Development of Vacuum Arc Thrusters and Diagnostic Tools

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Abstract: The Laboratory for Plasma Technology of the University of the Federal Armed Forces in Munich, Germany, is working on different topics regarding electric propulsion for small satellites. The main scope currently is the development of new concepts for vacuum arc thrusters (VAT) as well as innovative diagnostics. VATs have a variety of advantages in comparison to other propulsion systems like ion thrusters, FEEP thrusters or cold gas thrusters: useable for a wide variety of solid propellant, mechanically simple and robust design and no need for additional neutralization, while still providing high I_{sp} (~1000s). Moreover they are capable to produce very small impulse bits of the magnitude of µN-s which are highly directional, and can be controlled very easily. Prospective applications include use as main propulsion system for pico satellites as well as fine positioning for larger systems. In this regime VAT shows more potential than conventional chemical thrusters and simpler operation and control compared to other small electric propulsion systems. New diagnostics include tomography, ultra-high-speed imaging techniques and probe measurements, which are used to further understanding and enhance performance investigation of the µ-propulsion system.

Nomenclature

Δv	=	velocity increment
n_{ion}	=	ion density
v_{ion}	=	total ion velocity
I_{ion}	=	ion current
U_{probe}	=	probe potential
R_{probe}	=	measurement resistance
A_p	=	probe surface
Z	=	charge state
e	=	electron charge
U_{plasma}	=	plasma potential
v_{acc}	=	ion velocity due to acceleration of the probe current
v_{VAT}	=	ion velocity of the vacuum arc thruster
m_{ion}	=	ion mass
F	=	thrust

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x	=	displacement
k	=	spring rate
r	=	distance force to axis of rotation
U	=	electric voltage
$\varepsilon_L(\nu)$	=	volume emission coefficient
A_{mn}	=	transition probability
n_m	=	population density of the upper state
$h\nu_{mn}$	=	energy of the emitted light
λ_{mn}	=	transition wavelength
h	=	Planck´s constant
c	=	speed of light
p	=	pressure
T	=	Temperature
$Z_z(T)$	=	partition function
g_m	=	degeneracy of the upper state
E_m	=	energy of the upper state

I. Introduction

THE scope of future space-missions will more and more be determined by its costs. Therefore, the development of affordable systems in all areas of astronautics is necessary. In case of satellite development, this is achieved by minimization and specialization. Small, economical satellites can be brought into orbit with relatively small financial expense, even by private carrier systems. Because of their size, each one of those satellites can perform only a small amount of tasks. By organizing small satellites in a formation or swarm, more complex missions, so far exclusively done by big, expensive satellites, could be managed economically. Every single one of the satellites in the swarm is highly specialized for a pre-determined task. While some of them are occupied communicating with earth, others might, for example, be applied to the exploration of certain landscapes or meteorological evaluation of the atmosphere. Every swarm-member just needs to be able to communicate with others within the swarm. Due to the economical construction, several satellites with the same task can be brought into space to ensure systems redundancy and therefore avoid a loss of functionalities.

For position control, in relation to other satellites of the swarm and towards the surface of the earth, it is necessary to implement a light, compact and economic engine. So far chemical thrusters or reaction wheels are used to bring big satellites in position. The main disadvantages of these systems are their weight and size. For a determined velocity increment Δv, chemical thrusters consume more propellant, due to a smaller exhaust velocity. Chemical thrusters cannot be miniaturized as far as required and furthermore the scale of the minimal thrust is restricted to a certain minimum, which is not suitable for the fine positioning of small satellites.

As a consequence the target is to provide a plasma-thruster for these missions, which can be manufactured at reasonable costs, is very robust and temperature-resistant, features a low mass (approximately 250 g, incl. PPU), is small and very precise in dosing its thrust (1 µNs). Furthermore, low power consumption is required, as the energy supply in space is based on solar panels, which, in first place, should feed the scientific components of the satellite. The vacuum arc thruster (VAT) easily meets all these requirements[1]. Plans have been made to use this propulsion system on the so called UWE-4 satellite of Julius-Maximilians-University Würzburg. This mission should demonstrate the operational capability of small satellites within a swarm.

