SURFACE CHARGED SMART SKIN TECHNOLOGY FOR HEAT PROTECTION, PROPULSION AND RADIATION SCREENING

B. Göksel[1], I. Rechenberg[2]
Institute of Bionics and Evolutiontechnique, TU Berlin
Ackerstr. 71-76, Secr. ACK1, D-13355 Berlin
Email: berkant.goeksel@elektrofluidsysteme.de

INTRODUCTION

In January 1962 the Apollo command module heatshield requirements for several design trajectories were established. In March 1962 AVCO-Everett was selected by NAA to design and install an ablative material heatshield on the Apollo spacecraft outer surface.

Parallel to the Apollo development of ablative materials the AVCO-Everett Research Laboratory studied active plasma shields for heat protection by hydromagnetic braking in reentry and radiation screening [1]-[4], [7].

In 1969 Wernher von Braun published his paper "Will Mighty Magnets Protect Voyagers to Planets?" and discussed the general principle of magnetic shielding and the application of superconductors in plasma shields [5]. In 1970 Ali Bülent Cambel published his article "MHD for Spacecraft" and discussed the idea of hydromagnetic braking in reentry [6]. Cambel wrote in [6]: "Astrophysical data signify that heavenly bodies behave in accordance with the principles of MHD. A well-known example of man's attempts to exploit such phenomena is controlled thermonuclear fusion, and another is his attempt to generate electricity in an MHD power device. It might be suggested philosophically that, throughout his endeavours, the innovative engineer attempts to imitate nature. Most of the suggestions I will describe are but manifesttions of the phenomena constituting cosmic electrodynamics which our spaceship, Earth, obeys."

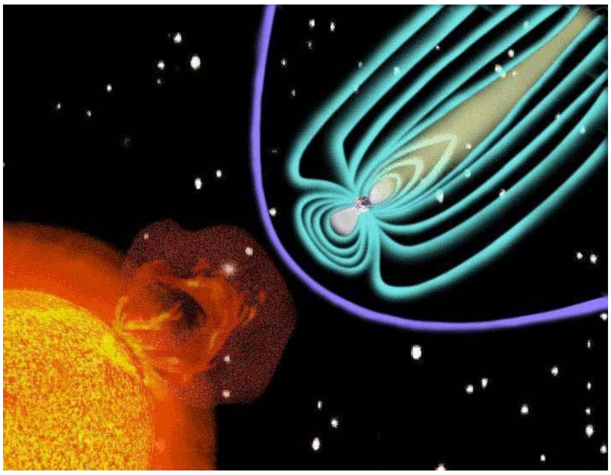

FIG. 1: The Magnetosphere - produced by the terrestrial magnetic field and plasma from the ionization of the upper layers of the atmosphere.

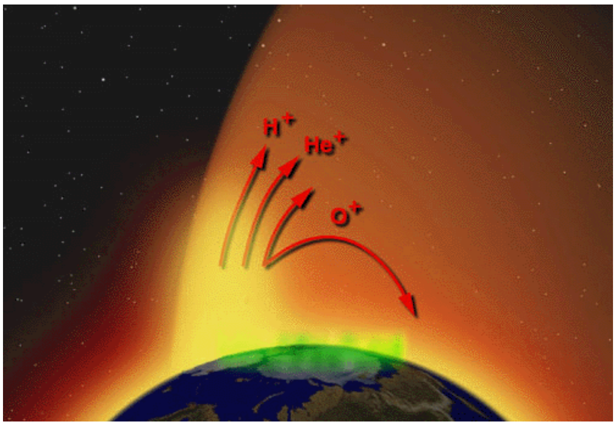

FIG. 2: Earth's ionospheric and magnetic radiation shield that protects us from cosmic and solar particles. The arrows show the outflow of plasma from the ionosphere into the magnetosphere.

In 1982 Birch revived the idea for radiation shields for ships and settlements [8]. But it was Landis from NASA who attracted more attention with his article "Magnetic Radiation Shielding – An Idea Whose Time has Returned?" published in 1991 [9]. In 1999 Sussingham et al. summarized "Forty Years of Development of Active Systems for Radiation Protection of Spacecraft" [10].

In 2000 Winglee et al. published a concept for a Mini-Magnetospheric Plasma Propulsion [14] (see Figure 3).

