A brief motivation for electric high-thrust propulsion in general; and in particular for the plasma propulsion concept "Helios"

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Abstract: *The journey to the planets and maybe to the stars one day is an old dream of the humankind; to leave mother earth and dare the next, the interplanetary, step of exploration. "Dare mighty things" is a key slogan of these days of Percy's arrival on the red planet. And this it is, space travel is still the great adventure of our days. Almost everybody, who is involved in space travel related activities, is passionate and enthusiastic and knows that she or he is part of something huge. Several technologies and research topics are part of space travelling. One cannot distinguish between the importance of the different involved technologies. But though, the basis and the origin of this journey is called propulsion. So, propulsion may not be more important than other technologies; but it is the fundament. And without propulsion there is basically no space exploration thinkable. For this reason, the following pamphlet is supposed to reflect the basic of propulsion in a rather naive way, which is more focusing on understanding the simple relations than to serve scientific wording. The further purpose is to derive from these relations a necessity of a very specific type of propulsion; the continuous electric high-thrust propulsion.*

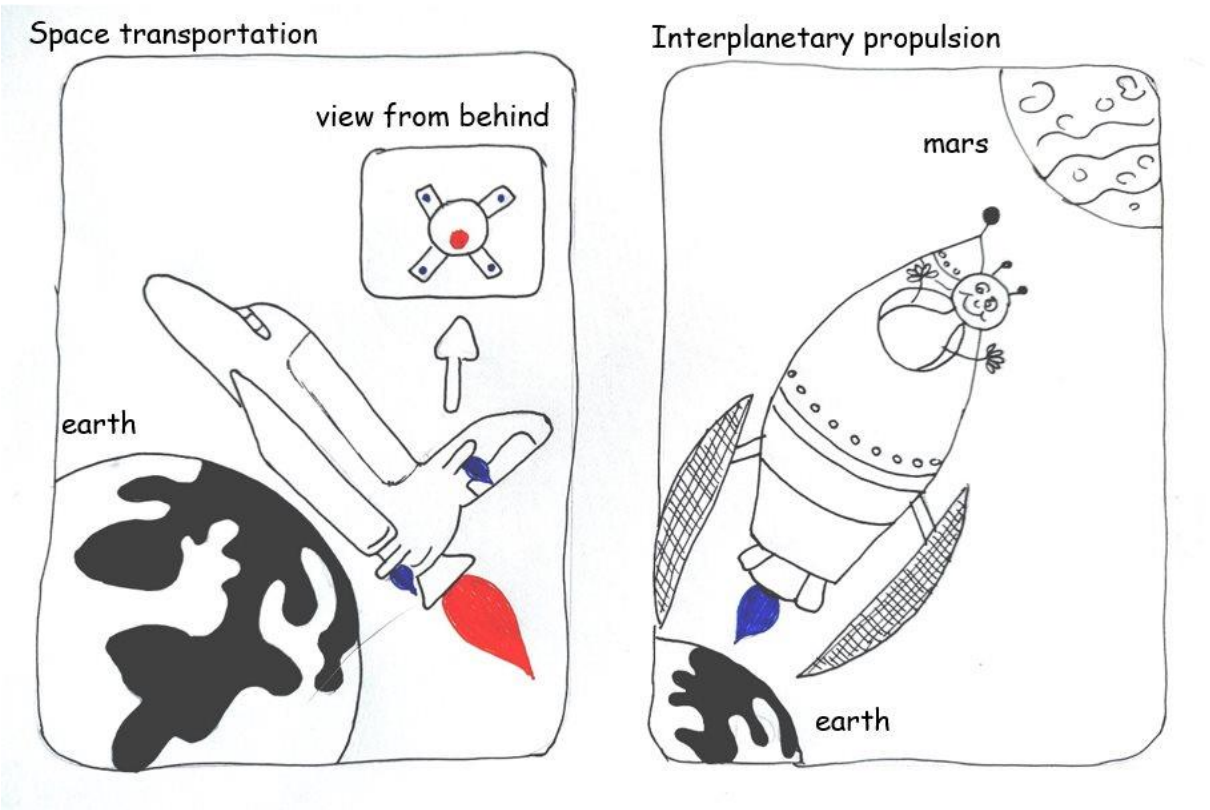


Figure 1: Supporting an upper stage of space transportation or as in-space main-engine for an interplanetary mission; continuous electric high-thrust can fight on many front lines of space travelling

Repulsion in general

Each and every spacecraft in the nearer or also in the deep space is a strictly closed system. For propelling, it needs to use internal parts of this closed system. No streets can be used to generate speed through friction, no walls can be utilized to produce an acceleration by pushing away; just empty space all around. The only way to create a change of the impulse of the spacecraft is to separate internal parts of the craft and to accelerate them. For the acceleration of each body, there is a force needed.

$$F = m * a$$

One of the most basic properties of a force is its mutuality. This means, the origin of a force is always identic with the coupling medium for a force; mass generates gravitation, gravitation influences mass and the influenced mass again generates gravitation; or charge generates electric field, electric field influences charge and the influenced charge again generates an electric field.

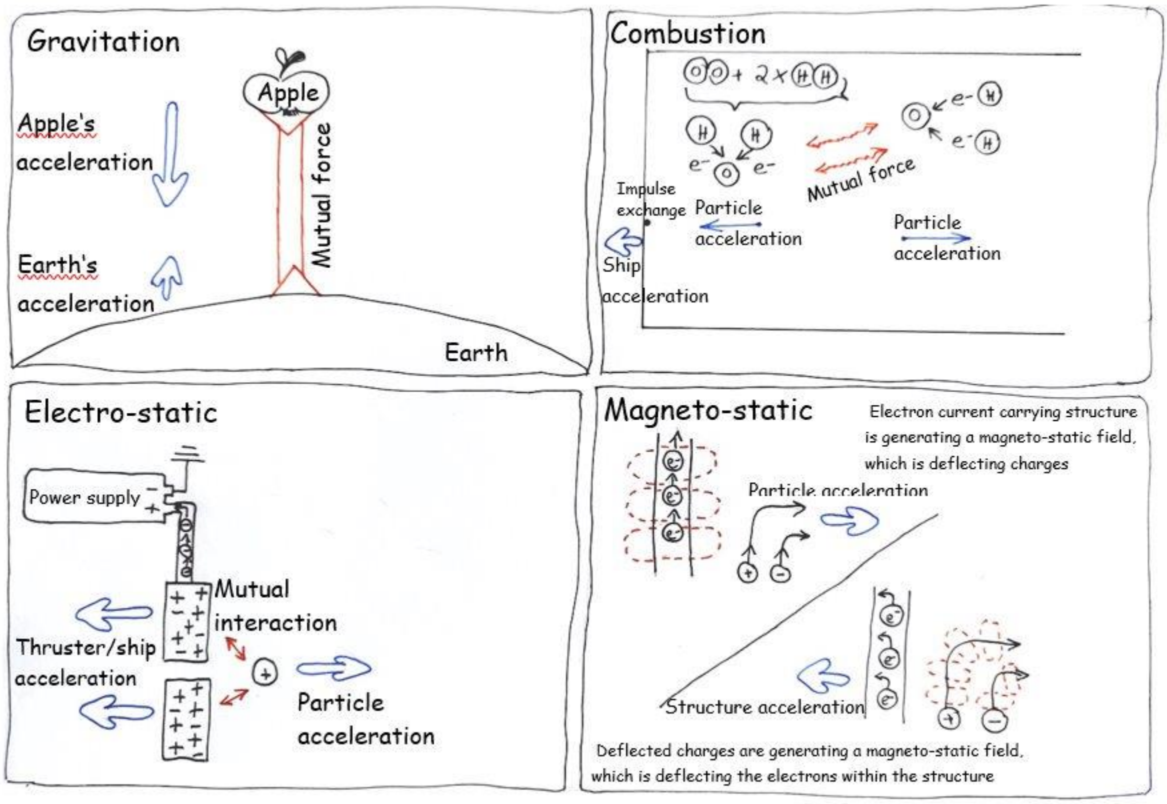


Figure 2: The mutuality of force or mutual interaction equals mutual propulsion!

In most easy words; one cannot accelerate anything without getting to be accelerated itself. This basic mutuality was concisely written down by Newton; action = reaction.

$$F_{12} = F_{21}$$

And if the force between two objects is mutual, the force, which is accelerating a part of the spacecraft away from the craft, is identic with the force that is acting on the spacecraft. This is briefly spoken the fundament of every kind of (conservative) space propulsion.

Commonly, such accelerated parts are called fuel…

In conclusion, each particle of fuel, which is accelerated…no matter whether the value of velocity is changed, or the direction…re-acts on the spacecraft through the accelerating force.

One of the most fitting citations regarding repulsion was in the movie "Interstellar", when TARS explained the reason, why they had to detach the orbiter to escape from the Black Hole: "Newton's third law – the only way humans have ever figured out of getting somewhere is to leave something behind." …usually it is fuel, what we leave behind.

