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APPLICATION OF CFIS FOR EP SYSTEMS SUMMARY REPORT

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List of acronyms and abbreviations

Indice degli acronimi e abbreviazioni

AD	Applicable Document
AEFT	Alternate Electric Field Thruster
CFIS	Cluster Fragmentation Ion Source
CFI	Cluster Fragmentation Ionisation
CST	Cluster Separation Thruster
CT	Charge Transfer
DM	Demonstration Model
DS	Dual Stage
EM	Engineering Model
EP	Electric Propulsion
EPS	Electric Propulsion System
GIT	Gridded Ion Thruster
HET	Hall Effect Thruster
HW	Hardware
MD	Molecular Dynamics
MPDT	Magneto Plasma Dynamic Thruster
MPQ	Max-Planck-Institut for Quantum Optics
N/A	Not Applicable
OM	Order of Magnitude
PIC	Particle in Cell
RD	Reference Document
RF	Radio Frequency
PM	Progress Meeting or Project Manager
WBS	Work Breakdown Structure
WP	Work Package
WPD	Work Package Description

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1 Introduction

Cluster Fragmentation Ion Source (CFIS) is a quite innovative *chemomechanical* ionisation process. A pressurized gas or vapour of polar molecules (pure or a mixture) is expanded through a nozzle into vacuum, to a temperature low enough for condensation to take place, i.e. the formation of molecular clusters. Controlled by the expansion conditions clusters of considerable size can readily be formed. Enclosing already a tiny volume they represent nanoscopic reaction chambers in which the said charge transfer reactions can efficiently take place under bulk-like conditions. Hence, geminate charge pairs are spontaneously formed within the molecular cluster. Separation of the charge pairs is achieved by fragmenting the molecular cluster via a cluster surface collision. Thus, the energy to transform the interacting charges into free charge carriers is provided via the kinetic energy that the cluster gained during its formation in the gas expansion. By carefully selecting the reaction system and the expansion conditions, it is therefore possible to create large amounts of free charge carriers inside a fluid by a simple adiabatic expansion into vacuum. No external power has to be supplied to achieve ion formation. Moreover, typically positive as well as negative charge carriers of considerable mass are created. Via the collision energy the size of the remaining solvation shell around the core ions can be influenced. This allows to tailor the mass of the formed free charge carriers to specific needs.

The CFIS technique appears to be interesting for application to space electric propulsion at least for the following three reasons:

- propellant ionization does not require electric power. With reference to a typical Hall-Effect Thruster operating at a discharge voltage of 300 V, basically coincident with the acceleration voltage V_{acc} , power losses associated to propellant ionisation are about 15% of the total electric power; this percentage decreases as $1/V_{acc}$. Then CFIS appears particularly advantageous with respect to other electric propulsion option for low power applications and/or high propellant mass flow rates (for instance in MPD thrusters, processing up to several grams per second, ionisation losses have a great impact on thrust efficiency).
- the mass of charge-carriers after clusters fragmentation is above ion mass for typical propellant (Xe); this means lower charge-to-mass ratios which are of interest particularly for Gridded Ion Thrusters whose specific impulses are typically too high for most near-Earth missions. Moreover through the appropriate choice of the expansion parameters in the CFIS stage, this ratio can be varied to a certain extent in order to match the desired specific impulse value at the same grids voltage.
- no neutralizer device is necessary, eliminating another source of power loss and simplifying thruster design and then increasing its reliability.

The program had the objective of assessing the feasibility and potential of CFIS application to EP field. In particular the identification of a possible innovative thruster concept was the main focus, together with the analysis of its main advantages and drawbacks with respect to the state-of-art in electric thrusters panorama.

The overall study, involving Cluster GmbH, as CFIS know-how owner and Alta Spa as leader in EP research, has been structured in two main parts.

The first part concerns the revision of CFIS technique in order to identify most promising CT reactions for EP application, according to EP specialists requirements, especially in terms of propellant utilisation efficiency and propellant suitability for space environment.

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At the same time Alta has carried out the necessary activities for conceiving one or more possible electric thruster concepts, exploiting CFIS as ionisation stage, and for analysing their performance and principal characteristics.

At the end of this phase, one particular concept has been selected as the most promising in terms of performance, feasibility and to a certain extent also in terms of mission application perspectives.

In the second phase the conceptual design for the selected CFIS-based thruster has been carried out and a very preliminary design for the first laboratory prototype has been proposed, aimed to be a proof-of-concept and to demonstrate the potential of CFIS technique in EP field.

Finally a development plan leading to an advanced model, precursor of an EM, has been prepared and main critical issues, that should be the focus of next R&D activities have been identified.

This document will review in a concise manner all above mentioned activities.

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2 Reference and applicable documents

2.1 Applicable Documents

AD	Document Identification	Is	Date	Title
1.	18458/04/NL/PM		20.09.04	Application of Cluster Fragmentation Ion Sources for Electric Propulsion - Contract
2.	ALTA/P-073/CFIS	1	15.04.04	Application of Cluster Fragmentation Ion Sources for Electric Propulsion - Proposal
3.	ALTA/CFIS/NMM		17.09.04	Negotiation Meeting Minutes (Contractual KO)
4.	ALTA/CFIS/InMM		28.10.04	Internal Meeting Minutes
5.	ALTA/CFIS/IMM		11.03.05	Intermediate Meeting #1 Minutes
6.	ALTA/CFIS/TN-1	1	17.08.05	Identification of potential areas of the CFI technique for Electric Propulsion
7.	ALTA/CFIS/TN-2	1	17.08.05	Survey and Analysis of potential charge transfer reactions for a Cluster fragmentation Ion Source
8.	ALTA/CFIS/TN-3	1	27.08.05	Performance of propulsion systems based on CFIS thrusters and identification of missions applications
9.	ALTA/CFIS/TN-4	1	13.02.06	Conceptual designs of CFIS electric thrusters and guidelines for the design of a prototype
10.	ALTA/CFIS/TN-5	1	13.02.06	Design and definition files of the laboratory prototype with expected performances
11.	ALTA/CFIS/TN-6	1	13.02.06	Design and Development Plan for a CFIS electric thruster