Still there are some issues to be solved: These are mostly connected with reliability[2]. The ignition process requires varying initiation voltages, the plume characteristic and thus the thruster vector can change due to a hard to control arc movement and a simple reliable feeding mechanism of the solid propellant does not exist. The Laboratory for Plasma Technology has currently focused its work on the improvement of the thruster geometry and the control of the plume characteristic. Moreover there are some efforts on the further development of an inductive PPU.

In order to improve the VAT system various diagnostic techniques will be used. In addition to a thrust measurement system a tomography diagnostic is under development the goal of which is the 3D reconstruction of the plasma discharge geometry as well as the determination of its electron density and temperature distribution via spectroscopic methods[3]. First measurements on mostly stationary flames of plasma torches resembling an arcjet thruster have already been made. High speed imagining has been employed to determine the location of the VAT plasma being initiated and is used in connection with a Langmuir probe array to determine the influence of the operational parameter on the thrust vector and intensity.

II. Thruster Development

The VAT has been developed in the past by various research institutions[4]. It has been found to be simple, robust and easy to operate and even back in 2001 thrust measurements have proven the feasibility of the concept. However, two issues have always been in the focus of investigations.

1. Reliable ignition
2. Propellant feeding

The ignition of a discharge in vacuum requires high voltage, an issue which is not convenient for small satellites, where high voltages may lead to arcing on circuit boards and produce noise, which might disturb the functionality of other on-board systems. A so-called "trigger-less trigger" was developed based on a conduction thin film deposited on the insulator between the anode and cathode. The thin film acts as short circuit (transferring the full applied voltage) as long as no current is flowing in the circuit. Thereby a high electric field is produced between the non-conduction tiny gap between the layer and the cathode. As soon as the plasma is initiated a voltage drop is produced across the thin film due to its non-zero resistance and the plasma provides the low resistance path between the anode and the cathode.

In principle the tiggerless trigger works just fine. Even though every ignition causes some erosion of the conductive layer the plasma itself – a metal vapor plasma – is supposed to provide some re-deposition and thus "heal" the conductive layer. Obviously the amount of material re-deposited depends on the amount of plasma produced and thus on plasma current and pulse length, while the erosion rate depends mainly on the voltage applied for ignition. With increasing erosion ignition requires higher and higher voltages, which in turn produces more erosion and so forth. On the other hand very long and high current plasma pulses may produce too much re-deposition leading to the buildup of a short circuit between anode and cathode. In short the VAT requires a carefully tuned balance.

Propellant feeding is the other issue. Using a coaxial setup as shown in figure 1, material eroded from the cathode (center) leaves a cavity (similar to a tooth) which leads to less effective propellant flow due to shadowing (imagine a plasma plume expanding from the bottom of a well) and produces problems with ignition due to an increase of the anode-cathode distance. Many attempts have been made to overcome these problems using completely different geometries however a satisfactory simple solution has not been found.

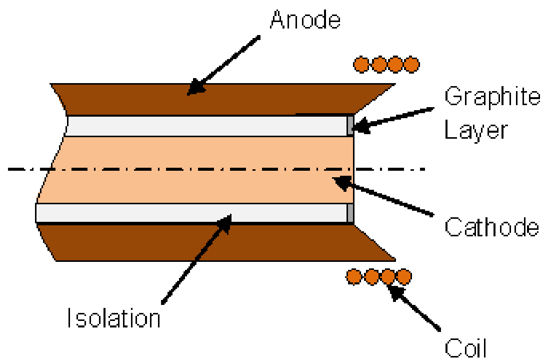

Figure 1. Schematic illustration of a VAT with inwards sloped cathode and coils for magnetically plume focusing.

In order to improve the problems of ignition and feeding an innovative approach based on a coaxial setup is evaluated. In order to control the arc movement a concentric thruster design with an inwards sloped anode is currently in the test phase (Fig. 1). This setup should support the discharge by providing a current path perpendicular to an axial magnetic field - produced by a coil - leading to a forced arc rotation as well as the magnetically focusing of the plume[5]. It is expected that an additional benefit of this design is an improvement of the self regenerating conducting layer on the isolation between anode and cathode[6], which is necessary for low voltage plasma initiation. By adapting the strength of the magnetic field the speed of rotation can be controlled which on the one hand leads to a more homogenous erosion of the surface and secondly controls the time each segment of the conducting layer is exposed to the re-depositing plasma flow. This approach should lead to propellant erosion which covers the complete surface and prevents establishing "preferred" ignition and/or erosion spots. This homogenous erosion is necessary for a new propellant feed system to be introduced. This new feed system is based on using a split cathode, one part of which is providing the main propellant whereas the second part will control the feeding.