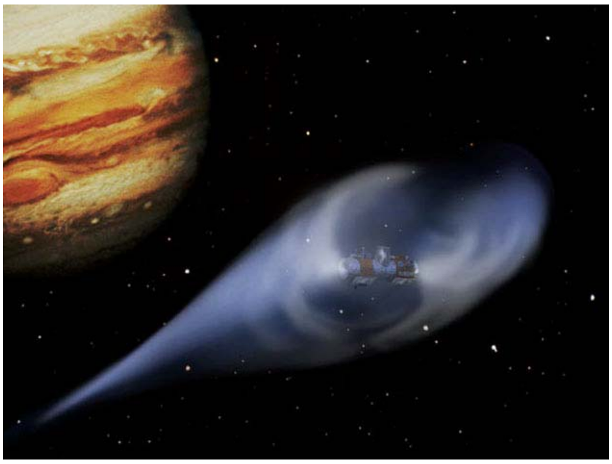

FIG. 3: Radiation Shielding Produced by Mini-Magnetosphere [15].

[1] PhD Student, Founder of Future Workshop Electrofluidsystems
[2] Professor, Head of Institute of Bionics and Evolutiontechnique

The Mini-Magnetospheric Plasma Propulsion (M2P2) (Figure 3) is ejecting plasma or ionized gas which then is trapped on the magnetic field lines generated onboard by a solenoid coil. The plasma can drag the magnetic field lines out and form a plasma bubble. This is similar to the Earth's magnetic field trapping a large volume of electrified gas - thus forming the magnetosphere - and forcing the solar wind to flow around it (Figure 1 and Figure 2).

1. SURFACE CHARGED SKIN TECHNOLOGIES

An alternative to pure magnetic shielding is surface charged skin shielding which is a form of electrostatic shielding.

1.1. AVCO-Everett Research Laboratory, Plasma Shielding Studies from 1961 - 1969

Von Braun wrote in [5]: “If a spaceship’s exterior could be kept positively charged, at a potential of some 300 million volts, that would repel the positively charged protons. The catch is that the negative-charged electrons in space, irresistibly lured by the positive charge, would flow to the ship and rapidly discharge it…. But a way around that is now seen: Superconducting rings, encircling the ship, would create a magnetic barrier that attracted electrons couldn’t cross. Instead, they would orbit around the ship in a cloud or plasma-for all the world like a circling swarm of voracious mosquitoes, eager to “bite” the craft (discharge it) but kept at a distance by its “Citronella” (magnetic field)”. This “plasma shielding” should be even more weight-saving than “pure” magnetic shielding, says its proponent, Dr. Richard H. Levy of Avco-Everett Research Laboratory, Everett, Mass. A lower-strength magnetic field, probably less than 3,000 gauss should prove sufficient.”

Figure 4 shows a design of a space vehicle with a plasma shield utilizing a four-coil superconducting magnet system. Ejection from the vehicle must be accomplished at a velocity greater than E/B velocity, or about 300 keV [2].

Levy wrote in [2]: “Further, any space vehicle configuration will possess a certain amount of solid shielding in the form of its skin and other equipment. This shielding may be estimated roughly at 2-4 g/cm² aluminium. Suppose, for example, that it is required to stop 100 MeV protons. If the skin thickness is 2 g/cm², reference to the range-energy tables shows that this thickness will just stop a 40 MeV proton. It is therefore only necessary to provide 60 million V of potential in the plasma radiation shield in order to achieve the desired effect. The incident 100 MeV proton crosses the plasma radiation shield voltage, losing 60 MeV. The remaining 40 MeV are then absorbed in the 2 g/cm² of skin. If the thickness is 4 g/cm², reference to the range-energy tables shows that this thickness will stop a 60 MeV proton. Thus a 40 MV plasma radiation shield outside of 4 g/cm² of skin would also suffice to stop 100 MeV incident protons… For example, to stop a 100 MeV proton requires 10 g/cm² of solid shielding. But we saw previously that 40 MeV plasma radiation shielding ahead of 4 g/cm² of skin will also stop a 100 MeV proton. In a sense, the 40 MeV plasma radiation shield is the equivalent of 6 g/cm² of solid shielding.

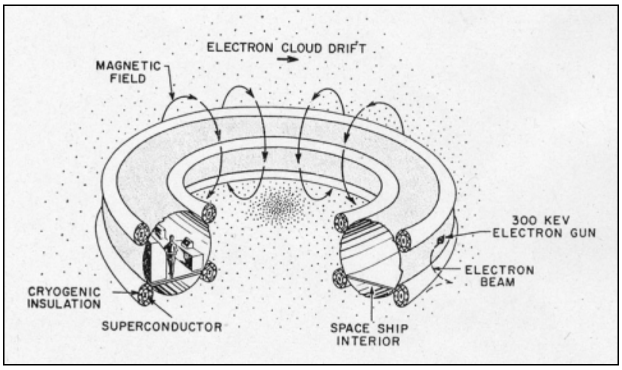

FIG. 4: Design of a space vehicle with a plasma shield [2].