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3 Phase 1 activities & results

3.1 Cluster Fragmentation Ionization

Cluster Fragmentation Ionization introduces chemical reactions to the field of electric propulsion. Specifically, it employs a charge transfer reaction to form pairs of oppositely charged ions within a propellant fluid. While the gas phase ionization of individual atoms or molecules is a energy consuming process that generally does not occur spontaneously, the situation changes drastically when ionization processes in the condensed phase are considered. Especially in polar solvent or in solvents of high polarizability, the interaction with the environment reduces the required energy to form a charge pair to such extent, that ionization processes can be driven by small, omnipresent thermal energies without external excitation.

Figure 3-1 depicts schematically this situation: Just by mixing two reaction partners in a macroscopic reaction vial, a charge transfer reaction takes place spontaneously, that converts part of the reaction partners into their ionic form. These ions are solvated and hence stabilized by the surrounding neutral molecules. The total amount of positive and negative charge is exactly equal. Well known bulk chemistry examples are acid/base reactions like HCl and water etc. As can be seen from the conductivity of pure water, it is sometimes not even necessary to combine to different reaction partners: Some systems exhibit self-ionization upon condensation, forming free positive and negative charge carriers with the remaining neutral molecules solvating the ionic cores.

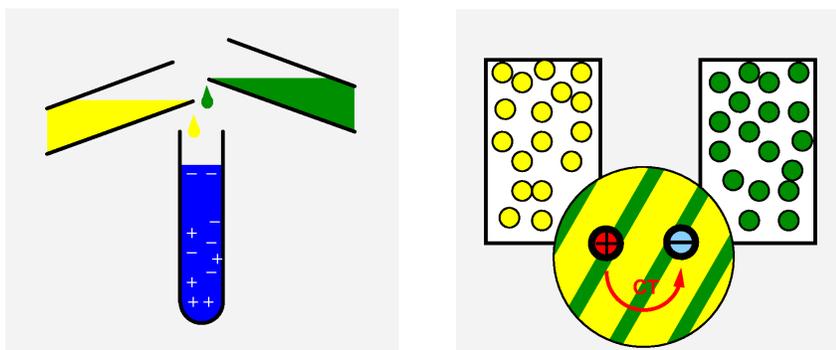


Figure 3-1: Charge carrier formation in the bulk and in molecular clusters

The concept of spontaneous charge pair formation in fluids at bulk density is also the key to CFI. As shown in Fig. 3-1, the only peculiarity consists in the usage of a reaction vessel that has nanoscopically small dimensions. The charge transfer reactions occur in molecular clusters namely aggregates of 10 to 10^6 molecules, with diameters from 0.1 to 100 nm. In spite of their small size, they contain already a sufficient large bulk-like volume in which the CT reaction takes place in a spontaneous manner. The formation of the cluster, e.g., out of the neutral, gaseous reaction partners via an adiabatic expansion into vacuum is equivalent to the mixing of the macroscopic substances in the reaction vial.

The reason to employ molecular clusters as reaction chambers becomes evident in the step that transforms the solvated charge pairs into free charge carriers. While the cluster itself may contain large

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amounts of positive and negative charge carriers, the charge neutrality of charge transfer reactions results in an overall neutral cluster that can not be accelerated electrically. In order to form free charge carriers, the reaction chamber has to be broken up. In CFI this transfer from the condensed to the gas phase is realized via the fragmentation of the molecular cluster. Ideally, the cluster is broken up into various fragments each containing just one ionic core. The gas phase plasma of heavy positive and negative charged cluster fragments formed in this way can then be separated and accelerated via electromagnetic fields.

Figure 3-2, depicts the proposed way for cluster fragmentation in CFI which consists in a surface collision. The cluster formation process endows the molecular clusters with kinetic energy. Upon surface impact this energy which is stored in the center of mass movement of the cluster is injected into its internal degrees of freedom. On a picosecond timescale fragmentation is brought about.

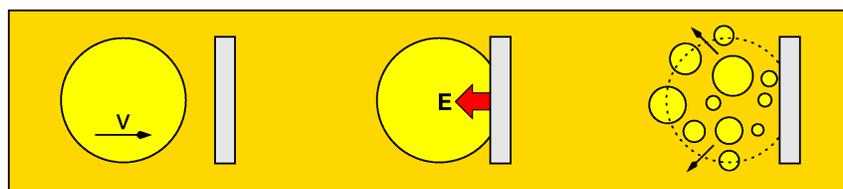


Figure 3-2: Surface impact induced cluster fragmentation via conversion of the kinetic energy of the cluster into internal excitation

The desired degree of fragmentation depends on the concentration of charge carriers inside the cluster. For a single charge pair, splitting the cluster in two is optimal. Additional fragments would be neutral and hence could not be accelerated electromagnetically. For higher concentrations of charge carriers, stronger fragmentation is desirable. Indeed, the amount of fragmentation can be tuned via the impact energy. As a rule of thumb, the kinetic energy per monomer has to be within a factor of 1 to 3 of the binding energy per monomer inside the cluster.