Types of space propulsion

The occurrence and effect of this accelerating force is basically different between electrical and chemical propulsion. It is a direct effect between fuel and craft with electrical propulsion; the fuel is accelerated by a field, which is applied direct from a structure of the craft. And the effect is a direct propelling of the craft through fuel acceleration. And it is an indirect effect only between the fuel itself with chemical propulsion; during the combustion, released chemical energy (released in form of electromagnetic radiation) is accelerating the involved neutral particles omnidirectional. Since one side of the combustion chamber is open, at this side the particles are passing uninfluenced. At the opposite side the particles colliding with the wall of the combustion chamber and transferring their kinetic impulse onto the wall; hence on the structure of the craft. In the result, the spacecraft is chemically accelerated into the direction opposite to the direction of the combustion opening. With nozzles in Laval-shape for instance, it is possible to partially utilize also the accelerated particles, which are colliding with the sidewalls.

Through this mutuality of interaction, the ejected mass is counting meter for the vehicle's thrust. Since we remember, there is always a reason that fuel leaves its position within the craft; so, when you see that something leaves a spacecraft suddenly (suddenly in the sense of: seconds before, this something was in rest), you know there is propulsion. And when you are able to estimate mass and velocity of the leaving something, you have an idea about the magnitude of propulsion. For this reason, the ejected mass is always the best indicator for thrust; though it can be possible that there is no direct correlation between ejected mass and the acceleration of the craft. Like it is with chemical propulsion: not the leaving particles are generating thrust but the ones colliding with the inner space of the thruster.

The basis relation of space propulsion, the Ziolkovski equation, seems suspicious in the light of a microscopic treatment of fuel and propulsion. Ziolkovski derives his equation from an impulse conservation; fuel is accelerated in one direction, ergo the rocket is accelerated into the opposite direction. And this mutual acceleration is complying with the laws of impulse conservation. So far, so good. But this is only true from a macroscopic point of view. The relation of impulse conservation is valid only for things, which have one direct force interaction in-between. A propelled rocket is only seemingly a closed system with only one impulse preserving interaction. The precise view shows: there are two separate interactions, which are conserving an impulse. The first one is the combustion itself and we have to focus only on the chemically reacting fuel particles here. The chemical energy before an oxidation is converted into electromagnetical energy after oxidation, which is finally accelerating the fuel particles in a repulsive way. The particles moving apart and the total impulse of all the fuel particles is conserved. Here ends the first part of chemical propulsion. The second part takes place at the inner walls of the thruster. There, the accelerated fuel particles are colliding with these walls.

During these elastical collisions, the fuel particles transfer their impulse to the walls. Also this procedure happens complying with the laws of impulse conservation.

This macroscopic impulse conservation has turned out as two separate impulse conservations. And only the second process, the second part of chemical propulsion, is involving the rocket into the conservation. But unfortunately, not all fuel particles are still involved into this second conservation; only the ones, which are colliding with the wall. So the question is, why Ziolkovski's macroscopic equation is valid; why it seems that the whole amount of fuel is involved within the impulse conservation? And this must be true, since it was observed with a thousand of rocket take-offs. The point is the difference of mass between each fuel particle and the wall of the thruster. When a particle collides with the wall, the wall remains almost in rest and the particle is reflected with almost the same velocity, as it was impacting but into the opposite direction. This whole process is very close to the borderline case of collision with an unmoveable structure; in this case no kinetic energy but the twice the impact impulse would be transferred. But it is just very close to this case, since at the end the rocket is moving.

Imagine a cube-shaped combustion chamber, where the chemical reaction takes place in the centre and the fuel particles are accelerated apart; and this chamber is completely open at one side. The particles, which are streaming out, do not affect the thruster. The particles, which are colliding with the wall opposite to the opening, do transfer the double of their impact impulse to the thruster wall. Simultaneously, these particles are reflected from the wall and stream out, too. The total impulse, which is transferred to the side walls of the thruster is complete symmetric and equals zero. Thus, the macroscopic resulting picture is as following: the amount of ejected fuel seems to transfer its impulse to the spaceship. But the microscopic reality looks like this: only the half of the amount of fuel is interacting with the spaceship, but this half is transferring twice its impulse.

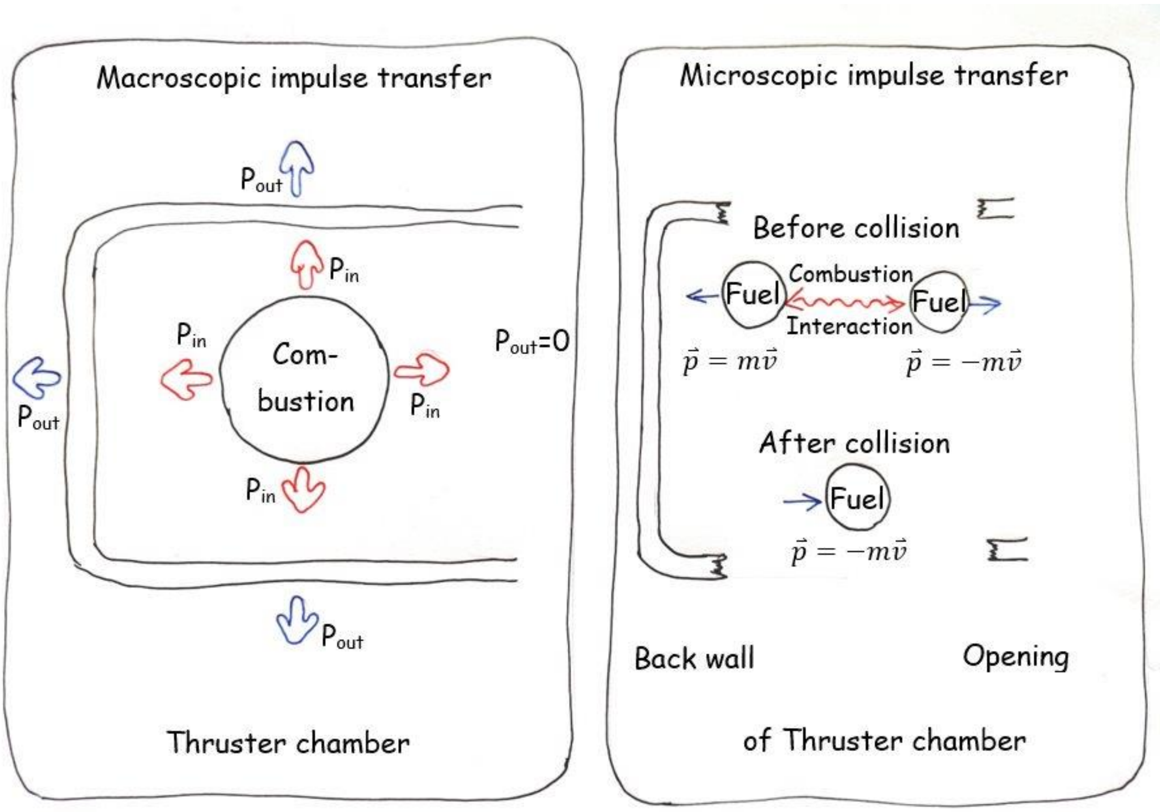


Figure 3: Chemical propulsion in a box

In opposite to chemical propulsion, the electrical kinds of propulsion are straight and direct. The accelerating interaction takes place between the fuel particles and parts of the spacecraft structure. Hence, in this case, we have only one impulse conservation; the impulse change due to fuel acceleration is equal but opposite to the impulse change of the thruster plus spacecraft. No matter if electro-static or electro-magnetic, electric always means direct interaction and therefore direct propulsion.

But also between electro-static and electro-magnetic is a significant difference: Charges in rest are establishing a field, which is accelerating the charges along the line of connection between them. This mechanism is described as electro-static. And when some of these charges are tied inside a (most often metallic) solid, which is a fixed part of the spacecraft and the other charges are freely moving; the mutuality of the electro-static interaction generates propulsion. Or more particular; if the charges are of the same species, the mutual electric force, which is pushing away the free charges is also accelerating the spaceship, where the charged solid is mounted on, into the opposite direction.

While fixed charges are determining the functionality of the electro-static propulsion; charges in move (commonly called current) are defining the behaviour of the electro-magnetic propulsion. Each charged particle of the current is the source of an electric field. And this electric field plus motion is called magnetic field. To gain an utilizable configuration of the magnetic field, the current is usually coil-shaped conducted. The effect of a magnetic field is a deflective one; the trajectory of every relative to the magnetic field moving charge is influenced in a kind, which is depending on the angle between the magnetic field lines and the direction of the moving charge. But also the free moving and deflected charges are the source of a magnetic field. And this field again is affecting the flowing charges inside the coil-current. This interaction of mutual deflection produces the acceleration of electro-magnetic propulsion.

The big point of electric propulsion

There is one more inconvenient fact within space; it is just hardly possible to refuel. Unfortunately this means, that the initially stored fuel is the whole amount, which is available to create impulse. Ziolkowski was mathematically expressing this fact and was telling us that everything is limited in the world of space propulsion. The more fuel one is storing in order to convert into thrust, the more mass the same one has to accelerate; a dead race at the end of the day. But there is one bright light at the horizon: the velocity of fuel as parameter.

When fuel’s mass is a fixed constant, and the impulse (m*v) or the thrust (m*a), respectively, are the target parameters we want to turn as high as possible; the acceleration of the fuel is the key to achieve a high efficient fuel utilization. Respectively the end-velocity after acceleration is the key when we talk about impulse.