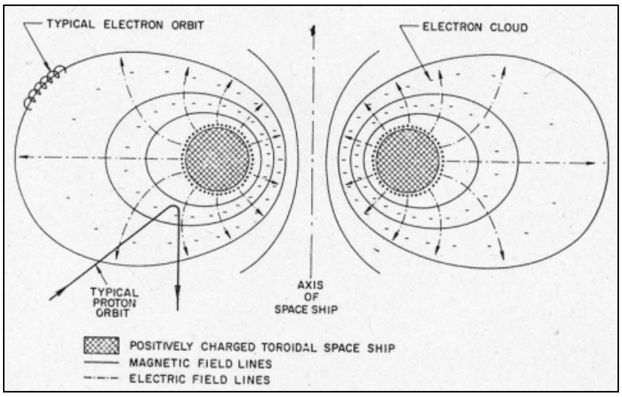

FIG. 5: Electric and magnetic field lines around a shield [2].

1.2. Diamond Film Layers as Cold Cathode

May wrote in [13]: “Diamond has some of the most extreme physical properties of any material, yet its practical use in science or engineering has been limited due its scarcity and expense. With the recent development of techniques for depositing thin layers of diamond on a variety of substrate materials, we now have the ability to exploit these superlative properties in many new and exciting applications.”

1.2.1 Principle of Cold Field Electron Emission

Fowler-Nordheim Equation is the classic relation showing emission current's dependencies:

(6.1) $$E = \frac{V}{R^2}$$

(6.2) $$E = \frac{100\ \text{Volt}}{100\ \text{Angstrom}} = 1 \times 10^{14}\ \text{V/cm}$$

(6.4) $$E = \beta V$$

(6.5) $$\frac{1}{V^2} = \frac{\alpha a \beta^2}{\varphi} \exp\left(\frac{-b\varphi^{3/2}}{\beta V}\right)$$

with

φ = work function
β = enhancement factor
a = emission area
E = electric field strength
R = tip radius
V = gate voltage
I = emission current
α, b = constants

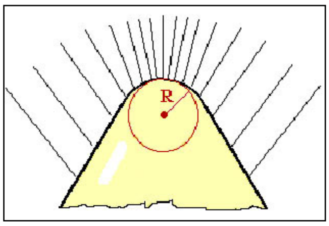

FIG. 6: Field Lines on Tip.

– Electric fields strongest where minimum radius of curvature

– High electric fields distort potential energy well for electrons in tip

– Electrons at Fermi Energy can tunnel out in a vacuum or gas

1.2.2 Specialities of Diamond Film Layers

– IDEAL cathode since diamond naturally repels e-'s

– Very low work function (0.2 to 0.3 eV)

– Negative electron affinity and wide band gap

– Donor e-'s need to have ~0.01 eV to eject (< KbT, 0.025 eV)

– Hence, emits electrons at much lower E-fields than Si or metals

– Simple, no need to microfabricate sharp tips

– Can operate at higher pressures

In general diamond cold cathodes offer higher stability, larger emission site density, much higher lifetime than other existing cold cathodes. The higher thermal conductivity, higher thermal difusivity and lower sputter yield discourages thermal evaporation of emission sites, and thus reduces the possibility of anode-cathode (A-K) gap closure. In addition, diamond negative electron affinity allows extremely high currents (~100 A/cm²) which can be emitted at low electric fields.

1.2.3 Further Properties of Diamond Film Layer

– Hardness 8,000 - 10,000 Kg/mm^2

– Electrical Resistivity 10*3 - 10*13 ohm-cm

– Dielectric Constant ~5.7

– Breakdown Voltage 100 - 300 volts/micron

– Loss Tangent (~15GHz) < 0.05

– Thermal Conductivity > 1,200 w/m-K

1.3. Diamond Layers as Superconductors ?

Physics Web announced in April 2003 that “a physicist (J. F. Prins) in South Africa claims to have created a new superconducting state of matter at room temperature. Johan Prins of the University of Pretoria observed the superconducting state in experiments with diamonds that had been doped with oxygen… Diamond is a semiconductor and Prins has long been interested in using n-type diamond as a "cold" cathode to replace the "hot" cathodes found in television tubes and many other devices. Moreover, he believes that the results of his experiments on n-type diamond surfaces - made by exposing the diamond to energetic oxygen ions - can only be explained by a new type of superconducting state. "If it is not superconductivity then it must be violating the second law of thermodynamics," he says.“