Expansion of the pure cluster constituents does not result in kinetic energies that allow extensive cluster fragmentation. Hence, seeded beam expansions are employed in CFI. By adding a light carrier gas to the expansion the necessary beam energies are reached. Since the carrier gas does not participate in cluster formation, the corresponding mass is not ionized and hence lost. Since hydrogen as lightest molecular gas is giving the highest increase in impact energy per given percentage in the gas mixture, the loss via carrier gas mass is still moderate when correlated to total mass. For example, a mixture of 10% HNO₃ in 90% H₂ results in a mass ratio of 78% HNO₃ versus 22% H₂. While the formation of free charge carriers via the CFI mechanism does not require electric energy, this advantage is penalized by the fact, that the presence of a non-condensing carrier gas does reduce the percentage of ionized mass.

It has been the aim of this project to identify optimal implementations of CFI regarding thruster design and reactive system. Figure 3-3 depicts the optimization process schematically. Starting from a stored reactive system, free charge carriers are formed via formation of molecular clusters and their subsequent surface impact fragmentation. Key property for the reactive system is the charge carrier concentration per volume it can achieve. It is the charge carrier concentration that determines the desired degree of fragmentation as pointed out above. In this way, the scaling parameter α is fixed, which stands for the ratio of kinetic energy per particle vs the binding energy per particle in the cluster.

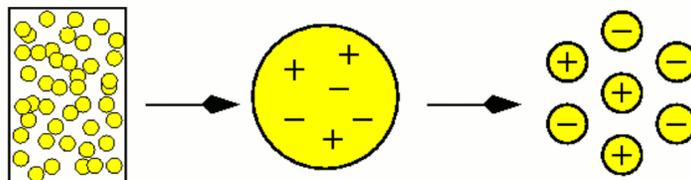


Figure 3-3: Optimisation task

The chosen α then fixes the ratio of seed gas to carrier gas, which is a function of the masses and heat capacities of the constituents for a given temperature of the expansion nozzle. If the reactive system is stored as a liquid, then also the vapour pressure curve of the reactive system has to be taken into account. In this case, the ratio of seed to carrier gas is defined by choosing an appropriate nozzle temperature, so that the desired α is realized.

Besides the physical and chemical properties of the reactive system, also the various ways to implement the charge transfer reaction have been analysed. The following gives a short overview about possible embodiments of CFIS.

CT in homogenous cluster

Figure 3-4 depicts the simplest hardware implementation of the charge transfer reaction based on homogeneous clusters. In this case, the reactive system consists in a single reactant that exhibits so called self-ionization or autoprotolysis. Cluster formation is achieved by expanding the single reactant through a nozzle into vacuum. The carrier gas necessary to adjust beam velocity is not shown in the schematic representation of Fig. 3-4.

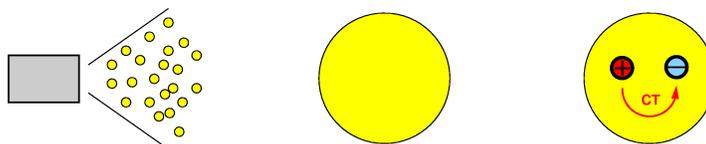


Figure 3-4: Charge pair formation in homogenous clusters

Charge-Transfer in Mixed Cluster: Coexpansion

Besides the unimolecular autoprotolysis reaction also bimolecular charge transfer reactions allow to create molecular clusters containing solvated charge carriers. In this case, both reaction partners have to be incorporated into the cluster. This is achieved straightforwardly by co-expanding the two substances as depicted in Fig. 3-5. Again, the additional carrier gas is not shown.

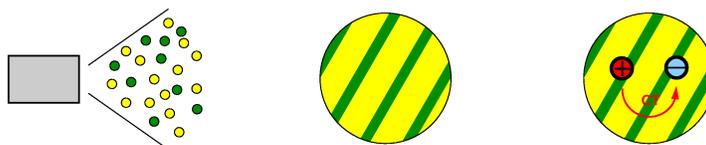


Figure 3-5: Charge pair formation in heterogeneous clusters.

Via the co-expansion a mixed cluster is formed in which the charge transfer reaction can take place. The stöchiometry of the reactive system predicts an optimal composition of the mixed cluster which would lead to a maximum of charge carrier concentration inside the cluster volume. However, the correlation of cluster composition to the composition of the expanded gas mixture is far from simple, as a kind of distillation process occurs during cluster growth. As a general rule, only reaction partners with very similar physical properties can be introduced into a cluster at the same time.

Gas-Phase Pickup of Reaction Partners

An alternative approach to form mixed clusters is depicted in Fig. 3-6. Instead of a co-expansion of all reaction partners, only one reactant is expanded. The second reaction partner is added to the formed homogenous cluster in a subsequent gas phase pickup step.

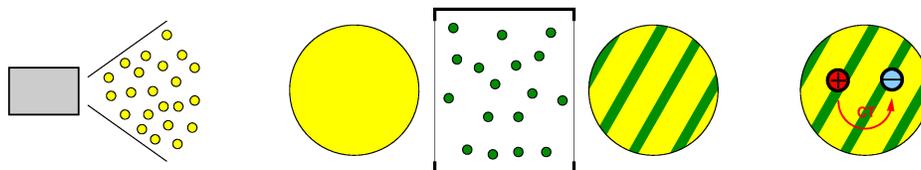


Figure 3-6: Charge pair formation via gas phase pick-up of reaction partners

Gas phase pickup is achieved by passing the cluster through a reaction with elevated background pressure of the desired pick up species. The incorporation of the reaction partner into the cluster is a statistical process and scales with the number of collisions between cluster and background gas. Hence, the amount of incorporated reactant is proportional to the cluster cross section and the product of pressure and length of the pickup region. Typical values for the reactant background pressure lie in between 10^{-4} mbar ... 10^{-1} mbar and for the pickup cell length between 1 cm and 1 m.