In Fig. 2 the principle of operation for this system is shown. A new cathode (orange) electrically insulated from but mechanically connected to the main cathode (grey) is inserted into the central part of the thruster (insulator: blue, anode: red). This cathode consists of areas with larger and smaller diameter forming a kind of tooth structure. A spring is used to push the cathode arrangement forward but is held back by an insulating tip pushing against the alternative cathode. The thruster is operated between the anode and the main cathode until the control electronics detects enhanced erosion, which will require higher mean burning voltages. Once

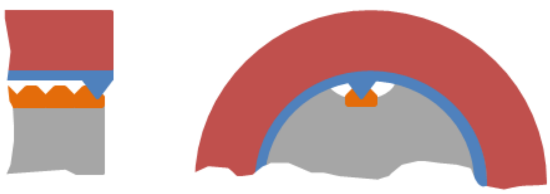

Figure 2. The concept of the new VAT design as described in the text.

erosion is detected, the PPU will switch its cathodic connection to the new cathode (orange) which will subsequently be eroded quickly. Once the erosion has progressed the insulating tip will no longer be able to retain the cathode arrangement and the spring will move it forward until the insulating tip catches onto the next "tooth". This way a simple feed mechanism built upon some electronics and a spring can be designed. First experiments using this setup are in progress.

The PPU that will be employed for the VAT will feature additional control in order to provide reliable propellant feeding and a controllable magnetic field. The principle of operation however will be similar to the inductive energy storage systems devised in the past and described elsewhere[7].

III. Diagnostics

As mentioned above several diagnostic techniques are applied for the thruster development. The primary diagnostic is a thrust balance which is able to measure thrusts with a resolution of 1 μm. For the optical investigation of the plasma plume a high speed imaging system is available. Furthermore an innovative tomography system is in development for the 3D reconstruction of the plasma plume. The electron temperature and density could be determined via optical emission spectroscopy. For the ion density of the plasma, its velocity distribution and the geometric jet characteristics a Langmuir probe system is in development. A first assembly for the measurement of the ion density is currently under testing. Striking ions are fully collected by the probe while electrons are repelled. With known ion velocities v_{ion} from literature (e. g. Ref. 8) and estimated plasma potential the ion density n_{ion} can be calculated from the ion current I_{ion} (which is given as the quotient of the applied Voltage U_{probe} and a measurement resistor R_{probe}):

$$n_{ion} = \frac{I_{ion}}{A_p Z e v_{ion}} \qquad (1)$$

Here A_p is the probe surface, q the charge state and e the electron charge. The plasma potential U_{plasma} is necessary to estimate the velocity gain of the ions caused by the probe acceleration voltage v_{acc} which is given by

$$v_{ion} = v_{VAT} + v_{acc} = v_{VAT} + \sqrt{\frac{2qe\left(U_{probe} - U_{plasma}\right)}{m_{ion}}} \qquad (2)$$

with the actual ion velocity of the vacuum arc thruster v_{VAT} and the ion mass m_{ion}. An improved assembly is planned to determine the shape of the plasma plume which is estimated to be similar to a cosine distribution.

A. Thrust Measurement

For satellites fine positioning in the orbit, it is fundamentally important to know the exact value of the thrust, produced by its thruster. Suitable for these measurements can only be a thrust balance with a very high resolution and sensitivity that can detect thrusts in a scale of μN.

The thrust balance used by the Lab for Plasma Technology to test vacuum-arc-thrusters is based upon the ARC design and consists of a spring link with two arms carrying, each one, a small plate on the outer side. On one of these plates, the thruster will be installed. A counterweight is placed on the other plate (Fig. 3).