Prins wrote in [17]: “It is generally believed that if an n-type semiconductor with negative electron affinity could be found, it would act as an ideal ‘cold cathode’. A model is proposed to describe the conditions at an ideal surface between such a semiconductor and the vacuum. When such an interface is created, electrons will have to exit the semiconductor owing to the difference inenergy *X* between the conduction band and the vacuum level. They leave a positively charged depletion layer behind, within which a barrier to further electron egression is generated. A self-consistent potential well has to form, which bounds the emitted electrons within quantum states such that they remain within an ‘electron-charge’ layer adjacent to the surface. Together with the depletion layer, the electron-charge layer forms a dipole that screens the field caused by the initial offset *X* between the energies of the conduction band and vacuum level. When applying an electric field to extract electrons, the barrier in the depletion layer increases. This impedes electron flow through the semiconductor into the vacuum.“

Prins continued in [18]: “It is shown experimentally that n-type diamond is a negative electron affinity material from which electrons can be extracted at room temperature. This is achieved by generating an 'ohmic' tunnelling contact to the vacuum. It is found that the extracted electrons within the gap between the diamond surface and the anode are able to form a stable, highly conducting phase. Band theory, combined with the equations that describe electron transport in a vacuum diode, unequivocally show that the distances between these electrons, as well as their speeds, must keep on decreasing as long as there is an electric field between the diamond surface and the anode. This implies that steady-state current flow, as experimentally observed, can only occur if this field becomes zero while still allowing a current to flow from the diamond to the anode. The only way to achieve such a situation is for the extracted electrons within the gap to form a superconducting phase. Because electrons are fermions, an unabated decrease in their nearest-neighbour distances as well as their speeds should eventually force them to violate the Heisenberg uncertainty relationship. At this limit, they become restricted, as pairs, within volumes or 'orbitals' which in turn fill the whole space between the diamond and the anode. Because these 'orbitals' have zero spin, they are boson-like charge carriers, and because they are as near to each other as is physically possible, they automatically constitute a Bose–Einstein condensate; i.e. they constitute a superconduc-ting phase.”

2. ELECTROHYDRODYNAMIC PROPULSION BY POLYPHASE SURFACE CHARGED SMART SKIN PLASMA ACTUATORS FOR TAKE-OFF AND LOW SPEED CRUISE MODE

In the NASA online article *Riding the Highways of Light - Science mimics science fiction as a working model flying disc - a "Lightcraft" - takes to the air*, Prof. Leik Myrabo from the Rensselaer Polytechnic Institute explains the design for a hypersonic trans-atmospheric vehicle (Figure 7 and 8). Myrabo has been building on the idea to use lasers to launch satellites since 1972, when it was developed by founder and former CEO of AVCO-Everett, Prof. Arthur Kantrowitz.

The article says: “The concept that evolved is a part airship, microwave receiver, and (the smallest part) jet and rocket engine, and as green as any space concept. The 12-person, 20-meter (66 ft) craft would be powered from the Earth's surface to the Moon by sunlight captured by an orbiting power station (1 km diameter, 20 GW power), converted to microwaves, and beamed to rectennas (rectifying antennas) that turn it back into electricity on the Lightcraft. That's where the saucer shape comes from.

The airship part is a pressurized helium balloon-type structure made of advanced silicon carbide film (transparent to microwaves) to make the craft partly buoyant and to provide for a large parabolic reflector for the energy beamed from space. The craft would be encircled by two superconducting magnet rings and a series of ion engines, and topped with solar cells (Figure 7).

FIG. 7: Trans-atmospheric vehicle design from Rensselaer Polytechnic Institute.

At launch, the Lightcraft would use electricity from its solar cells (powered by an infrared space-based laser at night) to ionize the air and move the craft through electrostatic discharges. The craft could move at 80 to 160 km/h (50-100 mph).”

Myrabo gives no details about the electroaerodynamic propulsion. It is an idea of the corresponding author to develop a solitary electrostatic wave propulsion by polyphase plasma actuators based on bionic principles by mimicking the flapping wing propulsion of birds and insects [19]. To test this idea, the Future Workshop Electrofluidsystems of the Institute of Bionics and Evolutiontechnique has recently acquired a new 300 Watt polyphase high-frequency (5-50 kHz) high-voltage (3-6 kV) power supply. The same electrostatic wave propulsion concept is currently in the review process for the BMBF (German Research Ministry) concept contest “Bionics – Innovations from Nature”.