In gas phase pickup, all reaction partners have to enter the cluster volume via the cluster surface. Although cluster are known for the large surface to volume ratio, it is evident that under typical experimental conditions only rather low charge carrier concentrations can be realized within the cluster volume. Therefore, gas phase pickup is best suited for small clusters.

Another potential disadvantage of the gas phase pick-up approach consists in the loss of reactant 2 from the pick-up chamber: To pass the clusters through the pickup cell, the latter has to be equipped with openings. As a consequence, reactant 2 streams constantly out of the pick-up cell. Given the elevated pressures, a substantial mass loss can occur via this channel.

Surface-Pickup of Reaction Partners

This approach, as depicted in Fig. 3-7 eliminates some disadvantages of the previously described gas phase pickup. The collision surface, however, serves two purposes. While it induces fragmentation, it introduces also the reaction partner into the cluster at the same time.

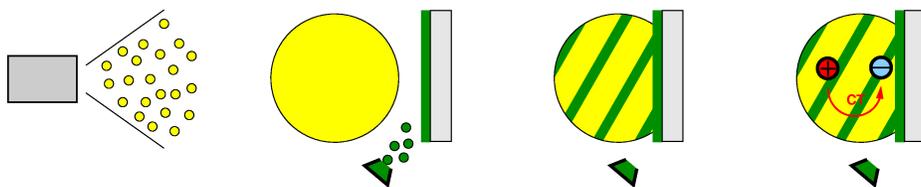


Figure 3-7: Charge pair formation via gas phase pick-up of reaction partners

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To this end, the impact target is dosed with surface adsorbates of reactant 2. This can be either achieved via an oven source or via capillary forces if the impact target is chosen to be nanoporous. Finally also intercalates, graphite blocks into which reactant 2 has been diffusively introduced between the graphite layer, are feasible. Most experience concerning surface pickup is entered around the pickup of alkali metals with polar molecule clusters [RD9, RD10].

While surface pickup requires a substantial sticking coefficient of reactant 2 towards the impact surface, it eliminates the loss of reactant 2 observed in gas phase pickup. With the surface approach it is also possible to realize large equivalent pressure length products on much smaller dimensions as compared to the situation in gas phase pick-up.

Dosing of the surface can be done continuously in equilibrium with the ablation rate by cluster impact, or discontinuously in regeneration cycles, e.g. by temperature flashing the intercalate target to initiate migration of reactant out of the volume onto the surface.

Concerning the achievable charge carrier concentration, the situation for surface pickup resembles the gas phase pickup. Generally only low concentrations are expected. Therefore, the scaling parameter α will be small which results in a less efficient charge separation: Large clusters impacting with small kinetic energy can stabilize themselves via monomer evaporation instead of fragmentation. Evaporation processes, however, always favor the least tightly bound components. Therefore, evaporation of ionic cores is not taking place under CFI circumstances.

Generally it is possible to subdivide the reactive systems in the following main groups.

- *Electron Transfer System*
The electron transfer group consists primarily in the spontaneous ionisation of alkali atoms inside polar solvents. Besides the ionisation probability of the alkalis in various solvents like ammonia, water, SO₂, an important factor for the estimation of ionisation yield and ionisation efficiency will be the way by which the alkalis are incorporated into the cluster: via gas phase pick up (the cluster passes through an area of dense alkali vapor before it collides with the surface) or via surface pickup (the alkalis are prepared as surface adsorbate are picked up during cluster impact).
- *Proton Transfer Systems*
This class of systems can be subdivided once more in to *homogenous/self-ionizing systems* and *heterogeneous systems*. For the first type no additional reaction partner has to be added to the cluster. This has the advantage, that ionisation yield is influenced only by the physical-chemical properties of the substance. Several such systems are known, ranging from water to pure nitric and phosphoric acid. Therefore this reaction type will make up an important focus of the present work. On the other hand, the group of heterogeneous proton transfer reactions is much bigger and thus offers more parameters to optimize the system. Typical representatives are acid-base reactions e.g. between water and HCl. Formation of mixed clusters is generally possible by co- expansion of the reaction partners.

Three systems have been selected for further system studies.

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3.2 Electric Propulsion Application

Operating principle of most conventional EP concepts (GIT, HET, FEPP) as well as of more advanced ones (MPDT, DS-HET, VASMIR, Colloidal thruster) have been revised in the first part of the work in order to assess CFIS technique potential applications in the EP field.

CFIS technique implementation on GIT scheme results feasible; main advantage of such application derives from attainable lower specific impulse values with respect to Xe-fed GIT, but propellant utilisation efficiency would result too much lower since only one charge specie would be accelerated, while the other one would be lost as neutrals, due to surface impact neutralisation and/or spontaneous neutralisation by electron emission. This fact has been judged strongly penalising for thruster performance.

Among advanced concepts CFIS technique could represent an interesting way for cancelling out energy loss due to propellant ionisation, that in MPDT and VASMIR concepts are very important due to the typical high mass flow rate processed. Anyway the premature development stage of such thrusters and the lack in space of the required electric power levels suggested to abandon any further investigation on this road, at least in the frame of this program.

The study concentrates on the identification and the assessment of completely new thruster configurations, developed around CFIS technique, aiming to exploit one of its most interesting peculiarities, that say the capability of producing both negative and positive charged particles, that if appropriately accelerated could avoid the need for any neutralisation device.

Two innovative CFIS-based thruster schemes have been elaborated, named:

- ❑ CST-2 (Figure 3-8)
- ❑ AEFT (Figure 3-9)

In CST-2 thruster, the principle of operation is based on the acceleration of negative and positive clusters through an electric and magnetic field.