The thruster balance works in two different modes, the compensation- and the displacement-mode. As the name suggests, the displacement-mode is based on detecting the displacement of the arm while the thruster is working. Measuring the displacement, which depends mathematically on the restoring spring rate, the conclusion about the actual force of the thruster is simple:

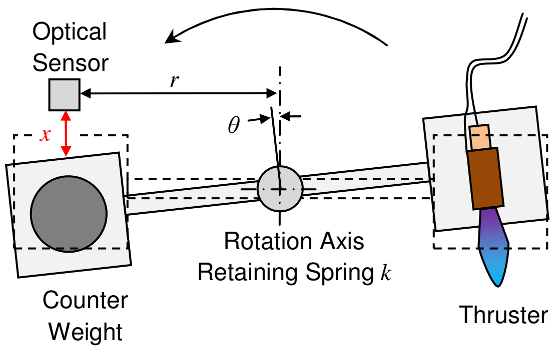

Figure 3. Principle drawing of the thrust balance.

$$F = \frac{360kx}{r^2\pi} = 3{,}133x \qquad (3)$$

This method depends very much on constant environmental conditions and temperature as otherwise the spring rate is changing permanently.

In the compensation-mode, electric voltage is applied to the electrostatic combs. While the thruster is operating, the voltage permanently adapts to the thrust, so that the force resulting from the electric voltage compensates it immediately. Therefore no displacement is taking place. The electric voltage, needed to compensate the displacement, is proportional to the thrust:

$$F = \frac{7{,}424 \cdot 10^{-11} \cdot U^2}{r} = 2{,}320 \cdot 10^{-11} \cdot U^2 \qquad (4)$$

For this mode, more static noise is expected than for the displacement-mode.

The maximum thrust, measureable with this balance, in compensation-mode is 2,1 mN and 1,25 mN in displacement-mode, whereas the static noise is expected to be about 240 nN and 300 nN.

D. High Speed Imaging

The high speed imaging system shown in Fig. 4 combines the characteristics of an image intensifier, a CCD-camera and a fast rotating mirror to an economical type of high speed camera[9].

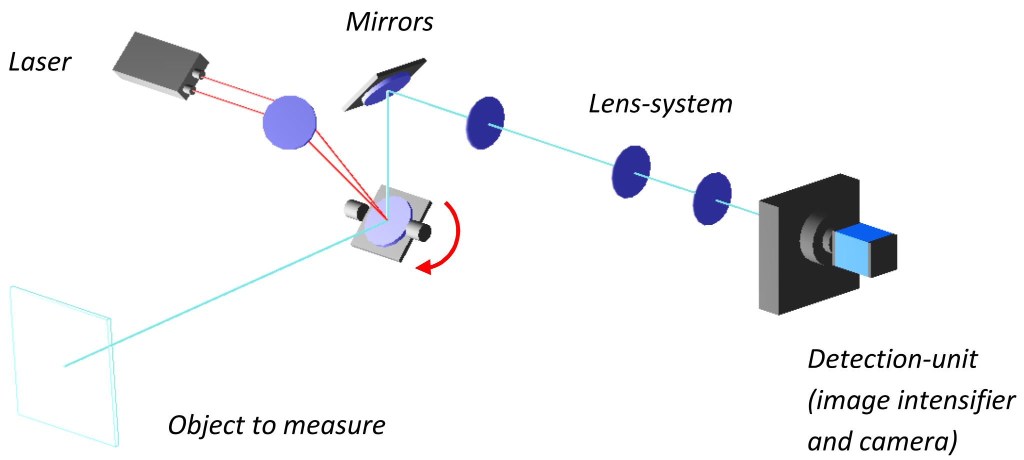

Figure 4. High speed imaging system, consisting of a laser-circuit, a rotating and a redirecting mirror, a lens system a detection-unit.

The image of the measured object is reflect by a rotating mirror and a redirecting mirror, passes through a lens system and is mapped on the cathode of an image intensifier (Fig. 4). In the next step, the image is intensified and projected by internal optics onto the CCD-chip of the camera. Due to the rotation of the mirror the image of the object on the CCD-chip is shifting. As a consequence, the exposure time should be in a scale of *ns* to make sure to obtain a sharp image of the measured object. The extremely short exposure time needs to be compensated by the applied image intensifier to provide sufficient light reaching the chip of the camera. In case the image itself is small, compared to the size of the chip, several images can be recorded in a chronological sequence. A minimum delay of *1* μs between two exposures is achieved by this arrangement. That corresponds to 1 million images per second.