Here may be the right place for a little intermezzo to say a few words about thrust and impulse. Both terms are very commonly used in the jargon of space propulsion. And it is often not really clear, which one of them describes the physical origin of propulsion better. In my opinion, it is definitely thrust! Since thrust equals force, and force is a fundament of physics. We talked already about the mutuality of force; when I accelerate fuel away, the acceleration of my spacecraft is the result. A phenomenon named propulsion. Newton’s first law, F=m*a, connects an acceleration with a force in any case. As long as the mutual interaction is working between fuel and craft, both is accelerated. Acceleration is a change of velocity per time; acceleration during a defined time period changes the velocity accordingly within this time period. And since impulse is m*v and thrust is m*a, the same can be said about thrust and impulse: Thrust is a change of impulse per time; thrust during a defined time period changes the impulse accordingly within this time period.

Or again in most simple words; thrust is the process, impulse (or better change of impulse) is the result.

In Ziolkovskis equation, the fuel exit velocity is taken to calculate the gained impulse of a spacecraft through fuel output. In other words, the part of acceleration of the fuel is considered as finished at the point when the fuel leaves the thruster.

This is true for chemical propulsion. The combustion interaction (released through intra-molecular electron-jumps) is happening during the chemical reaction inside the thruster, and it is finished when the fuel leaves the thruster or collides with the thruster walls, respectively. And since the interaction is finished at this point, we are dealing with a constant velocity of fuel during ejection. The gain of impulse for a spacecraft is ejected fuel mass times fuel velocity.

But, this is an estimation for electrical propulsion. The interaction is working between a part of the ship and the fuel and it is not timely limited, like the chemical reaction at chemical propulsion. The interaction between ship and fuel is persisting; also beyond the moment, when the fuel leaves the vehicle. So, the interaction may decrease rapidly when the fuel moves away from the ship; especially when for instance the ion beam is neutralized with electrons or we have a coil-shaped magnetic nozzle, where the magnetic field is mainly distributed in the inner-space of the coil. But basically and physically, the acceleration ends not with leaving the thruster, and it is not completely precise to use the exhaust velocity of fuel to calculated the gained impulse of a spacecraft.

Back to the topic; we recognized that an increased fuel exit velocity is the solution, when the gain of impulse of a spaceship has to be raised on basis of a fixed and defined amount of fuel. One knowledge out of the last two paragraphs is as following: The ability to accelerate the fuel particles of chemical propulsion is limited, since the accelerating interaction is only during the chemical reaction and the strength of this interaction is limited by the states-gap that an electron is covering during this reaction. For instance the exothermal reaction of Oxygen with Hydrogen to form water; two valence electrons of Hydrogen jumping into the valence electron shell of Oxygen, in order to fill this shell with eight electrons and to achieve stability. These two electrons are generating an electromagnetic pulse on their transfer between the states. And when this pulse is emitted, it is accelerating other particles nearby. Here we have the microscopic origin of what we are recognising macroscopically as kinetic of an explosion or combustion, respectively. One can often hear: With chemical propulsion, the energy of propulsion lies in the fuel itself and the kinetic of chemical propulsion is limited by this fact. This phrase means exactly the same.

Contrary to this, electric propulsion do not have such a basic limitation. The acceleration mechanism of fuel particles is not already included within the fuel, but it has to be externally provided. This may sound like a disadvantage. But in opposite, it is the major advantage, since this means that the ability of acceleration of fuel is basically not limited. It is just a technical limitation, how high one can raise the accelerating electrical fields, but no basic limitation. But also with a realistic consideration of the technical limits, the ability of fuel acceleration is with electric propulsion much beyond this ability with chemical propulsion.

At this point, we have worked out the first key knowledge of this pamphlet. It is not really new, but it is worth it to be written down: When you work with repulsion and the fuel is limited (as it is with space propulsion); you should try to eject the fuel with a velocity as high as possible. And the electric propulsion provides this “as high as possible”.

A general motivation for electric high-thrust

If we just look at the efficiency of converting fuel into change of impulse, electric propulsion is doubtless the most suitable kind of propelling. But why, facing this knowledge, electric propulsion is not for each and every space manoeuvre the top choice? The reason is rather simple. So far, we have focused on the total efficiency of converting fuel in impulse. The time this takes does not matter; as long as at the end of the manoeuvre or mission delivers the maximum of changed impulse. But for some missions, a general effective utilization of fuel is just one side of the medal; it is also important to rapidly gain a change of impulse for the space ship.

And this is already the second key knowledge: A tremendous high acceleration of fuel, ejected low-frequent particle by particle, may be a very effective utilization of fuel; but it could be not enough to spend months for changing the impulse, no matter how efficiently this may happen. Sometimes you need the change of impulse of the ship shorted-termed.

In the following, we should try to align this with the technical vocabulary of space propulsion: The significant parameter concerning the absolute efficiency of fuel-utilization is the specific impulse. The specific impulse is more or less an artificially designed parameter; in contrast to the thrust, which is identic to the basic physical quantity force. The specific impulse is the ratio of the impulse, the fuel is generating during its ejection with an exit velocity, divided by the weight of the fuel. And please mind, the weight of the fuel is meant, not the mass; the weight is the attractive force generated by the earth in the distance of normal-null from the centre of earth’s mass, which is influencing the fuel’s mass. Hence, the specific impulse is always the exit velocity divided by the gravitational constant at normal-null and results in a quantity with second as unit.

$$I_{sp} = \frac{m * v}{m * g} = \frac{v}{g} = \frac{v}{9{,}81\, m/s^2} = \cdots [s]$$

The meaningful parameter regarding the per-time efficiency of fuel-utilization is the thrust. The thrust is basically a force, and it is according Newton’s second law the infinitesimal change of impulse divided by the infinitesimal time this change takes. Thereby, the impulse of the fuel is meant; its mass times its velocity. But as we learned above, change of impulse is always mutual; the impulse that ejected fuel has is always identic to the impulse, which the space ship gains. Just the gained velocity is scaled by the mass difference between fuel and ship. It is trivial but since it is one of the main messages of this work, it should be clarified again at this point: both is mutual, the change of impulse (per time or per ejected particle) as well as the absolute and complete impulse, which was gained when the propulsion processes are completed.

$$thrust = F = \frac{dp}{dt} = \cdots [N]$$

The same like above from a slight different point of view: Specific impulse and thrust are both ratios, ratios of changed impulse per a specific physical quantity. The specific impulse is the ratio for the impulse-change per ejected particle. The specific impulse multiplied with the weight (not the mass) of a fuel particle and times the number of ejected fuel particles delivers the absolute impulse. The specific impulse itself is more or less just a technical coefficient to compare and to assess propulsion systems; the value that really counts for a space mission is the derived absolute impulse, derived by scaling the specific impulse with the amount of the completely carried fuel.

The thrust is the ratio for the impulse-change per time this change lasts. The thrust multiplied with the time of the whole propulsion manoeuvre results in the absolute impulse. In contrast to the specific impulse, the thrust as ratio is already an important parameter for each mission. Because it is crucial to know for the trajectory planning but also for unexpected manoeuvers, how the space ship can be influenced per time by the propulsion system.

No matter whether the specific impulse is summed up over the fuel or the thrust is summed up over the time; the result is always the absolute impulse, which is produced by propulsion and gained by the space vehicle.

Two possible requirement scenarios for rapid change of impulse are imaginable. The first one is the need of a sudden manoeuvre like e.g. an evasion action. Characteristic for such kind of manoeuvre is the limitation of time. The trajectory has to be changed within a defined time-frame; ideally before a collision occurs.