Synthetic diamond and silicon carbide are the best materials to develop cold-emission electron guns powerful to ionize air under atmospheric conditions (see section 1.2). Presently, such cold cathodes are under development for the next generation of flat screen monitors. The same technology could be used to develop a synthetic diamond and silicon carbide based smart skin technology applicable on wing and fuselage surfaces of several square meters. In the case of silicon carbide the skin has to be micro-structured with protected tips whereby synthetic diamond is independent from sharp tips and may be the most promising smart skin material for applications on future hypersonic trans-atmospheric flight vehicles (Figure 8).

FIG. 8: Microwave Lightcraft Design.

3. MAGNETOHYDRODYNAMIC PROPULSION IN HYPERVELOCITY MODE

As Myrabo says: “That (the EHD mode) is just low gear. Switching on the microwave transmitter would make the Lightcraft disappear in less than an eye blink. The microwaves would be focused by the internal reflector to heat the air on one side or the other of the craft and push it in the opposite direction.”

The principle of the hot plasma spike is shown in Figure 9.

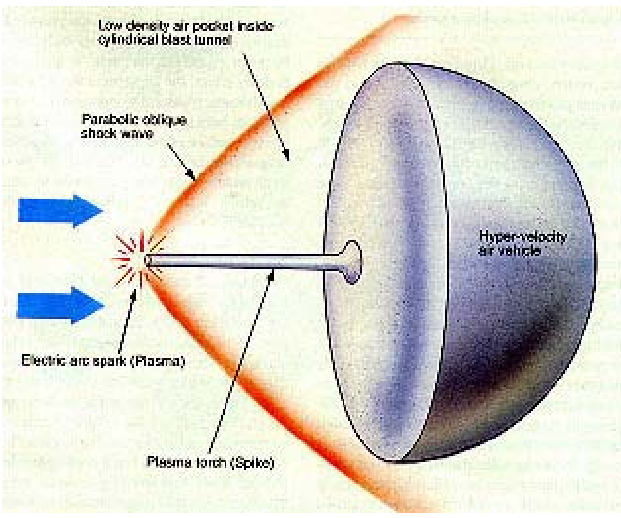

FIG. 9: Principle of air plasma spike for hypervelocity mode.

"This is used to climb out to a good altitude and beyond the speed of sound where you use the magnetohydrodynamic drive," Myrabo continued. Now the craft tilts from flying edgewise to flying flat into the air stream. That seems wrong but for another trick. The microwaves are reflected forward to create a superhot bubble of air above the craft and form an air spike that acts as the nose cone as the Lightcraft accelerates to 25 times the speed of sound."

"This cleans up the aerodynamics of a vehicle that does not look like it should fly in that direction," Myrabo said. Even better, when the load is properly balanced the craft sails through the air without leaving a shock wave and virtually no supersonic wake. Water is used by the craft to cool the rectennas and as a propellant in the last stages of ascent."

"At least initially, during the prototype phase, it won't be for everyone, just NASA and military test pilots. The hyper-energetic performance will require that the crew ride in liquid-filled escape pods to protect them from g-forces greater than even fighter pilots occasionally endure. In some Air Force Space Command schemes, the crew would breath an oxygenated fluid to protect their lungs."

"It all sounds a bit too much like science fiction, but Myrabo points out that most of the technologies or principles have been demonstrated. Faculty and students at Rensselaer have demonstrated the MHD slipstream accelerator and the air spike concept in a high-speed wind tunnel, and will test new models of other parts of the propulsion system later this year." (Figure 10)

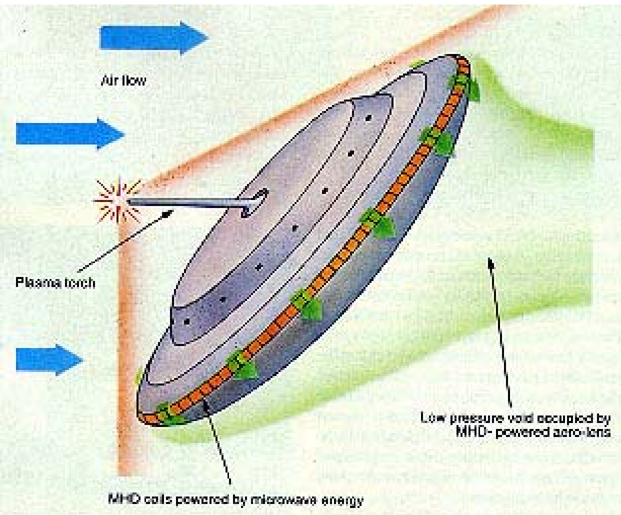

FIG. 10: Principle of the MHD slipstream accelerator.