The high speed imaging system is used to study the location of arc roots and their propagation along the cathode of the VAT. Therefore the time between two exposures was set to be 50 μs with an exposure time of 300 *ns*. The current pulse, to activate the thruster, was set to be 800 μs of duration and 385 *A* of amplitude. A reference image of cathode and anode (red marks) was used as a template for the recorded pictures of

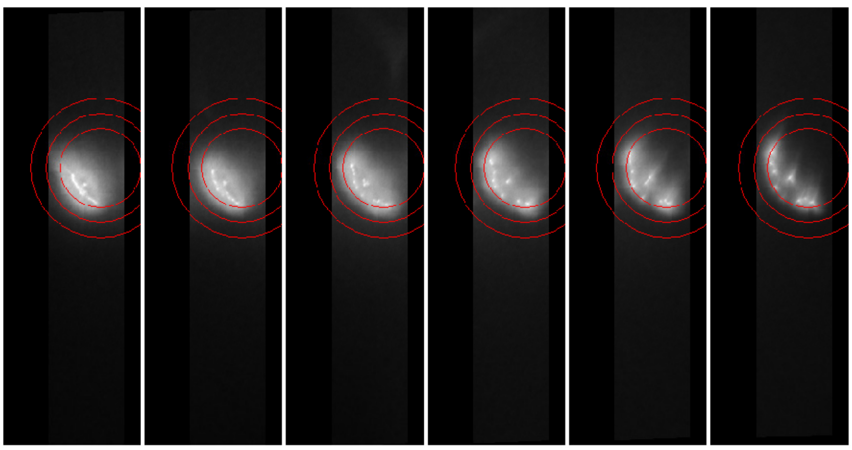

Figure 5. Recorded arc roots on the VATs cathode in a chronological sequence.

the discharges. The results are shown in Fig. 5.

It was found that the arc roots prefer to appear at some isolated points on the border of the cathode and then propagate along the edge.

In a next step, the recordings with the high speed imaging system and the current at the electrodes were measured synchronously, so that the amperage at a certain time index can be assigned to a single frame on the chip of the camera. The correlation between current and frame implies that there is a causal relationship between current level of the VATs electric circuit and the number of the arc roots appearing on the cathode. The colored marks in Fig. 6 relate the current measurements to the pictures taken by the high speed imaging system, to demonstrate the relationship between the two scales.