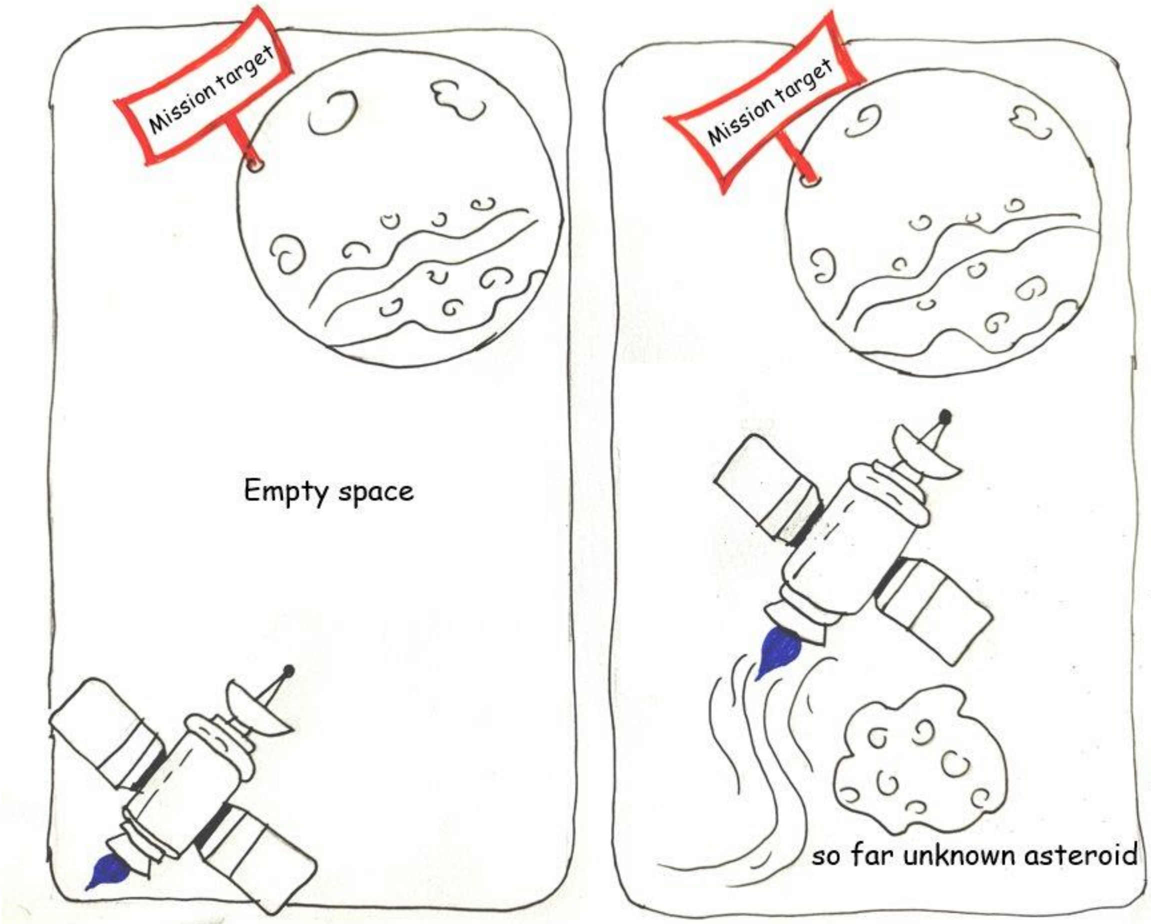


Figure 4: For some missions a high gain of absolute impulse is enough…for some not!

The second scenario, which requires also a fast impulse change, is related to the travel time. For some missions, especially for those with humans on-board, the time of travelling is pretty crucial. It is not only necessary, for those missions, to converse the fuel into impulse as efficient as possible; it is also necessary, to do the conversion as fast as possible.

It is a little bit like cooking potatoes; the faster the water is boiling, the earlier the potatoes are done. Quite the same considerations a Mars traveller may have while sitting in his space ship; of course not concerning done potatoes but regarding his arrival at Mars. He may also hope that his propulsion system is reaching the maximum velocity as fast as possible, in order to shorten his travelling time. Since it is a simple insight, the earlier a ship is reaching its maximum speed, the higher is the average velocity of the complete journey, and last but not least the shorter is the travel time. As meanwhile every mindful reader knows, the ejected fuel is changing the velocity; and therewith the impulse of the spaceship. With the use of an electric thruster we already took care that the conversion of fuel into impulse is efficient in general. But how to realize that this conversion is not just efficient but also fast? This is easy in theory; impulse change per time is called thrust. Ergo, for a fast change of impulse, or velocity respectively, one needs high thrust.

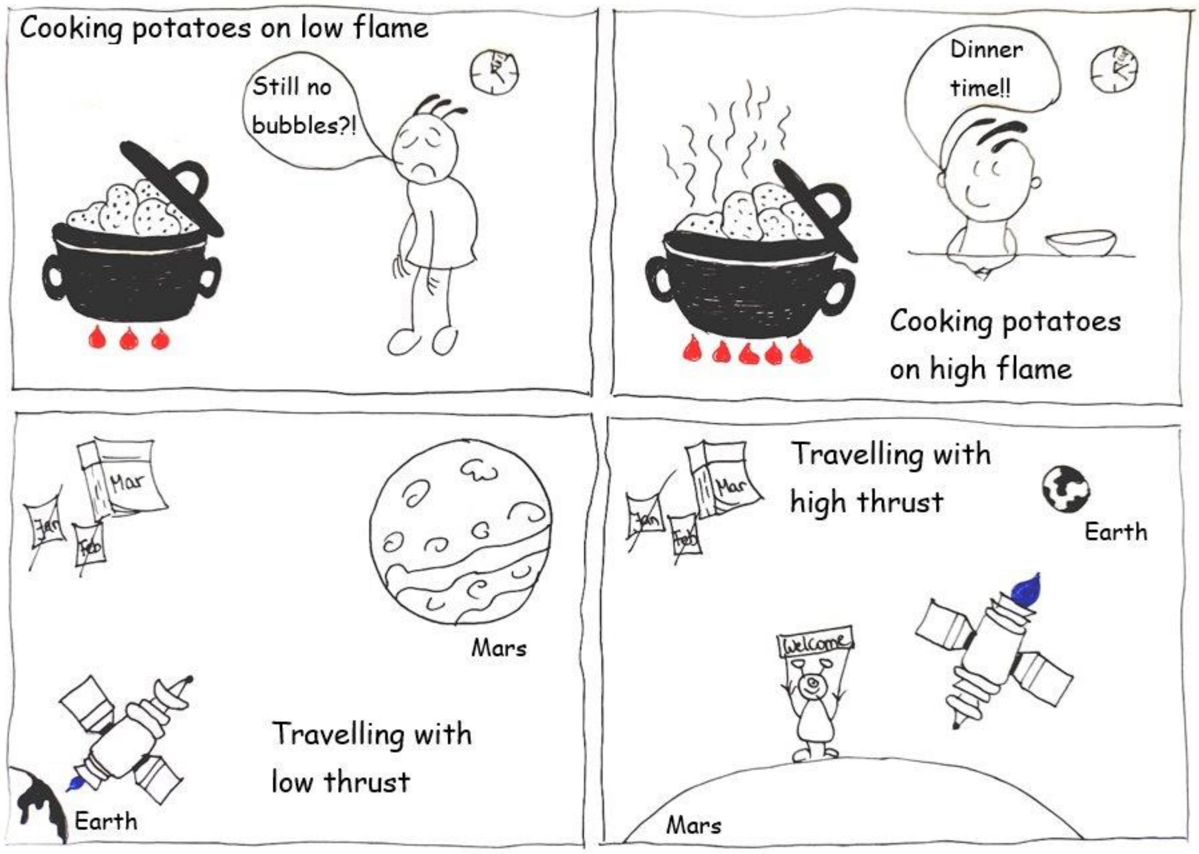


Figure 5: An efficient Mars mission is like cooking potatoes

The summary and derived insight of this general part can be expressed as following: The properties of electric space propulsion are doubtless superior compared with other kinds of propulsion. Especially two features are outstanding: the ability to be switched on and off on demand and the high efficiency of conversion fuel into gain of impulse. One disadvantage is only the technology-based limitation of the number of ejected fuel particles, which leads to a low rate of changed impulse per time; to low thrust. And we have seen above, a sufficient high thrust level also of a continuous propulsion system like electric propulsion is absolutely desirable for the needs of space travelling.

Ideally, a perfect realization of continuous high-thrust propulsion would mean an electric propulsion mechanism (high-speed particle ejection) as fundament and basing on this, the ejection of many particles per time.

<u>A specific motivation for the "Helios" concepts</u>

The possibilities to realize electric propulsion are manifold. One needs only neutral medium (most often a gas, and in the following we want only want to have the focus on gases). Then the same one ionizes this neutral medium; and this is very important, since this opens the gate for electromagnetic influencing of the medium and for externally accelerate it.

So far electric propulsion in general. But how to increase the thrust, how to increase the amount of ejected fuel per time?

Basically, there are two options: to eject heavier particles or to eject more particles per time. The first option end up in a not very useful scenario. Since, the more the thrust is supposed to be raised, the heavier the single fuel-particles have to be. This means, for a significant increase of thrust, a more and more granular behaviour of the thrust has to be accepted. This means, the second option is the more promising approach.

Thus, the challenge is now, to enhance the number of per time emitted fuel particles. As mentioned, electric propulsion bases on the influencing of charged particles, which are ionized and formerly neutral particles. Hence, and there is no choice, one have to increase the number of neutral particles, which are ionized and influenced subsequently. And since the physical meaning of a higher number of particles at the same time (and of course inside the same volume, because we are talking about identic thruster systems) is a higher pressure of the neutral gas, our problem can be reduced to the challenge of ionizing a gas under high pressure conditions.

Cracking the insulator high-pressure gas

At the end of the day, the specific mechanism to ionize a gas doesn't matter. No matter whether with an electrostatic field, inductively or capacitively coupling high-frequent alternating electric fields, electromagnetic waves, or even light or radioactivity, only the result counts: to converse an insulating gas into a conductive plasma. For this reason, everybody is free to use and to prefer his own mechanism of ionization; here is none better than the other is. Just some special conditions have to be considered, which are connected to the planned utilization in space. The conditions are the long distance to the next opportunity to repair or exchange worn parts and the very limited resources to produce electricity; to generate applied voltage and to collect charge carriers for currents, more particular. And the derived requirements are high durability and less erosion of all parts and to budget with all activities that need electricity. This means in the context of gas ionization, that terrestrial normalities become astronautical crucial concerns.

On the earth, high applied voltages for direct or capacitive gas-breakthroughs or high currents to achieve an inductive ionization of a gas also under high-pressure conditions are normally no problem, as long as the laboratory owner is paying his electricity bills. In space, the basic resources for electricity are limited in general. The main source to produce electricity is still the sun. But solar cells are not really know for the generation of a plenty number of electrons; especially when you are travelling to the outer regions of the solar system. And even radioactivity as electricity source, a radionuclide battery or a handy little nuclear reactor, is not comparable with a terrestrial power plant. And this means for every electric propulsion designer: come clear with the limited value of voltage or current, respectively, you have available in space.