After the cluster impact, both negative and positive charged clusters will tend to move at the same time towards opposite direction due to the effect of the applied electric fields to the two grids perpendicular to target. The application of a magnetic field is then used in order to bend the charged clusters trajectories in the thrust direction. Two other grids, parallel to target in the scheme, have the purpose to bend the particle trajectories in the thrust direction and to further accelerate them.

The two separated fluxes are then expelled through two separated exit nozzles and naturally they should merge together outside the thruster leaving the satellite neutral.

In AEFT concept, the neutral clusters beam is directed towards the target plate, high voltage biased with respect to thruster wall. The impact induces cluster fragmentation and produces free charge carriers of both positive and negative sign. By floating thruster wall through an alternate electric field is possible to accelerate both polarities and exhaust them through a grid-shaped plate, in order to achieve the required thrust, avoiding spacecraft charging.

The thrusters concepts were analyzed and their performance has been derived. Body forces accelerating ions are purely electrostatic in AEFT concept, while they are of electromagnetic nature in CST models. A simplified analytical model has been considered in order to evaluate the thruster performance characteristics. A simplified parametric study was performed and specific impulse, thrust, power, mass flow rate were derived as function of the magnetic field and potential applied. The AEFT thruster concept presented propulsive performance characteristics similar to GIT thrusters even if the specific impulse is lower.

Concerning this last point it should be highlighted that calculation have been performed assuming an ionisation efficiency of 50% (percentage of total injected mass converted in charged fragments); higher ionisation efficiencies would give proportionally higher specific impulses. Finally specific impulse also depends on the square root of particles charge-to-mass ratio, that for CFIS involving nitric acid, is about 10 times lower than for Xenon; different CFIS systems, like those previously indicated as most interesting for this application, will be characterised by different q/m values, unfortunately not yet predictable at this stage.

The CST-2 thruster concept presented propulsive performance characteristics similar to FEEP thrusters at lower applied potential, but higher mass budget mainly because of the presence of a magnetic circuit.

Table 3.1-4 summarize the main performance of the thruster schemes obtained using simplified analytical model.

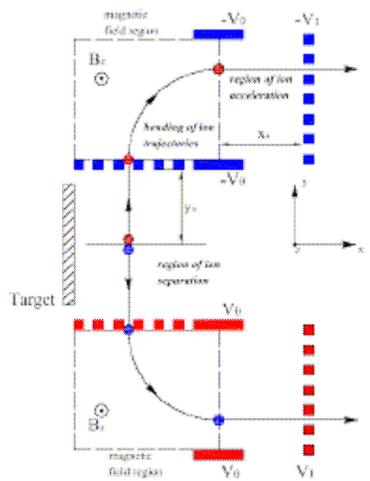


Figure 3-8: Ion separation thruster base concept (CST-2).

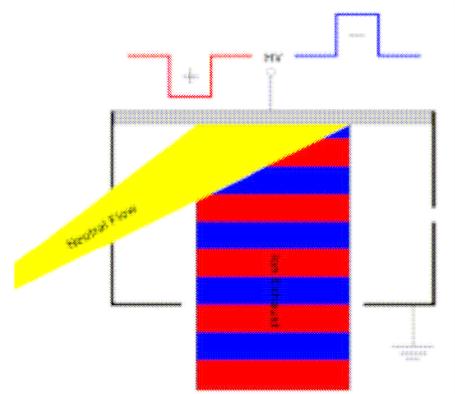


Figure 3-9: Essential elements of the CFIS alternate electric field thruster scheme (AEFT).

Potential [kV]	I_{SP} [s]	$\frac{T}{A} \left[\frac{mN}{m^2} \right]$	$\frac{P}{A} \left[\frac{W}{m^2} \right]$	Specific Power $\left[\frac{kW}{N} \right]$
0.5	892.02	0,0003	0,0024	12,25
1.0	1261.51	0,0004	0,0047	17,33
1.5	1545.03	0,0005	0,0071	21,22
2.0	1784.05	0,0005	0,0095	24,50
2.5	1994.63	0,0006	0,0118	27,39
3.0	2185.00	0,0007	0,0142	30,01
3.5	2360.07	0,0007	0,0165	32,41
4.0	2523.02	0,0008	0,0189	34,65
4.5	2676.07	0,0008	0,0213	36,75
5.0	2820.83	0,0009	0,0236	38.74

Table 3-1 Typical performance obtainable with a CST-2 thruster. The data refer to an applied magnetic field $B_z = 40 \text{ mT}$, maximum cyclotron radius $R_{\max} = 10 \text{ cm}$ and half target dimension $y_A = 5 \text{ cm}$. The specific electric power is computed assuming thruster efficiency $\eta = 40\%$.

Potential [kV]	I_{SP} [s]	$\frac{T}{A} \left[\frac{mN}{m^2} \right]$	$\frac{P}{A} \left[\frac{W}{m^2} \right]$	Specific Power $\left[\frac{kW}{N} \right]$
0.5	892,02	0,0823	0,7204	12,25
1.0	1261,51	0,1164	1,4407	17,33
1.5	1545,03	0,1426	2,1611	21,22
2.0	1784,05	0,1646	2,8815	24,50
2.5	1994,63	0,1841	3,6018	27,39
3.0	2185,00	0,2016	4,3222	30,01
3.5	2360,07	0,2178	5,0426	32,41
4.0	2523,02	0,2328	5,7629	34,65
4.5	2676,07	0,2470	6,4833	36,75
5.0	2820,83	0,2603	7,2036	38,74

Table 3-2: Typical performance obtainable with a CST-2 thruster. The data refer to an applied magnetic field $B_z = 40 \text{ mT}$, maximum cyclotron radius $R_{\max} = 14.5 \text{ cm}$ and half target dimension $y_A = 0.5 \text{ cm}$. The specific electric power is computed assuming a thruster efficiency $\eta = 40\%$.