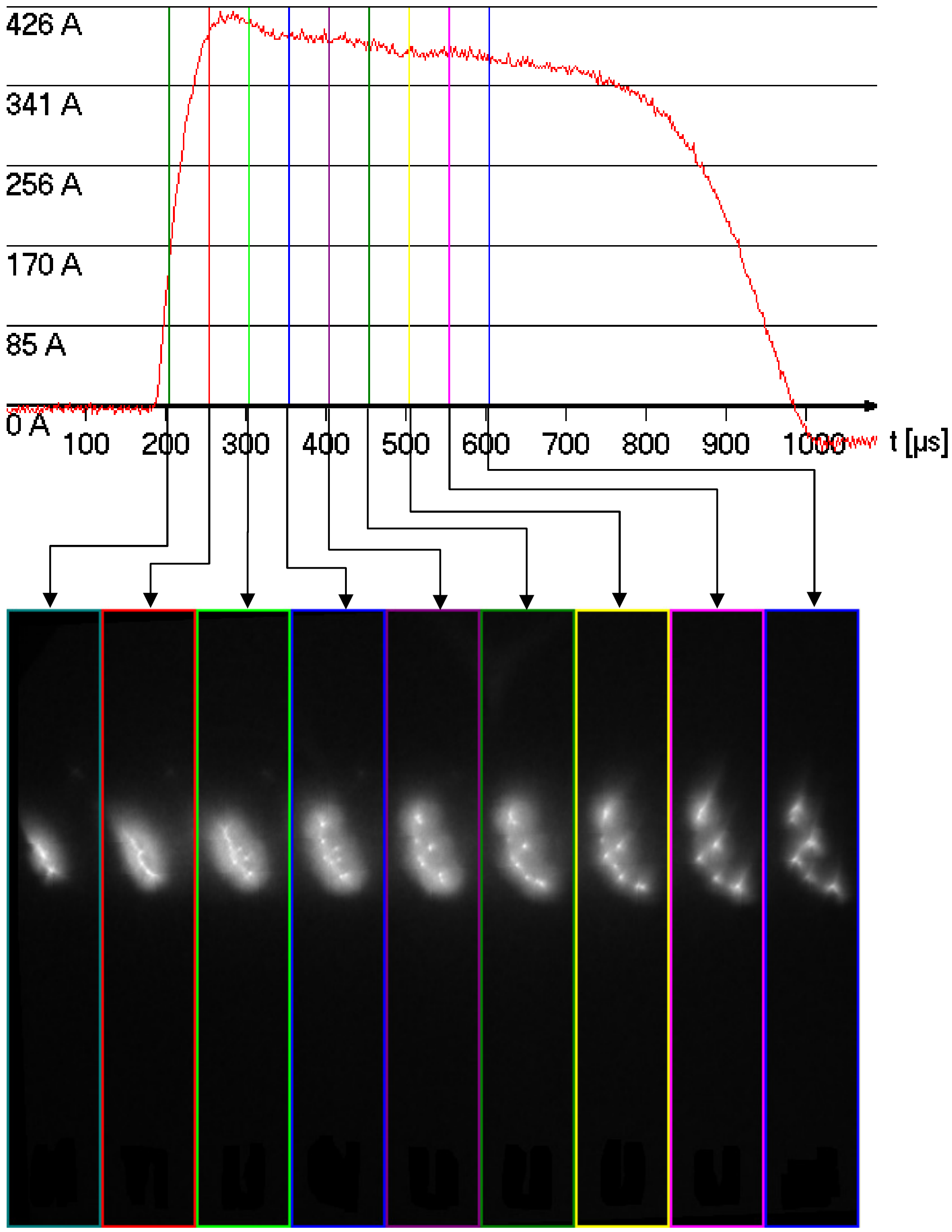

Figure 6. Correlation between electric current and single frames recorded by the detection unit.

With increasing current intensity the number of arc roots grows, as the amount of current handled by a single arc root is limited. Later, when the amperage is almost constant (at approximately 350 *µs)*, the number of arc roots stays just about the same. These investigations will be used to measure the parameters determining erosion mechanisms and provide design assistance for improved thruster geometries.

C. Computer Tomography

The core of tomographic reconstruction is a mathematical method which enables the determination of local properties of the measured object from a series of integral images of the measured object. The basic reconstruction algorithm was developed by Johann Radon in 1917[10]. The so called Radon transformation is given by

$$f(\varphi,p) = \int_{K_\varphi} f(x,y)ds \tag{5}$$

with the intensity distribution $f(\varphi,p)$ detected by a camera and the intensity distribution $f(x,y)$ of the measurement object in the x-y-plane. Therefore the detected function f(φ,p) is given by the integration of all values of $f(x,y)$ over the integration path K_φ. The angle φ follows from the rotation of the camera around the z-axis whereas the coordinate p gives the value of the p-axis which is passed by the integration path K_φ (Fig. 7). For the CCD camera, a discretized form of the Radon transformation is used. Due to modern computer technology this method could now be realized and applied.

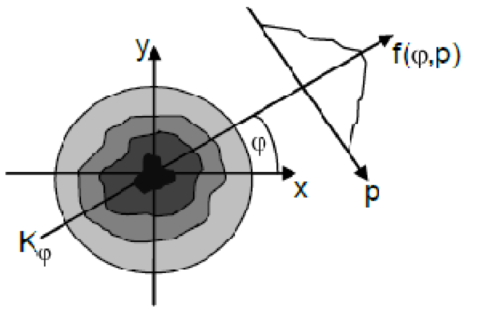

Figure 7. The Principle of the Radon transformation as described in the text.