The means of choice with the “Helios” thruster concept to handle the limitation of voltage and current values is to conduct the gas ionization basically in two stages. The idea behind is as following: The maximum requirement concerning voltage (capacitive ionization) or current (inductive ionization) is due, when the gas, which is supposed to be ionized, is within a complete neutral state; this is the broadest gap that one have to jump over from an energetic point of view. And in this picture, several but lower gaps would care for moderate voltage or current levels along the staged and sequenced ionization, instead of demanded high levels for an ionization at once.

The first stage or pre-stage of a “Helios” ionization system is always meant as a conditioner of the initial situation of the complete and main ionization. For that reason, the chosen title of this section is “cracking the isolator neutral gas”. And it is a kind of cracking or breaking the ice in other words; when free electrons are generated, only little amounts or in a small region of the ionization area, then the external applied electric field is able to couple in these free electrons. These electrons will be accelerated, electrical energy converts into kinetic energy of free electrons, and kinetic energy of free electrons converts into inner energy of atoms in case of a collision between the free electrons and the neutrals of the gas. And at the end, when this inner energy is surpassing a specific threshold, ionization is the result. Thus, this whole avalanche called ionization starts with that tiny little snowball of free electrons, which are generated by the pre-stage.

The “Helios” concept knows two different kinds of such pre-stages; an electrical and a chemical, which distinguishes the thruster concepts “Helios-1” and “Helios-2”. The electrical pre-stage of “Helios-1” is a locally limited capacitive discharge. The electrodes of this discharge are generating a path of plasma near the neutral gas feed inside the thruster. The flow of neutral gas is distributing the released electrons of this pre-plasma, which act as ionization seed for the main discharge, inside the whole discharge chamber of the thruster. The origin of the alternating electric field, which is sustaining the capacitive discharge is a loosely coupled resonance transformer designed by Nikola Tesla; that’s why it is commonly called Tesla coil. The functionality in short words: an externally supplied primary coil is resonantly coupled to a secondary coil. The primary coil has just a few windings, but the secondary coil much more. This huge difference in the numbers of windings is effecting a high voltage between the ends of the secondary coil. This voltage is causing the discharge. The feature of such a Tesla transformer is a huge peak output, but only a medium average power. So it is ideal for the utilization inside a high-thrust plasma propulsion system; on the one hand side it is possible to supply it under space conditions with only limited electric power resources, on the other hand side it is producing voltages on a level that enables the ionization of a high-pressure gas; at least the partial ionization.

The pre-stage of the thruster concept “Helios-2” is a chemical one. The combustion of a burner is firing near the inflow of the fuel for the thruster. To prevent confusion, the fuel for the thruster is a neutral gas, which is supposed to be ionized; Argon or something similar. The combustion is an oxidation, and the fuel for this chemical pre-stage is an oxidizing agent and a reducing agent, both are conducted into the burner and react chemically. During this reaction, binding electrons are moving between orbits and emitting in this way electromagnetic radiation. This emitted radiation is accelerating other particles, which are nearby. The result is a microscopic increase of the kinetic energy of the involved particles, which is identic with a macroscopic increase of the temperature after combustion. Inside such a collision-dominated ambience, the distribution of particle velocities is according Maxwell’s regarding law: For each macroscopic defined temperature, there is a broad distribution of the velocities of the microscopic involved particles. Therefore, for a given combustion temperature is always a specific amount of particles existing with a kinetic energy beyond the ionization energy of the main fuel, e.g. Argon. This means, passing Argon is heated up beyond the value, that a thermal collision is sufficient to ionize neutral Argon and forms a plasma. The free electrons within this small amount of thermal plasma is in this case the seed for the main ionization.

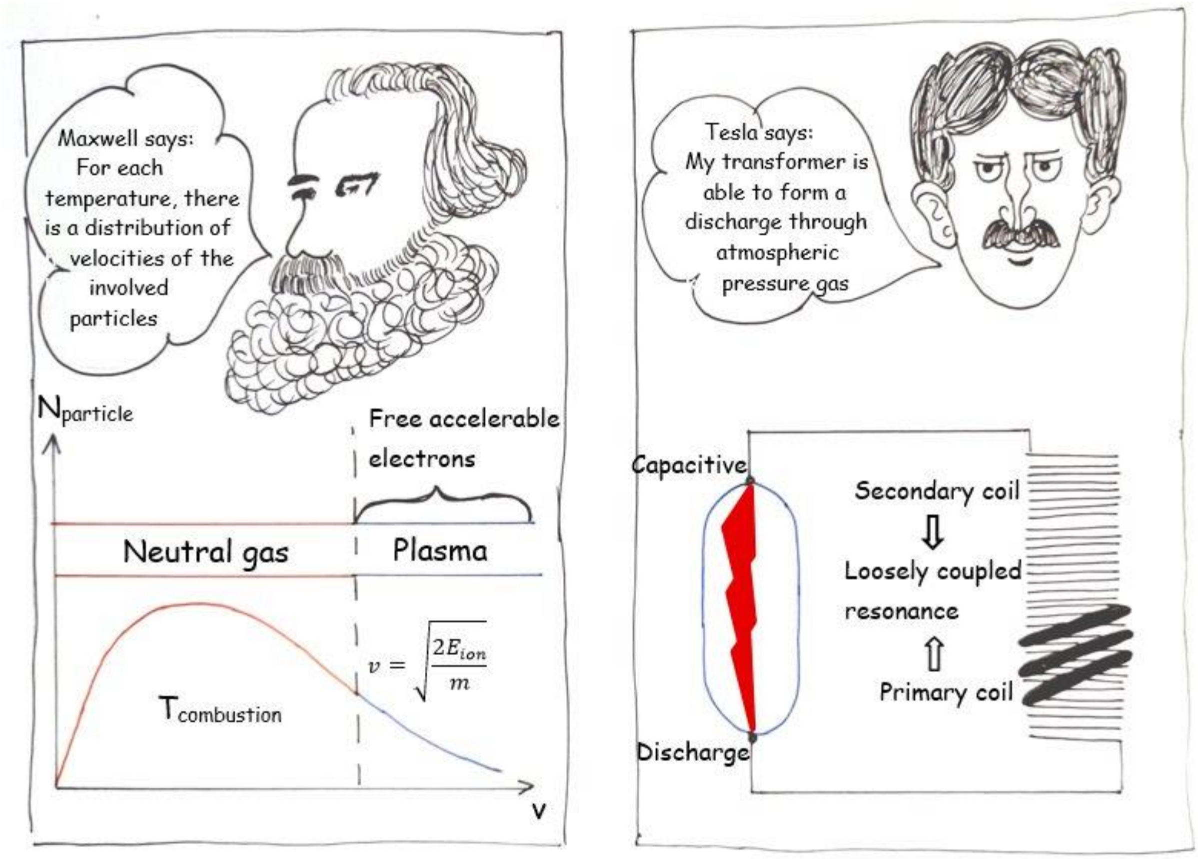


Figure 6: The two ways of "Helios" to crack a high-pressure gas

The second or main stage of ionization is for both thruster concepts, "Helios-1" and "Helios-2", an inductive coil, which is carrying a high-frequent alternating current. At the pure electric "Helios-1" concept, the mentioned coil is identical with the secondary coil of the Tesla arrangement. This coil or current, respectively, is the source of electric eddy-fields, which are penetrating the inner-space of the coil. There, the alternating fields are coupling into the free electrons, provided by the respective pre-stage, and accelerate them. The rest is simple electron bombardment ionization; when the accelerated electrons are fast enough, they are able to generate inner energies beyond ionization energy through inelastic collision with the neutral atoms. These atoms are ionized by this and plasma is the result.

The two regimes of conversion electricity into thrust

The purpose to create these thruster concepts was to realize an electric propulsion system with an enhancement of thrust. The chosen means to achieve this was to try to increase the number of per-time ejected fuel-particles. With the two-staged ionization system, which was described above, we have made the half way: we are able now to produce a sufficient number of potentially thrust-generating particles inside the thruster. The rest of the way is to find an extraction system, which is able to eject such particle densities.

A perforated grid, where an electrostatic field arises from, is always accelerating only one charge species away from the thruster. Usually, for space propulsion applications, this species are positive ions. Hence, such gridded systems are also called ion thrusters. An applied electrostatic field is a direct and very efficient method to accelerate an ion. It is possible to achieve very high ion velocities while extraction. This is the huge advantage of ion propulsion systems; the specific impulse (I_{sp}) can become incredible high. This means in other words, the over-all utilization of fuel with ion propulsion is just hardly beatable.

But the same circumstance is also responsible for the huge disadvantage of ion propulsion; the limitation of thrust. When just one charge species is accelerated, in this case positive ions, one has within the ejected particle current internal repulsive electrical forces. Each ion is repelling each neighbour ion inside the current. This fact is counteracting the intention to eject a particle current as dense as possible, in order to achieve high thrust. Per particle, the conversion of fuel into thrust is outstanding with ion propulsion. But it takes time to eject a given amount of fuel. So, per time, the gain of impulse is very limited with this type of propulsion. Phenomenal I_{sp}, but only a small thrust.

One remark; it is commonly known that ion beams of space propulsion systems are neutralized with electrons. So, the internal repulsive electric forces are compensated after neutralization. But still, directly at the grid in the moment of extraction, there are only positive ions. Right here is the weakest link in the chain. Right at this place the density of extracted particles is limited. So also neutralized, ion propulsion is obviously not the right tool to achieve high thrust levels.