Potential [kV]	Frequency [MHz]	I_{SP} [s]	$\frac{T}{A} \left[\frac{mN}{m^2} \right]$	$\frac{P}{A} \left[\frac{kW}{m^2} \right]$	Specific Power $\left[\frac{kW}{N} \right]$
0.5	1.48	446.06	218.62	1.91	12.3
1.0	2.08	630.79	874.49	10.82	17.3
1.5	2.55	772.54	1967.60	29.82	21.2
2.0	2.94	892.05	3497.95	61.22	24.5
2.5	3.28	997.33	5465.55	106.95	27.4
3.0	3.59	1092.52	7870.39	168.70	30.0
3.5	3.88	1180.05	10712.48	248.02	32.4
4.0	4.15	1261.53	13991.80	346.31	34.7
4.5	4.40	1338.05	17708.38	464.88	36.8
5.0	4.63	1410.43	21862.19	604.98	38.7

Table 3-3: Typical performance obtainable with a AEFT thruster. The data refer to a distance between the electrodes $x_A = 0.3 \text{ cm}$.

	AEFT	CST-2_ 10 cm	CST-2_14.5 cm
Thrust Range [mN]	5 - 3500	$2.4 \cdot 10^{-6} - 1 \cdot 10^{-3}$	$7.2 \cdot 10^{-4} - 0.3$
Specific Impulse Range [s]	400 - 1400	890 - 2800	890 - 2800
Mass Flux Range [mg/sec]	0.3 -25	$5.5 \cdot 10^{-7} - 6.8 \cdot 10^{-5}$	$1.6 \cdot 10^{-4} - 0.02$
Electric Power Range [W]	$75 - 1.5 \cdot 10^4$	$2.1 \cdot 10^{-5} - 5 \cdot 10^{-2}$	$6.3 \cdot 10^{-3} - 15$
Applied Magnetic Field Ranges [mT]	-	20 -100	20 - 100
Applied Potential Ranges [kV]	0.5 - 5	0.5 - 5	0.5 - 5
Estimated Propulsion System Mass [kg]	15-30	10-20	10-20

Table 3-4: CFIS thruster concepts: main characteristics and propulsive parameters.

Tables 3-5, 3-6 report typical performance of mini ion thrusters and colloidal thrusters, that possibly represent direct competitors with the proposed CFIS-based concepts.

AEFT concept results really interesting since it has thrust density values higher than ion thrusters at comparable voltage values, at the same time maintaining interesting specific impulses (even higher than 1000 s), above most tested colloidal thrusters.

Model & Manufacturer	Thrust [mN]	Isp [s]	Power [W]	Specific Power [W/mN]	Thrust Eff.	Thruster dia [mm]	Thrust Density [mN/m2]	Thrust Power Density [kW/m2]
DERA T5	25	3110	636	25	0,60	100	3185	49
Hughes	17,8	2585	439	25	0,51	130	1342	17
JPL	31	3900	900	29	0,66	150	1755	34
NASA Lewis	10,9	2650	300	28	0,47	80	2170	28
Keldysh Res. Center	5,6	3650	152	27	0,66	50	2854	51
Keldysh Res. Center	19	3500	500	26	0,65	100	2420	42

Table 3-5 Typical performance of mini-GITs [19].



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Model & Manufacturer	Propellant	Thrust [μ N]	Isp [s]	Power [W]	Specific Power [W/mN]	Thrust Eff.	Oper. Voltage [V]
Alta FEED-1000	Cs	1200	10000	72	60	0,82	+6000 / -4000
Alta FEED-100	Cs	120	10000	7,2	60	0,82	+6000 / -4000
ARCS InFEED-25	In	25	10000				
ARCS InFEED-100	In	100	10000				
Electro-Optical Systems [†]	Doped glycerol	7,6	700	0,033	4,4	0,78	+4400 / -5800
TRW [‡]	Doped glycerol	0,84	1450	0,009	10,3	0,69	+12300 / -2000
TRW/Edwards AFB [‡]	N/A	159	1382	1,398	8,8	0,77	+19000 / -2000
TRW/Edwards AFB [‡]	N/A	129	1405	1,153	8,9	0,77	+18200 / -2000
TRW/Edwards AFB [‡]	N/A	334,5	1029	2,409	7,2	0,7	
Phrasor [‡]	Doped glycerol	0,022	529				4000
Busek**	Formamide	189	400	6			
Stanford*	Doped glycerol	1	500	0,010	10	0,25	6000

[†] Command frequency related

[‡] Data are per single emitter

* Estimated performance goal

** Power and mass including FE neutraliser, PPU and propellant

Table 3-6 Typical performance for Colloidal Thrusters [19].

3.3 Selection of the most promising concept (AEFT)

Alternate Electric Field Thruster concept (AEFT) was finally selected as the most promising for the application of CFIS technique on Electric Propulsion with respect to CST-2 system concept for the following reasons:

- Reduction of the system complexity;
- No separation of charge species is needed.
- No magnetic field is needed to accelerate both the positive and negative clusters
- One only grid system.
- Lower limitation in the maximum current density that can be drained (reduced space charge effects limitation)
- Higher achievable thrust density.
- Most promising mission scenario (according to the preliminary analytical computation).
- Comparable thrust level to GIT but lower specific impulse.
- Decelerating grid typical of GIT is not necessary.
- Specific impulse is adjustable to specific mission requirements by varying ion mass.
- AEFT represents a completely new concept in the present EP panorama.