In case of a radiating plasma as found on a VAT the appropriate examination method is emission tomography. Thereby the electromagnetic radiation, which the object of interest emits by itself, is detected by suitable sensors. The radiation emitted by the plasma contains characteristic spectral distribution which can be analyzed by spectroscopic methods. The combination of both, the detection and the spectral analysis of the emitted radiation, lead to tomographic emission spectroscopy. Several variants of tomographic systems have been developed and are currently in use to investigate thermal spray processes using plasma sources similar to those used in arcjet thrusters. The main components are a CCD camera and an interference filter for a particular wavelength. Therefore only the light of this particular wavelength is detected by the camera. By the use of several different filters it is possible to determine the plasma temperature.

In case of a rotational symmetric plasma jet with a known intensity distribution (e. g. Gaussian profile) images with different wavelengths from along a single line-of-sight are necessary. The reconstruction of the local emissivities of the different wavelengths is then achieved by an Abel inversion. Unfortunately in most cases the plasma jet is not rotational symmetric. Therefore it is essential to obtain images from different angle positions. If the plasma jet is approximately stationary the camera with different filters can be rotated around in small angle steps (Fig. 8).

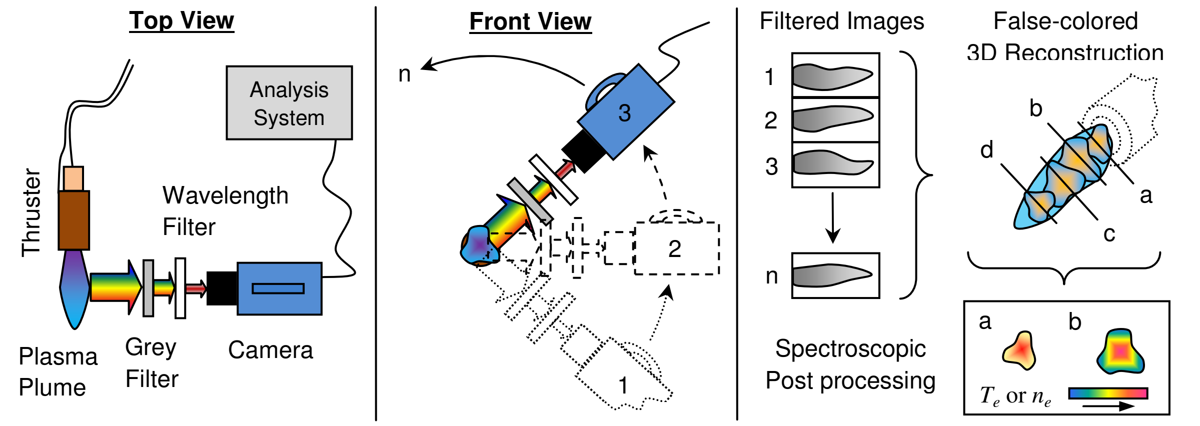

Figure 8. Schematic principle of the tomographic reconstruction of a plasma plume to determine the influence of U, I, p_{Gas} and Γ_{Gas} on T_e, n_e and Geometry.

Unfortunately this method is not applicable for fluctuating plasma jets. Therefore multiple images from different angles at the same time are needed. Moreover from each position at least two wavelengths have to be detected for the local temperature measurement. One approach is the application of several cameras equipped with different filters. However this method is not applicable in vacuum since air inclusions within the cameras could destroy them. For high vacuum tests a new system is currently under development at the Lab for Plasma

Technology. Around the plasma jet multiple mirrors are attached at the same distance but with different angular positions. The images are collected into one optical path in which different filter systems via beam splitters are applied. Finally all images are mapped together on a high speed CCD camera chip featuring with a high spatial resolution which allows many different images to be obtained on one single chip. A special algorithm will then be applied to determine the shape of the plasma jet and the local temperature distribution.