We need a mechanism, which is basically ejecting both charge species at once and into the same direction; the positive together with the negative ones. Only in this case, there are no internal electric fields inside the extracted particle beam during the whole extraction procedure. There are no restrictions to increase the density of extracted particles. The extraction of increased numbers of fuel particles per time is achievable; high thrust is possible. The key word for this mechanism is plasma propulsion. In contrast to ion propulsion, the plasma propulsion is ejecting electrons together with positive ions. This is not possible with applied electrostatic fields. But the Lorentz force is able to deflect positive and negative charges into the same direction. This general property of charge-influencing by magnetic force, which Lorentz describes with his law, is determining magnetism as key for a high-thrust extraction. For that reason, an applied magnetostatic field is the means of choice of extraction for the "Helios" plasma thruster concepts. A coil, which is carrying a constant electric current, is generating a static magnetic field at the exit of the plasma thruster. The task of this applied magnetic field is to generate a directed thrust.

Basically, the thrust generating particles are gaining their kinetic momentum already inside the main-ionization stage. The inductive electric field, which is responsible for ionization, is also accelerating the charged particles after ionization. Actually, only the electrons are accelerated by these fast alternating eddy fields; since only the light electrons are able to follow the fast change of field direction, the much heavier ions are just too kinetic inert. Thus, the conversion of electric energy into fuel particle momentum is a direct mechanism only for the involved free electrons. And above this, that gained particle momentum is not directed, the particle directions are distributed over the whole space; so it is not utilizable to deliver thrust or space ship impulse, respectively.

So we are facing two challenges: We have to transfer the gained kinetic momentum from the electrons onto the ions. Since the ions are the massive particles, which are able to produce significant thrust by repulsion. And additionally, we have to align the repulsive particles when they leave the thruster. Since only with directed ejection of particles, we will establish a defined thrust vector for the space ship. When the acceleration of the particles inside the thruster is stochastic, also the microscopic transferred thrust is stochastic; which means, the resulting macroscopic thrust is zero. The static magnetic field at the thruster's exit is solving the second problem: The magnetic lines of the field are parallel to the thruster axis. Each particle's movement can be expressed basing on two basis vectors;

one parallel to the thruster axis and one perpendicular to this axis. According the rules of magnetic deflection, the perpendicular component is forced into a circle and the parallel component remains unaffected. The result is a spiral-shaped trajectory of the charged fuel particles on their way out of the thruster. We have a direction of ejection and hence a generation of thrust.

The concrete mechanism to handle the first challenge, to transfer the momentum from the electrons to the ions in order to generate thrust, is depending on the gas pressure of the applied neutral fuel gas; and we will see that we are facing actually two concrete mechanisms. The efficiency of transferring impulse from electrons onto ions by elastic collision is depending on the frequency of collisions. The mass difference between electrons and ions is tremendous, almost like a tennis ball is colliding with a wall of bricks. The wall remains in rest, the ball comes with the same speed back as it was thrown against the wall; when we look at a pure elastic collision. In this scenario, the transferred impulse is at its maximum; it is two times the velocity times the mass of the electron ($2*v_e*m_e$). But as said, the ion is only almost a wall. It will move slightly, when an electron hits it. This means for an ion, the transferred impulse is always smaller than this maximum value of $2*v_e*m_e$. And this means for the electron, the absolute value of the impulse after collision is smaller than before collision. Thus, many collisions (many is scaled by the mass difference) are needed for a significant transfer of impulse between two such mass-different particles like electron and ion. Precisely spoken, an ion needs many collisions with electrons to gain significant impulse, and an electron needs many collisions with ions to lose significant impulse. It is not necessarily always the same pair of ion and electron, which have to collide; the rate counts to transfer an impulse from a total number of electrons onto a total number of ions. This is the first mechanism, how the electrons are able to transfer their externally received impulse to the ions. And this mechanism is determined by collisions.

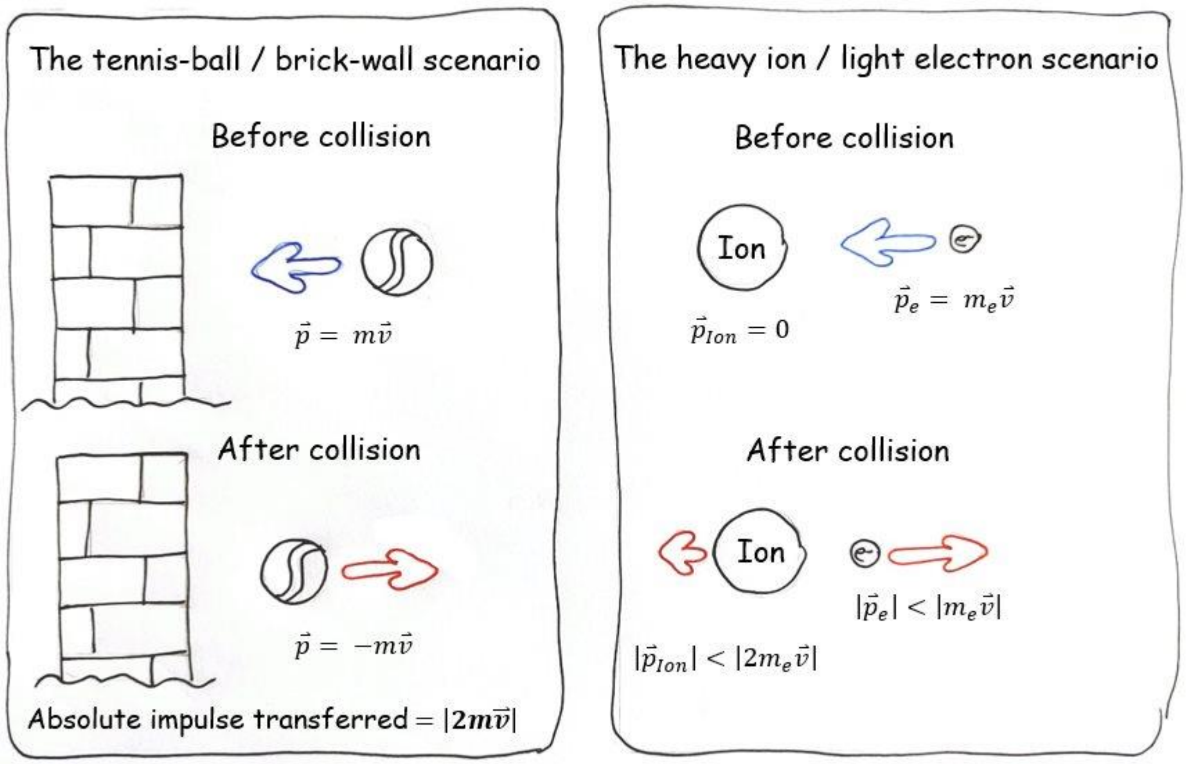


Figure 7: Transferring electron's impulse to an ion

In comparison, the second mechanism is determined by a field effect. Since the externally applied and rapidly alternating electric field is coupling exclusively into the electrons with their low inertial mass, the electrons are the charge species, which is accelerated by the eddy fields. As a result, the electrons become much faster than the ions. Due to the collisional processes inside a plasma, the trajectories of the accelerated electrons are stochastically distributed. By passing the magnetic field at the exit of the thruster, the movement of the electrons will become aligned parallel to the thruster axis, as well as the ions. After this alignment, there are two charge-currents; the slow ion current and the fast electron current. This velocity difference of the two charge species is responsible for a negative charge accumulation at the exit of the thruster, which leaves behind an accumulation of positive charge. A resulting electrostatic field between these charge accumulations is responsible for the thrust-generating acceleration of the ions out of the thruster. This constellation can also be named “dynamic grid”. Since in opposite to a usual grid configuration nothing is fixed and static here, but the mechanism of acceleration through electrostatic fields is basically identic with a gridded system.