In his paper "MHD for spacecraft" [6] Ali Bülent Cambel already wrote: "Our experiments have demonstrated that operating an electromagnet inside a re-entry model causes the shock wave ahead of the model to be pushed away from the body at a steeper angle. Clearly the magnet influences the flow field. It is not difficult to imagine that a magnet three dimensionally gimballed could be used to modify the flow field in any desired way and to vary the lift and drag upon command."

3.1. Laser-Driven Water-Powered Propulsion

FIG. 11: Lightcraft flying atop a beam of laser light.

Figure 11 shows an illustration of Myrabo's lightcraft flight tests from July 1996 to Sept. 1999 where the lightcraft vehicle was launched with a 10 kW military laser at White Sands Missile Range in New Mexico [12]. The laser energy is converted into propulsive thrust as it strikes a parabolic condensing reflector mounted on the bottom of the lightcraft. This area has a thin coating of propellant which after struck by laser pulses detonates and thrusts the lightcraft upward.

Recent publications reveal that the overlay structure is using water which is insulated from vacuum by an "air curtain" to avoid evaporation or freeze in vacuum conditions [16].

4. HYDROMAGNETIC BRAKING IN RE-ENTRY

In 1967, at the height of AVCO-Everett's research on plasma radiation shielding utilizing superconductive magnets made of the silvery metal niobium with tin, Sampson et al. wrote in [3]: "A large magnetic field could produce hydromagnetic drag in the cloud of ionized air the vehicle produces as it enters the atmosphere. With hydromagnetic braking the kinetic energy of the vehicle would be absorbed through the magnetic field rather than through heating of the vehicle itself, with the result that the total weight required to protect the vehicle from overheating and destruction could be markedly reduced."

The concept of hydromagnetic braking in re-entry was worked out in detail by Ali Bülent Cambel who made extensive computer analysis and calculated that MHD braking can increase drag appreciably, in first experiments by almost 40 percent [6]. In his paper "MHD for spacecraft" [6], Cambel wrote: "Re-entry to the Earth's atmosphere must always be made at the correct angle. Too steep and the spacecraft may burn up; too shallow and it may skip out again into space and be unable to return home. ...

The key feature of the proposed space vehicle is that it would carry one or more electromagnets which could be adjusted in field strength and in direction. Strong fields would be required and so it is certain that superconducting magnets would have to be used, because only these promise to be light enough. …

Magnetic braking is as important as electric propulsion, since it offers a solution to the difficult problem of slowing down during re-entry to the Earth‘s atmosphere. Space vehicles do not use wings, because space is practically a vacuum and they would be of no use. ... A spacecraft travelling through space has an enormous amount of kinetic energy. A small one tonne vehicle travelling at 15,000 m/s has a kinetic energy corresponding to 23 MW-h; at a re-entry speed of 6000 m/s it would have energy corresponding to 4.9 MW-h. In today‘s spacecraft this energy is not used profitably but is dissipated by firing retro-rockets or in aerodynamic heating. But an MHD generator could convert part of this enormous energy to useful electricity. When a vehicle enters or re-enters a planetary atmosphere at high velocity the gas in front of it is carried along with it; relative to the vehicle it is drastically slowed down. The vehicle‘s kinetic energy is largely converted into thermal energy, resulting in an extremely high temperature which could consume the vehicle. …

Aerodynamic drag can appear in at least two ways: friction drag, which heats the vehicle, and pressure drag which heats the stagnating gas. Heat transfer from the gas demands that the vehicle be protected. The present method of using a heat shield has shortcomings. It adds a weight penalty. It melts and results in asymmetrics which can cause instabilities. It introduces a variety of chemical species into the flow field surrounding the vehicle. The ablating shield concept is being pushed to its limits and is of questionable merit when the atmosphere of a planet is not accurately known. Finally, the vehicles with ablative shields are not readily re-usable without extensive refurbishing.

As an alternative to a heat shield it is possible to repel the incandescent gas away from the vehicle and thus prevent contact between the two. As the temperature of a gas is raised its degrees of freedom increases with its energy level. As a gas molecule is heated it assumes first a rotational mode, then a vibrational mode and then, if it is diatomic, it dissociates. If its temperature is raised still further, the gas becomes ionized. In this state the positively charged ions and the negatively charged electrons constitute an electrically conducting plasma. Like a metal, the plasma will be susceptible to the influence of a magnetic field and so can be manipulated with a magnet. Indeed, this is what the Earth’s magnetic field does in creating the Van Allen belts which surround it.”