3.4 Other CFI-based devices for EP applications

Aside from CFIS-based electric thrusters, that were the focus of the program, but still in the EP field, other devices could be thought using cluster fragmentation process: arc ignition system and neutralizer devices.

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Arc Ignition System

The most common method used to form a plasma is to make an electric discharge between two electrodes in a neutral gas. When voltage is first applied, the current to the anode increase slowly as the electrons, produced by cosmic ray, move through the gas with an average velocity determined by their mobility for the field strength existing at the particular value of voltage.

Further increase of voltage results in a saturation; i.e., all electrons emitted by the cathode are drawn by the anode. Assuming that no electrons are produced by the effects of the field, there should be no further increase in current with voltage. In the saturation region all the ions and electrons produced by the natural ionization are removed from the discharge volume.

When the voltage reaches a certain critical value, the current increases very rapidly and a spark results in the establishment of one of the self-sustaining discharges such as the glow or the arc. The nature of the sustained discharge depends on the discharge path and the nature of electric circuit.

The energy that an electron receives from an electric field will depend upon the strength of the electric field and upon the distance in which the electron is accelerated by the field between collisions. The number of ionizing collisions is a function of the “first Townsend coefficient” and of the saturation current. The saturation current may be greatly increased by the additional collisions arising from the effect of the electric field. The current obtained from this process is relatively small and does not represent a sustained discharge because it depends directly on the saturation current.

CFIS process may be the way to increase free electrons with high energy then those produced by the cosmic radiation. By this way, to obtain a self sustained discharge, a lower breakdown voltage may be obtained. The identification of the main benefits connected to the application of CFIS technique is however hard to estimate. Lots of other phenomena than those discussed influence the breakdown voltage and the sustained discharge between electrodes, like the process of electrons extraction from cathode or the streamers formation.

The possibility to apply CFIS process to arc ignition systems results interesting but it requires more resources to be used in a specific research on the field of intensified ionization and breakdown of gases in order to understand in depth the involved phenomenon.

Neutralizer

The need for neutralization in space propulsion is twofold: there is the need for current neutralization to avoid charge buildup on the spacecraft and there is the need for charge neutralization to avoid charge build up within the ion beam. Typical thermionic emitter liberates electrons with mean velocities much higher than that of the ion beams of interest. One thus faces the choice of constructing much more elaborate sources to prepare low velocity electron beams, or of injecting the electrons with a broad velocity distribution and hoping for a rapid automatic adjustment within the mixed beam. Estimation of the effectiveness of such internal adjustment is a challenging theoretical problem.

There are four basic types of neutralizers, each of which has certain disadvantages.

- The thermionic electron emitter can be placed exterior to the beam, and the electrons drawn into the beam by a potential difference established between the beam and the emitter.
- The thermionic electron emitter can be placed within the ion beam improving the emission at a given neutralizer bias.
- As an alternative, the source can be in the form of an electron gun, which independently accelerate the electrons to a desirable speed at the desired density prior to injection.
- Finally a “plasma-bridge” technique may be used wherein the electron source simultaneously vaporizes atoms of the propellant used. These atoms are ionized by the emitted electrons and a plasma bridge is formed between the emitter and the ion beam.

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For each of this techniques CFIS application can be conceived in order to produce electrons. The main apparent advantage should be the possibility to produce electrons with low velocity and with broad distribution. In addition using CF concept it is possible to generate electrons without the need of extracting biased grids or focalizing optics.

The possibility to apply CFIS process to neutralizer systems results interesting but the conclusion at this level is the same of that reported in preceding section. More resources should be put in research to understand in depth the involved phenomenon.

4 Phase 2 activities

4.1 AEFT conceptual design

The conceptual design of AEFT was started after the thruster concept selection. This phase was dedicated on the detailed study of the AEFT concept. The thruster schematic was analysed and an estimation of its performances was derived by the use of a dedicated PIC code in the frame of 1-dimensional and 2-dimensional simulations. In particular, the 2-dimensional PIC code results necessary in order to estimate the characteristics of the ionic flow and then the losses due to the divergence of the flow.

The adopted philosophy mainly impacted on the propellant choice for this first prototype. Beside one of major results from the performed work has been the selection of two specific CT reactions as the most promising for thruster performance optimisation, the well-known nitric acid has been chosen in this phase.

First of all were discussed the models and the assumptions adopted to perform the one dimensional simulation. The problem definition and the adopted code convergence criteria were considered and the main problem parameters were highlighted. Subsequently the one dimensional analysis and the main obtained results were exposed.

The main parameters governing the AEFT performances were found to be:

- | | |
|--|-------------|
| ▪ Target to grid distance: | d |
| ▪ Particle's charge to mass ratio: | q/m |
| ▪ Mass flow rate per unit area: | \dot{m}/A |
| ▪ Ion velocity after the wall impact (absolute value): | v_0 |
| ▪ Amplitude of the applied electric potential: | V_0 |
| ▪ Frequency of oscillation of the quadratic wave: | f |

Only three of them resulted independent:

- Target to grid distance (d)
- The amplitude of the applied potential (V_0)
- The kind of propellant used (q/m)

From this analysis some useful scaling laws, relating an AEFT with the analogous GIT, were derived and defined.

	V_0 [V]	d [m]	R [m]	q/m [C/kg]
Configuration 1	2000	0.004	0.050	$8.1607 \cdot 10^4$
Configuration 2	5000	0.010	0.050	$8.1607 \cdot 10^4$
Configuration 3	5000	0.010	0.035	$8.1607 \cdot 10^4$

Table 4-1: Analysed conceptual design configurations summary. V_0 is the amplitude of the applied potential, d is the target to grid distance, R is the target radius, q/m is the charge to mass ratio of the substance.

