerospace Sciences Meeting and Exhibit*, 36th, Reno, NV, 1998.
- <sup>9</sup>Petit, J. P., "Is supersonic flight, without shock wave, possible?," *International Conference on MHD Electrical Power Generation*, 8th, Moscow, Russia, Proceedings Vol. 2, 1983.
- <sup>10</sup>Petit, J. P., and Lebrun, B., "Shock wave cancellation in gas by Lorentz force action", *International Conference on MHD Electrical Power Generation*, 9th, Tsukuba, Japan. Proceedings Vol. 3, 1986, pp. 1359-1368.
- <sup>11</sup>Lebrun, B., "Theoretical study of shock wave annihilation around a flat wing in hot supersonic argon flow with Lorentz forces," *Engineer-Doctor thesis*, Aix-Marseille University; & *Journal of Mechanics*, France.
- <sup>12</sup>Petit, J. P., and Lebrun, B., "Shock wave annihilation by MHD action in supersonic flow. Quasi one dimensional steady analysis and thermal blockage," *European Journal of Mechanics B/Fluids*, Vol. 8, No. 2, 1989, pp. 163-178.
- <sup>13</sup>Petit, J. P., and Lebrun, B., "Shock wave annihilation by MHD action in supersonic flows. Two-dimensional steady non-isentropic analysis. Anti-shock criterion, and shock tube simulations for isentropic flows," *European Journal of Mechanics B/Fluids*, Vol. 8, No. 4, 1989, pp. 307-326.
- <sup>14</sup>Petit, J. P., and Lebrun, B., "Theoretical analysis of shock wave annihilation with MHD force field," *International Conference on MHD Electrical Power Generation*. 11th, Beijing, China. Proceedings Vol. 3, 1992, pp. 748-753.
- <sup>15</sup>Petit, J. P., and Geffray, J., "MHD flow-control for hypersonic flight", *Acta Physica Polonica A*, Vol. 115, No. 6, 2009, pp. 1149-1151.
- <sup>16</sup>Forestier, B., Fontaine, B., Bournot, P., and Parraud, P., "Study of the variations in the aerodynamic flow parameters of ionized argon subjected to Laplacian accelerating forces". *CRAS*, Paris, French Academy of Sciences, B series, No. 271, 1970
- <sup>17</sup>Petit, J. P., "The Silence Barrier," now available as a free download on [savoir-sans-frontieres.com](http://savoir-sans-frontieres.com)
- <sup>18</sup>Petit, J. P., "Perspectives en magnétohydrodynamique," (tr. "Prospects on Magnetohydrodynamics") *Technical Report CNRS on behalf of CNES*, 1979.
- <sup>19</sup>Rice, W. A., "Propulsion system," US Patent 3,106,058, filed 18 July 1958.
- <sup>20</sup>Way, S., "Examination of Bipolar Electric and Magnetic Fields for Submarine Propulsion," *Preliminary Memorandum Communication to U.S. Navy Bureau of Ships*, October 15, 1958.
- <sup>21</sup>Myrabo, L. N., "Hypersonic MHD Propulsion System Integration for a Manned Laser-Boosted Transatmospheric Aerospacecraft," *ASME, SAE, and ASEE Joint Propulsion Conference and Exhibit*, 31st, San Diego, CA, July 10-12, 1995.
- <sup>22</sup>Myrabo, L.; N., and Myrabo, K. A., "Human factors integration for hyper-energetic microwave-boosted aerospacecraft," *AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, 33rd, 1997.
- <sup>23</sup>Myrabo, L. N., Raizer, Y. P., and Surzhikov, S., "Air Plasma Formation in MHD Slipstream Accelerator for Mercury Lightcraft," *International Symposium on Beamed Energy Propulsion, AIP Conference*, 2nd, Proceedings, Vol. 702, 2004.
- <sup>24</sup>Myrabo, L. N., and Rosa, R. J., "Hypersonic MHD Propulsion System Integration for the Mercury Lightcraft," *International Symposium on Beamed Energy Propulsion*, 2nd, AIP Conference Proceedings, Vol. 702, 2004, pp. 544-558.
- <sup>25</sup>Myrabo, L. N., and Lewis, J. S., *Lightcraft Flight Handbook LTI-20: Hypersonic Flight Transport for an Era Beyond Oil*, Collector's Guide Publishing, Inc., 2009.
- <sup>26</sup>Petit, J. P., and Billiotte, M., "Method for eliminating the Velikhov instability," *CRAS*, Paris, French Academy of Sciences, No. 292, Series II, 1981, pp. 1115-1118.
- <sup>27</sup>Petit, J. P., "Cancellation of the Velikhov instability by magnetic confinement," *International Conference on MHD Electrical Power Generation*, 8th, Moscow, Russia, Proceedings Vol. 4, 1983.
- <sup>28</sup>Petit, J. P., and Geffray, J., "Non equilibrium plasma instabilities," *Acta Physica Polonica A*, Vol. 115, No. 6, 2009, pp. 1170-1173.
- <sup>29</sup>Petit, J. P., "New MHD converters," *CRAS*, Paris, French Academy of Sciences, Vol. 11, No. 281, 1975, pp. 157-160.
- <sup>30</sup>Petit, J. P., and Viton, M., "New MHD converters: induction machines," *CRAS*, Paris, French Academy of Sciences, No. 284, 1977, pp. 167-179.
- <sup>31</sup>Filippov, N. V., et al., "Dense, High-Temperature Plasma in a Noncylindrical 2-pinch Compression," *Nuclear Fusion Supplement*. Pt. 2, 577, 1962.
- <sup>32</sup>Lerner, E. J., "Prospects for P<sup>11</sup>B Fusion with the Dense Plasma Focus: New Results," *Symposium Current Trends in International Fusion Research: A Review*, 5th, Washington, D.C., 2003.
- <sup>33</sup>Petit, J. P., Billiotte, M., and Viton, M., "Magnetohydrodynamics: Spiral-current accelerators," *CRAS*, Paris, French Academy of Sciences, Vol. 5, No. 291, 1980, pp. 129-131.
- <sup>34</sup>Petit, J. P., and Geffray, J., "Wall confinement technique by magnetic gradient inversion. Accelerators combining induction effect and pulsed ionization. Applications," *Acta Physica Polonica A*, Vol. 115, No. 6, 2009, pp. 1162-1163.
- <sup>35</sup>Gurijanov, E.P., and Harsha, P.T., "AJAX - New directions in hypersonic technology," *International Space Planes and Hypersonic Systems and Technologies Conference*, 7th, Norfolk, VA, 1996.
- <sup>36</sup>Warwick, G., "NASA studies hypersonic turbojet using MHD energy bypass cycle," [Flightglobal.com](http://Flightglobal.com), November 29, 2007.