The local plasma temperatures are reconstructed under the assumption of an optically thin plasma and local thermodynamic equilibrium (LTE). According to Ref. 11 the integral volume emission coefficient $\varepsilon_L(\nu)$ of one particular wavelength for the transition from state m to n is given as

$$\varepsilon_L(\nu) = \frac{1}{4\pi} A_{mn} n_m h\nu_{mn} \tag{6}$$

with transition probability A_{mn}, the population density of the upper state n_m and the energy of the emitted light $h\nu_{mn}$. In the assumed case of LTE all state densities are responding to a Boltzmann distribution. If all atoms are in an excited state, Eq. (6) merges to

$$\varepsilon_L(T) = \frac{hc}{4\pi\lambda_{mn}} A_{mn} g_m \frac{p}{kTZ_z(T)} e^{-\frac{E_m}{kT}} \tag{7}$$

with the transition wavelength λ_{mn}, pressure p, the Temperature T, the partition function $Z_z(T)$ and the degeneracy g_m and energy E_m of the upper state m. Due to this connection the Temperature T of the plasma could be determined. Using an algebraic reconstruction technique local emissivities are calculated for three wavelengths for different temperatures with a resolution of 0.25 x 0.25 mm^2 per pixel [12]. A comparison between this calculated emissivities and the measured ones lead to the actual local plasma temperatures. Figure 9 shows a typical reconstruction of the temperature distribution of an industrial used plasma jet. The shape and four temperature profiles for different distances are pictured.

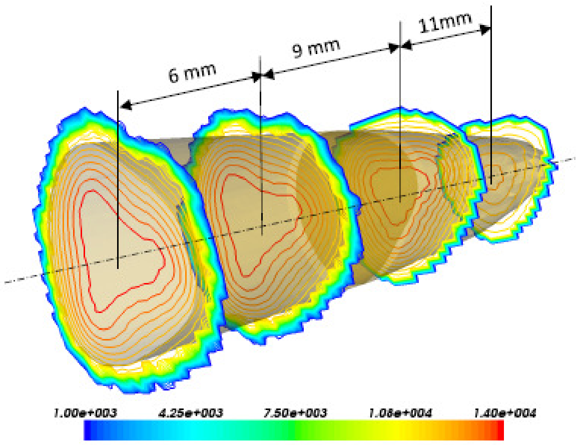

Figure 9. Reconstruction of the temperature distribution of a plasma jet.

Currently there are some efforts to improve the algorithm in terms of the self absorption of the plasma and the estimated LTE. In the meantime the main scope is to reconstruct the shape of the plasma plume created by a VAT with a real time tomography suitable for vacuum application. Due to the complicated composition of a metallic plasma plume of a VAT the first application of the improved temperature measurement algorithm would be industrial plasma jets and electric propulsion systems with plasma plumes which consist only of gas like in classical ion thrusters.

IV. Vacuum Facilities

The Laboratory for Plasma Technology is equipped with several vacuum facilities for the development and diagnostics of VAT and thermal spray systems. For the thrust balance, a 0.35 m diameter, 1.0 m long chamber is in use. The initial evacuation is performed by a double-stage rotary vane pump with a pumping speed of about 16 m³/h. High-vacuum conditions are provided by a turbo molecular pump with a pumping speed of about 300 l/s. Thereby a vacuum of 10^{-6} mbar could be reached. To prevent the thrust measurement from artifacts by pumping vibrations the chamber can be separated from the pumps via slide valve. After the pumps finally came to stop a vacuum of 10^{-3} mbar can be maintained long enough for several thrust measurements. This chamber is to be equipped with a heating and a liquid N_2 cooling system to simulate space conditions. Furthermore an improved pumping system is planned. With exception of the rotating camera tomography all introduced diagnostic systems could be applied to this chamber. However some measurements where conducted in another chamber which is about 1.0 m diameter and 0.8 m high. A similar but weaker pumping system provides also a vacuum of about 10^{-6} mbar but with a much longer pumping time. Whereas the first system is sealed with copper joints the second vacuum chamber has a rubber sealed top flange over the whole diameter which allows a comfortable and fast access to the interior.

V. Conclusion

The Laboratory for Plasma Technology is currently building up its capabilities in connection with electric propulsion. The Vacuum Arc Thruster is the main µ-propulsion system used and new approaches are taken to improve reliability and lifetime using a combination of advanced diagnostics, innovative geometric design and electronic control. Once these innovations will be concluded, the new system will be tested using an in-house thrust balance as well as some space environment simulation chambers.

Acknowledgements

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