The developed 2D-axysymmetric PIC code was used to compute more accurately estimate thruster performances. The results of the computations, relative to three different thruster parameters

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combination, were reported and the obtainable performances were shown. Table 4-1 and Table 4-2 summarize the main results obtained with the 2D analysis.

	$I_s [s]$	$T/A [N/m^2]$	$P_k/A [kW/m^2]$	$T_R/T [\%]$	$f [MHz]$
Configuration 1	693.07	2.8778	25.6668	2.7	1.6261
Configuration 2	1049.9	2.8375	39.478	6.3	1.0710
Configuration 3	1003.7	2.7142	36.106	6.9	1.0710

Table 4-2: Performances of the analysed design configurations.

In this contest a validation of the scaling laws was performed obtaining that the scaling law performances computation is a good approximation with respect to the 2D-axisymmetric PIC analysis.

4.2 Preliminary design of the first laboratory prototype for AEFT concept

In this phase of the work the conceptual design of AEFT has been described reporting the main design justifications and the thruster electrostatic/performances analysis. Starting from a review of the design concepts developed in the previous work phase, some relevant requirements have been defined.

A description of the chosen functional scheme and of the thruster main components was reported and the relevant performances of the thruster were computed with the aid of the set of scaling laws previously determined. A more accurate 2D-axisymmetric PIC performances analysis followed and then the electrostatic analysis gave a clue for choosing the material of the thruster assembly parts.

The preliminary thruster assembly, with its main needed components, was elaborated and the mass budget with indications of the main thruster dimensions closed the conceptual design of an AEFT laboratory prototype.

4.3 Development plan for AEFT technology

A development plan for AEFT technology from the proof of concept level, represented by the prototype proposed in the frame of this activity to an advanced demonstration model, precursor of the engineering model has been elaborated.

The plan has a time duration of two years, during which the group of CFIS technique specialists and the group of EP experts work in strict collaboration.

Planning accounts for all research, development and experimental activities necessary to effectively address main critical issues, at thruster design level.

They mainly consist of:

- propellant selection and optimization of relevant charge transfer reaction and CF process, that say identification of optimum expansion parameters (temperature, pressure and nozzle geometry), nozzle-target relative position;
- target technology, strictly related to the previous point (selection of a particular CT reaction).
- grid electrode design with respect to sputtering-corrosion and structural-thermal concerns (as for conventional GIT), but also exploring possible materials with transparency characteristic, that say minimum interference with neutral clusters (innovative aspect).

Other important concerns are:

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- development of space-qualified power supply and distribution system, able to provide high voltage (1-10 kV), high frequency (MHz) signal;
- in-space propellant storage and feeding system.

Although these aspects would surely have a great impact at system level, at present they do not represent obstacles to R&D activities on thruster concept.

On the other hand, before addressing these topics towards space application, AEFT and in general CFIS-based EP potential should be demonstrated.

Finally the contamination issue seems in principle of main importance. It is related to chemical reactivity of the involved substances and to the fact that an important percentage of the exhausted propellant will not be ionised and then can not be appropriately addressed far from sensitive surfaces (of thruster or satellite).

Preliminary experimental studies on DM1 and DM2 would be helpful in addressing this topic, allowing to better define the problem and consequently to think to appropriate solutions.

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5 Conclusions

The CFI technique results interesting for application to EP since:

- propellant ionization is not electric power consuming,
- mass of the charge carriers after clusters fragmentation is above ion mass for typical propellants,
- no neutralizer device is required.

Potential applications of the CFI techniques in the field of electric propulsion systems were identified and studied in detail. Some possible thruster schemes were identified and their performances evaluated with the aid of simplified thruster model. This analysis brought to define a thruster scheme which uses an alternating electric field to accelerate both charged carriers deriving from cluster fragmentation (AEFT).

AEFT reveals to be potentially interesting for low-power applications, where it retains some operating and performance characteristics of GITs, as operating voltage, grids spacing and thrust density, while it is characterised by specific impulses higher than 1000 s, then above corresponding values for most colloidal thrusters.

AEFT could be the answer to most technological issues in the scaling-down process for GITs, in particular:

- reducing electron wall losses in small discharge chambers;
- poor scalability of magnetic confinement fields;
- miniaturisation of cathodes.

On the basis of AEFT scheme, a dedicated PIC model was developed and used to deeply investigate the parameters affecting thruster performances. The major results on the application of CFIS on EP were analysed and a preliminary thruster prototype was proposed.

The adopted philosophy mainly impacted on the propellant choice for this first prototype. Beside one of major results from the performed work has been the selection of two particular CT reactions as the most promising for thruster performance optimisation, the well-known nitric acid has been chosen in this phase.

Of course, this particular CFIS process results in poor propellant utilisation efficiency, η_u defined as ratio of charged fragments mass to total mass, while optimum charge-transfer reactions promise to reach η_u values above 50%, but deep investigation on optimisation of relevant processes is required.

At this stage, considering the strong innovative aspect of the proposed concept, the validation of its working principle through testing of a simple thruster, as that proposed in this work, appears to be the mandatory first step, before employing a great deal of resources for intensive development activities.

On the base of main results of the present study a possible development plan is proposed aimed to develop an advanced model of the AEFT concept. Planning accounts for all research, development and experimental activities necessary to effectively address main critical issues, at thruster design level. In a time frame of about two years, thruster technology is expected to reach the maturity level appropriate for the successive engineering phase.