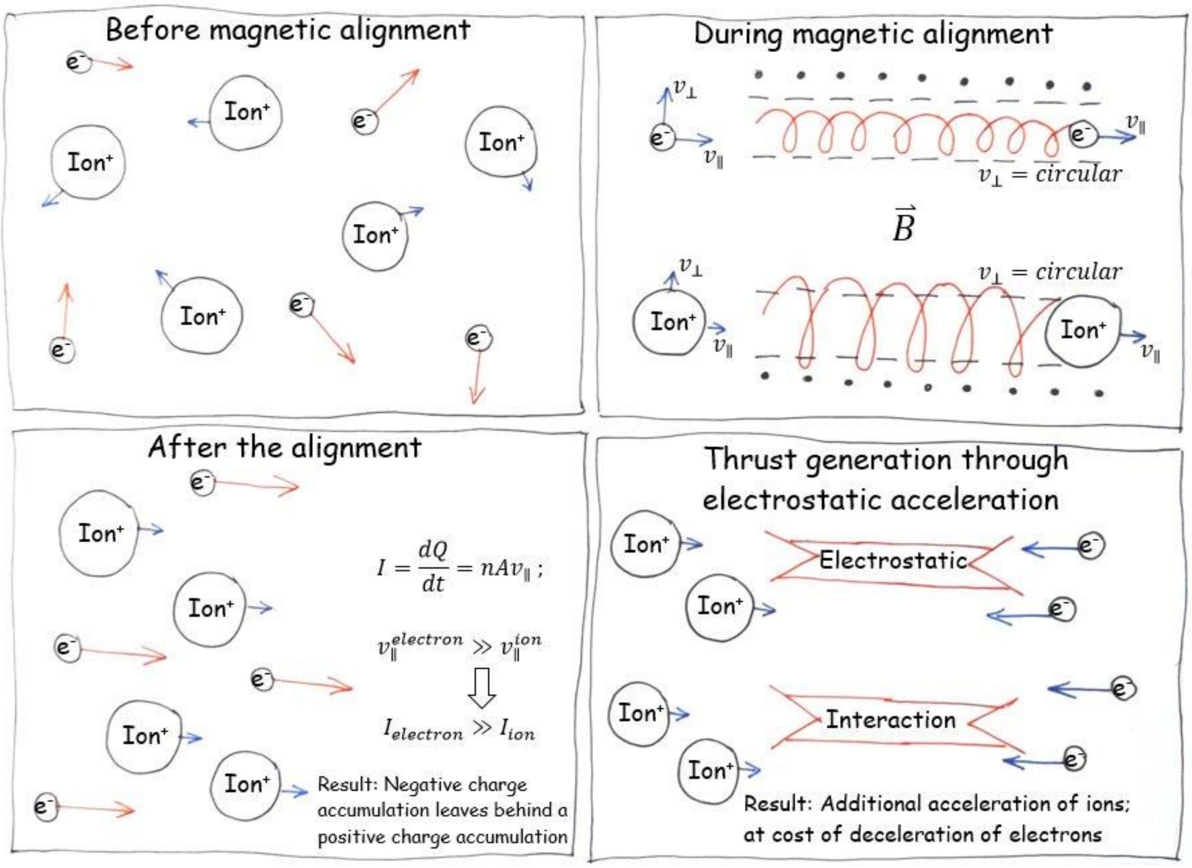


Figure 8: The second mechanisms of impulse transfer of “Helios”; the dynamic grid

Basically, both mechanisms of impulse transfer from electrons to the ions are coexisting within a “Helios” thruster. But which mechanism is the dominant one, this is depending on the pressure of the fuel gas. The first mechanism is dominant if the pressure is high-enough to form a high-dense plasma. Because in this case the frequency of the collisions is sufficient that the electrons are able to balance their impulse with the ions, on the one hand side. And on the other hand side and also due to the high-frequent collisions, the difference of velocities between electrons and ions becomes not that high.

But when the produced plasma is low dense, basing on the ionization of a low-pressure gas, the low-frequent collisions are not able to care for a balancing of impulse. But the electrons will gain additional velocity on their accelerated but collision-less path. And this will be responsible for a maximum of negative and positive charge accumulations. The resulting electrostatic field becomes maximal too, and ergo this second mechanism is the dominant thrust generation. Collision-dominant and field-dominant processes are both pressure depending; the first one directly proportional and the second inversely proportional.

Therefore, we can define two regions of impulse transfer between electrons and ions: The pressure of the neutral fuel gas is high enough to form a plasma, which is dense enough to provide collisions in a frequency, which cares already within the ionization stage that the electrons have balanced their exceeded impulse with the ions. We remember, the excess of electron impulse comes from the direct coupling of fast alternating fields exclusively into the electrons. In this case, we have a direct and initial transfer of impulse. The magnetic field at the exit of the thruster just needs to align the trajectories of the fast ions in order to produce a directed thrust. Within the second scenario, the impulse balancing between electrons and ions happens inside the extraction stage; when the electrostatic fields, caused by the charge accumulations, is attracting ions and electrons towards each other; with the result of an additional acceleration of ions.

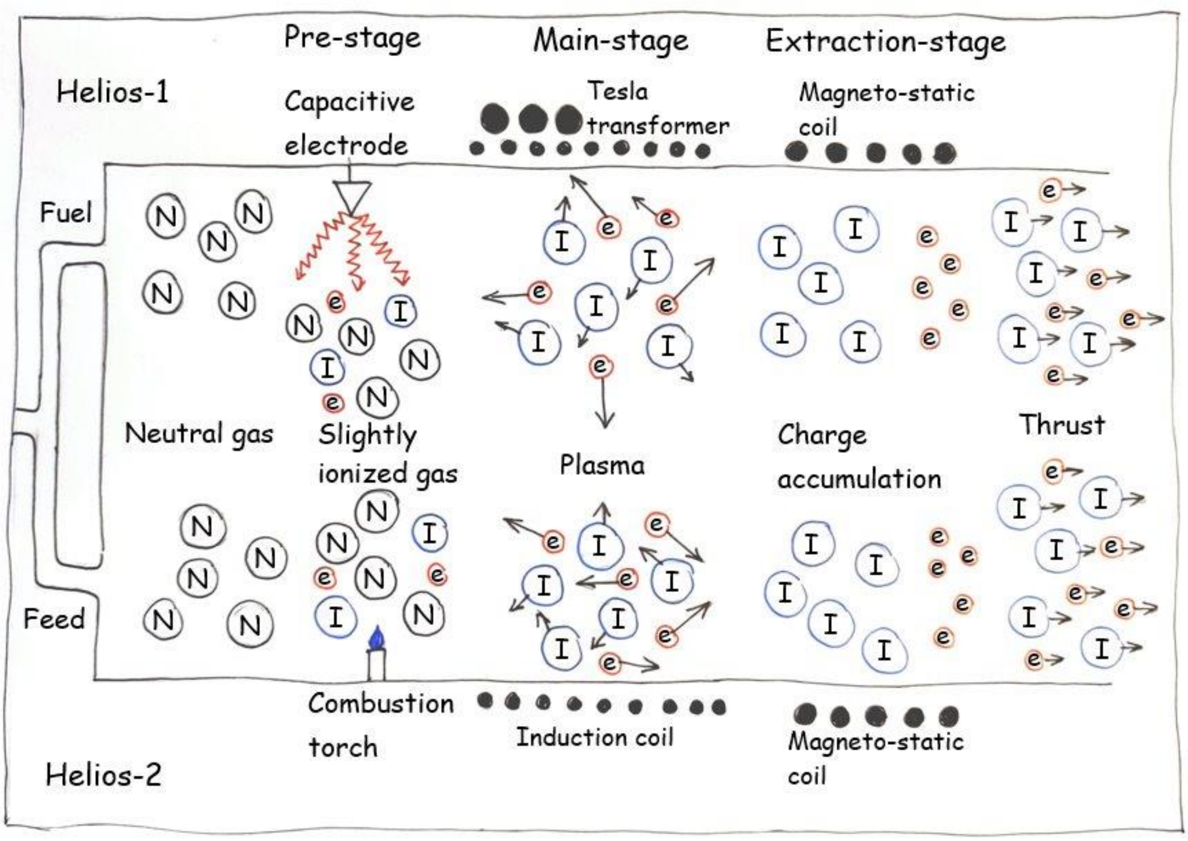


Figure 9: Scheme of both propulsion concepts “Helios-1” and “Helios-2”

At the end of the reading, the smart reader may have recognized that so far the specific mechanism, how “Helios” is driving a spaceship, was not mentioned. Of course, we talked about the macroscopic gain of impulse through collision transfer from electrons to ions, aligning charged particle trajectories inside a magnetic field and electrostatic acceleration by charge accumulations. But under the magnifier of microscopic physics, it is not clearly defined, where the interaction happens that brings the impulse from the fuel particles onto the ship. It is not enough to see particles leaving the ship; the interaction, which is accelerating these particles outside, has to involve the ship’s structure. Otherwise, nothing is accelerating the ship.

And here on microscopic scale, we have again two mechanisms, which are responsible that the spacecraft gains impulse. The first one is preparing the conditions that the fuel is enabled to transfer impulse to the ship. The magnetic coil at the thruster exit is aligning the omnidirectional charged particles. Due to the huge difference of inertial mass, the electrons inside the plasma and under affection of the fast alternating electric field are much faster than the ions; but the movement is stochastic. When they are entering the exit stage of the thruster, which is surrounded by the magnetic coil, they are aligned along the magnetic field lines. The result is the generation of a directed current of electrons, which is leaving the quasi-neutral plasma. This exodus of electrons is generating strong electrostatic fields inside the now positively charged plasma. In this initial situation, the second mechanism of impulse transfer from fuel to ship starts.

The second mechanism is very similar to the microscopic mechanism at chemical propulsion. The aligned and faster electrons are leaving behind a charge accumulation of slower ions. Within this cloud of ions, repulsive forces are working between each and every ion. And this really sounds like the chemical propulsion scenario; but there is electromagnetic radiation, which is emitted by the valence electrons of a chemical reaction, the means of interaction. In the current case, electrostatic forces are responsible to have the ions accelerated apart. But the consequence is identic: the ions are accelerated in random directions. The impact at the symmetric side-walls compensates. And when the ions hit wall-structure in opposite to the thruster exit, they exchange impulse by collision.

These reflected ions after collision are leaving the thruster together with the rest of the ions. This extraction of ions is strongly supported by the cloud of electrons, which was formed as an effect of the current of faster electrons towards thruster exit. Thus, an additional feature of the “Helios” thruster is the balanced ejection of ions with electrons. This prevents the charging of the spaceship; which is always a potential risk with electric propulsion.