Regarding the Figure 12, Cambel wrote that the “MHD spacecraft is depicted opposite during entry to a planetary atmosphere, causing interactions between the electrically conducting plasma sheath over the blunt nose and the magnetic field produced by the powerful electromagnet (shown larger than true size in relation to a typical manned vehicle). In the presence of Hall currents, which in the case of a conducting spacecraft return through the vehicle structure itself, the magnet experiences forces in the radial, polar and azimuthal (roll) directions. By suitably controlling the magnetic field strength and orientation the vehicle drag and/or flight path can be altered in a powerful way. Moreover, by using the principle of the homopolar generator, the magnet can be made to produce electric current; in this example the magnet is spun on its axis by the Hall current reaction and power is produced at a fixed disc armature.“

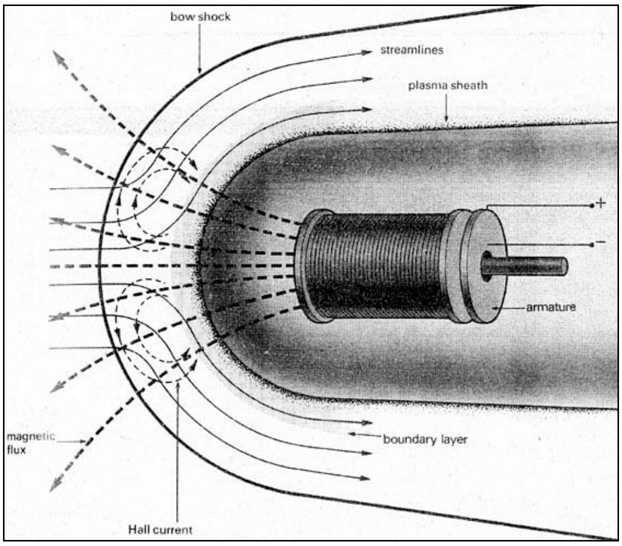

FIG. 12: Principle of Hydromagnetic Braking [6].

5. BLACKOUT CONTROL IN RE-ENTRY

According to Ali Bülent Cambel there is also the possibility of blackout control during re-entry [6]: “The charged particles are in constant agitation, jumping back and forth. With this oscillatory motion is associated the ‘plasma frequency’, which is a characteristic parameter of a plasma depending on its density. For an electromagnetic signal to pierce the plasma its frequency must be much higher than the plasma frequency. This means that its wavelength must be very small, and this is directly related to the size of signal source equipment. … When a magnet is applied to a plasma the plasma be-comes anisotropic because the charged particles assume preferential motion just as do electrons in a cyclotron. In addition to their oscillatory motion the charged particles rotate around the magnetic field lines. They do so at the so-called cyclotron frequency, the magnitude of which is governed by the magnetic field strength. Whereas an isotropic homogeneous plasma can be characterized by its plasma frequency alone an anisotropic plasma has both its plasma frequency and cyclotron frequency. It can be shown that the propagation of a signal through such a plasma depends on the relative magnitudes of the signal frequency and both the plasma and cyclotron frequencies. So if a magnetic field is applied there is no longer a necessity for a microwave system which operates at an exceedingly high frequency. Depending on the combinations of frequencies used, signals can propagate through the plasma even when the plasma frequency is higher than the signal frequency, provided that the applied magnetic field is sufficiently strong or that the cyclotron frequency has the proper value. This can be achieved for various plasma and cyclotron frequencies, and for a useful range of signal frequencies. The frequency combinations at which the signal can penetrate are called passbands or magnetic windows. The existence of such ‘windows’ suggests the possibility of eliminating communications blackout. They also offer the potential for changing their position, according to varying ambient conditions, allowing the ground station to use a single frequentcy. If the spaceship should encounter hotter plasmas, the plasma frequency would change. This could be compensated for by changing the magnetic field strength; as long as the correct ratio of the cyclotron to plasma frequency is maintained, the magnetic window will allow the signal to penetrate."

6. SUMMARY AND OUTLOOK

In the dense air of low altitude up to the rarefied atmosphere at the edge of space, microwaves are reflected forward to create a superhot bubble of air above the craft and form an air spike that acts as the nose cone as was shown in Figure 9 and 10. The MHD craft is propelled by accelerating the ionized air rapidly over the lip of the edge forcing with superconducting magnets placed around the circumference of the ring of the disc shaped vehicle.

But outside the earth atmosphere, the MHD slipstream ionized air accelerator would not work. MHD propulsion would be restricted to propulsion by magnetic field interaction with the solar wind which is moving at 300-800 km/s (see also [14], [15]). Alternatively the craft could us ablative coatings of chemical propellant ignited by intense masers or lasers from ground or orbiting power stations (see Figure 11).