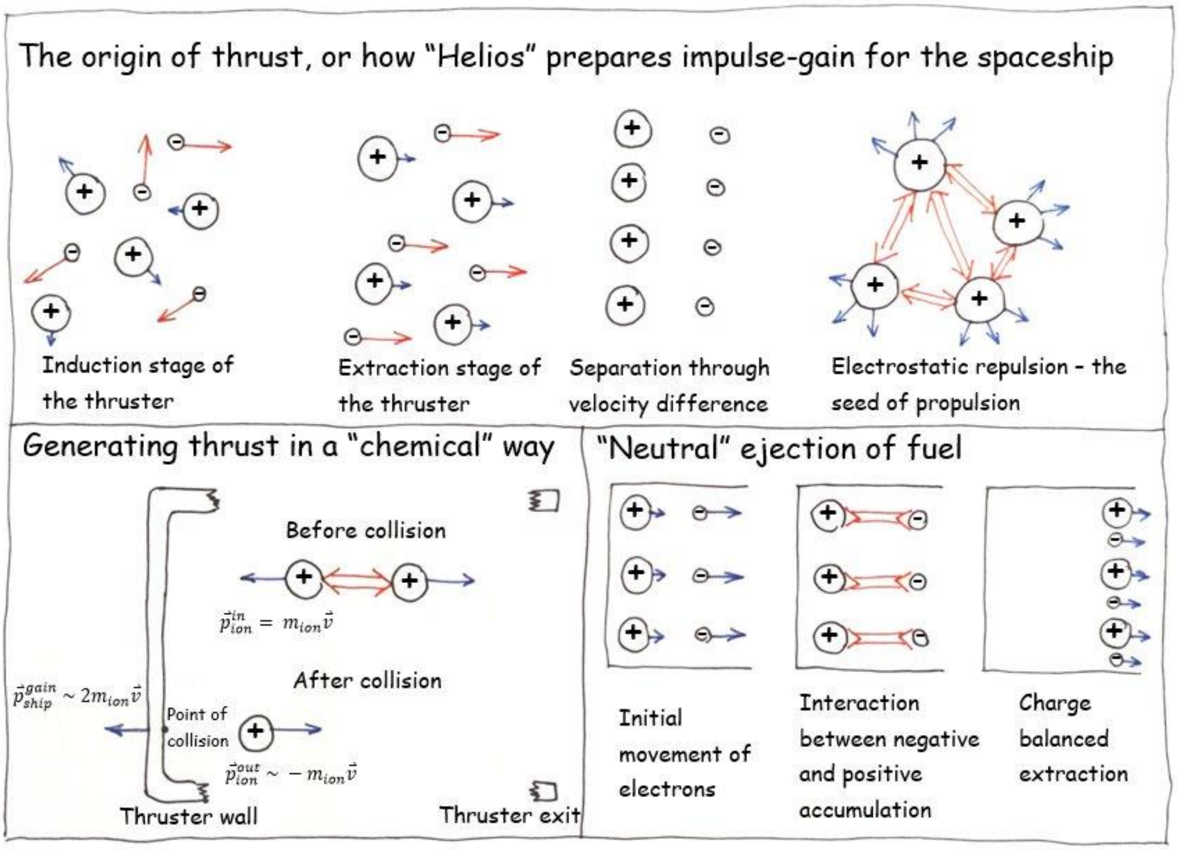


Figure 10: The microscopic view on the impulse transfer of "Helios"

Summarizing these facts above, the "Helios" thruster can be seen as electrical thruster with chemical-like thrust generation. The major parameter, which is determining the performance of the thruster, is the velocity difference between electrons and ions. This velocity difference is proportional to the kinetic energy, which is working against the quasi-neutrality of the produced plasma. This means, it is working against the electrostatic fields, which occur when one of the different charge species is shifted against the other, with the purpose to get back into electrostatic balance. The faster the electrons are, the larger is the shift between electrons and ions and the higher is the electrostatic force within the ion cloud and finally, the higher is the thrust performance of the propulsion system. The minor parameter in this context is the rate of collisions of electrons with ions; since also the impulse, which is transferred directly from the fast electrons onto the ions, is increasing the thrust-generating ability of the ions.

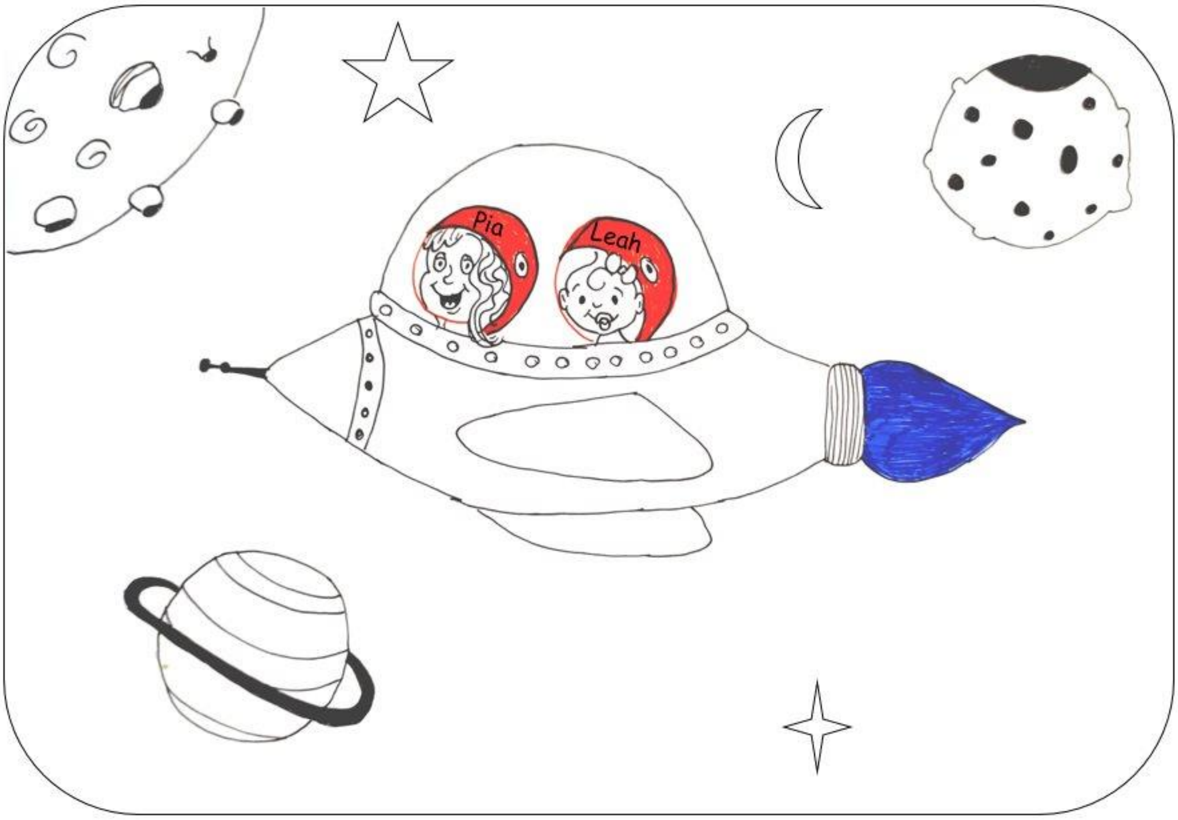
Epilogue

Derived from the basic relations of repulsion and propulsion, we found the niche of electric high-thrust propulsion. This type of propulsion represents an overlap of two, normally divided, propulsion-benefits; a high ejection velocity on one hand side, and on the other hand side a high ejected particle density. Both combined provides efficient fuel utilization together with impulse-change flexibility. A propulsion system with such properties is able to fit for several challenges of space exploration. But most of all, it can help to solve the transportation problem for human interplanetary travelling. With its unique combination of thrust and specific impulse, it provides the opportunity to shorten the time of journey and to react on needs of emergency corrections of the trajectory of the ship. Both is essential for human space exploration.

One more potential application could be the support of an upper stage of a space transportation system. Regarding thrust, there is no alternative to chemical propulsion currently. Only a chemical reaction is able to provide the magnitude of density of ejected fuel, which is able to change the impulse of a rocket in a quantity that it is possible to overcome the earth's gravity attraction. The fuel ejection may be dense, but the propulsion in general is not really efficient regarding conversion into impulse. It would make sense, to add a more efficient propulsion component in order to raise the over all efficiency. The requirement for this additional component is to be in a thrust-magnitude significantly comparable with the chemical main-thruster; otherwise, it would be like adding a hamster wheel to the main engine of a Ferrari. However, if there is once a high-thrust electric propulsion available, this could be an adequate auxiliary thruster for a space transportation system in order to improve the fuel utilization. Of course, the maximum possible improvement of the efficiency of the fuel utilization would be the use of ambient atmosphere gas as fuel for these auxiliary thrusters; since in this case, none of the fuel has to be accelerated with the spaceship and fuel would be no burden for the gain of impulse of the ship. And because the Helios thrusters are designed to ionize a gas with high pressure, to breathe atmosphere would definitely be an option for them.

But these two examples are only possible flagship applications. Over the whole field of space activities, there are multiple utilization options for electric high-thrust. And it is a clear statement for the future of propulsion; continuous electric high-thrust will enrich the landscape of propulsion and has the potential not only to improve mission scenarios but rather to lift space exploration to the next level.

For Leah and Pia…



…you are the generation that will go beyond!

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