To overcome the need for chemical propellants in the future, one could speculate about unknown natural principles to be discovered which could strongly use collective neutrino-plasma interactions and the ponderomotive force of neutrinos in a magnetized plasma [11]. Presently there is intensive research in the new field of 'neutrino plasma physics'.

Without knowing more about neutrino plasma physics it is speculative but fascinating to think about how to create a superhot bubble of neutrino plasma above a MHD craft and how to accelerate this exotic plasma by using collective neutrino plasma interactions on a surface charged smart skin. In analogy to the "MHD propeller" such a system could be called a "vacuum propeller". A breakthrough in these cutting edge technologies could open new dimensions for space flight.

REFERENCES

[1] Levy, R. H. (1961) Radiation Shielding of Space Vehicles by Means of Superconducting Coils. ARS Journal, 31(11), pp. 1568-1570.

[2] Levy, R. H.; Janes, G. S. (1964) Plasma Radiation Shielding. AIAA Journal, 2(10), pp. 1835-1838.

[3] Sampson, W. B.; Craig, P. P.; Strongin, M. (1967) Advances in Superconducting Magnets. Scientific American, March, pp. 114-123.

[4] Levy, R. H.; French, F. W. (1968) Plasma Radiation Shield: Concept and Applications to Space Vehicles. J. Spacecraft, 5(5), pp. 570-577.

[5] Von Braun, W. (1969) Will Mighty Magnets Protect Voyagers to Planets? Popular Science Monthly, January, pp. 98-100.

[6] Cambel, A. B. (1970) MHD for Spacecraft. Science Journal, January, pp. 69-73.

[7] French, F. W. (1970) Solar Flare Radiation Protection Requirements for Passive and Active Shields. J. Spacecraft, 7(7), pp. 794-800.

[8] Birch, P. (1982) Radiation Shields for Ships and Settlements. J. Brit. Interplanetary Soc., 35, pp. 515-519.

[9] Landis, G. A. (1991) Magnetic Radiation Shielding – An Idea Whose Time has Returned? In Space Manufacturing, 8, American Nuclear Society, pp. 196-202.

[10] Sussingham, J. C.; Watkins, S. A.; Cocks, F. H. (1999) Forty Years of Development of Active Systems for Radiation Protection of Spacecraft. J. Astronautical Sci., 47, pp. 165-175.

[11] Silva, L. O. ; Dawson, J. M.; Mori, W. B.; Bingham, R; Shukla, P. K. (2000) Ponderomotive force of neutrinos in a magnetized plasma. Physica Scripta T84, pp. 57-59.

[12] Messitt, D.G.; Myrabo, L.N.; Mead Jr., F.B. (2000) Laser Initiated Blast Wave for Launch Vehicle Propulsion. AIAA 2000-3848, 36th AIAA Joint Propulsion Conference, Huntsville, AL.

[13] May, P. W. (2000) Diamond thin film: a 21st century material. Phil Trans. R. Soc. Lond. A 358, pp. 473-495.

[14] Winglee, R. M.; Slough, J.; Ziemba, T.; Goodson, A. (2000) Mini-Magnetospheric Plasma Propulsion: Tapping the Energy of the Solar Wind for Space Propulsion. J. Geophysical Research, 105 (9), pp. 21067-21077.

[15] Winglee, R. M.; Ziemba, T.; Euripides, P.; Slough, J. (2002) Radiation Shielding Produced by Mini-Magnetosphere. Proc. 2002 Space Radiation Shielding Technology Workshop. (http://www.geophys.washington.edu/Space/SpaceModel/M2P2/technical.html)

[16] Yamaguchi, M. et al. (2002) Laser-Driven Water-Powered Propulsion and Air Curtain for Vacuum Insulation. In A. V. Pakhomov (ed.) Beamed Energy Propulsion: First International Symposium on Beamed Energy Propulsion, Springer Verlag, pp. 557-570.

[17] Prins, J. F. (2003) The diamond–vacuum interface: I. A model of the interface between an n-type semiconductor, with negative electron affinity, and the vacuum. Semicond. Sci. Technol. 18, pp. 125-1300.

[18] Prins, J. F. (2003) The diamond–vacuum interface: II. Electron extraction from n-type diamond: evidence for superconduction at room temperature. Semicond. Sci. Technol. 18, pp. 131-140.

[19] Goeksel, B.; Rechenberg, I. (2004) Drag Reduction and Propulsive Power by Electric Field Actuation. BIONIK 2004, Hannover (to be presented).