Overview of the research activities of the RITSAT-project

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Abstract: The research of the RITSAT project is founded on a wide scientific and technological basis bringing together engineers, materials scientists, chemists and physicists. The research covers engineering aspects of EP technology, in particular, the further development of RIT-technology ranging from µN-RIT to prototypes of large RIT-35 and corresponding peripheral electronics, but also investigates new concepts of micro propulsion. It also comprises the development of plasma and plume diagnostics and their employment in test facilities. The corresponding theoretical and numerical description of ion thrusters is conducted on various levels and includes plasma modelling, thermal modelling, and circuit modelling. Materials science aspects such as the development of alternative propellants and the assessment of material damage by SC/EP interaction are also investigated. In the framework of the RITSAT activities, the EP test facilities at JLU Giessen (foremost the Jumbo tank) and at DLR Göttingen (High Vacuum Plume Test Facility Göttingen – Electric Thrusters, STG-ET) have joined forces and can compete with the largest EP test facilities in Europe. Cooperation agreements between JLU Giessen, DLR Göttingen and Airbus DS have been signed and will further consolidate these activities. The paper gives an overview of ongoing RITSAT activities highlighting the progress made in the various fields of research and giving perspectives of future work. Furthermore, the test facilities and their diagnostic equipment will be described, giving an overview of their capabilities.

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Nomenclature

RIT	=	radio-frequency ion thruster
EP	=	electric propulsion
CP	=	chemical propulsion
LOEWE	=	Landes-Offensive zur Entwicklung Wissenschaftlich-ökonomischer Exzellenz

I. Introduction

SINCE the first, albeit unintended, but successful demonstration of orbit raising by EP during the Artemis mission in 2002/2003, using a RIT-10, much progress has been made in the field of EP. However, for about one decade the focus of the employment of EP was not seen in the commercial sector, but driven by the use in scientific missions such as DARWIN, LISA, GOCE, TPF where the highly specialized mission requirements (such as thrust control, high specific impulse etc.) could only be fulfilled by EP systems.

The idea of orbit raising by EP has become competitive with solely employing chemical propulsion in the commercial sector, when Boeing introduced its first all-EP-satellite in March 2012. This development increased the commercial importance of EP considerably. All-EP-satellites define a new generation of satellites, for which it is estimated that the cost arising from assembly via launch to in-orbit operation are reduced by about 30% compared to conventional satellites. Main reasons for the cost reduction are the weight reduction and launching of the satellite at a lower orbit. The disadvantages which need to be conceded comprise a longer time to orbit in space and, thus, until the satellite goes into operation. This also translates into a higher risk of damage during this period of time. Nevertheless, all the global players, e.g. Boeing, China Aerospace Corp., Lockheed Martin, Space Systems/Loral, Thales Alenia Space as well as Airbus DS now make serious efforts to develop, test, qualify and, of course, sell all-EP systems.

The space agencies have reacted to this development and offer support by providing platforms for testing novel EP systems in space, e.g. the private-public partnership programs Electra and Neosat of ESA or Horizon 2020 of the European Union. Such programs necessarily are specifically designed to suit the needs of industry and to explore the benefits of EP propulsion either as all-EP systems or hybrid systems combing EP and CP. However, this also implies that the role of universities and research institutes in the field of EP has changed. Before 2012, when the focus was on highly specialized science missions, i.e. niche applications to some extent, the allocation of tasks was more evenly distributed between universities, research institutes, and industry. This naturally has changed in the case of the novel agency programs driving commercialization, here, leadership of the industrial partners now becomes mandatory. Thus, universities and research institutes have to rethink their strategy for the future and new alliances have to be formed.

In this contribution, we discuss the ideas and the strategy behind such an alliance which was formed between the Justus-Liebig University of Giessen, the University of Applied Sciences at Giessen, the DLR Institute of Aerodynamics and Flow Technology and Airbus DS at Lampoldshausen during the RITSAT-project.

II. RITSAT-project

The RITSAT project was funded within the Excellence Initiative of the State of Hesse LOEWE. The partners were initially the Justus-Liebig University of Giessen and the University of Applied Sciences at Giessen who received altogether a funding of about 5 Mio € between 2012 and 2015. The DLR Institute of Aerodynamics and Flow Technology, the Gesellschaft für Schwerionenforschung (GSI) at Darmstadt and Max Planck Institute for extraterrestrial Physics in Garching acted as associated partners. The starting point of the project was Giessen's expertise in EP-technology, in particular RIT-technology, which goes back to the invention of the radiofrequency ion thruster concept in the 1960s by Horst Löb.[1] The aim of the project was to use this expertise as a basis to develop further activities in space research and plasma research and to put Giessen's research in the field of EP on a wider, more solid basis. Instead of one research group in physics working on RIT technology at Justus-Liebig University, there are now about ten research groups from physics, chemistry, materials sciences, and electric engineering working together on EP-related subjects in a consortium of Justus-Liebig University and University of Applied Sciences at Giessen. The extension of the personnel basis and the cooperation between the groups allows us to address a wide range of subjects related to EP and to tackle in particular interdisciplinary challenges. The research subjects now comprise theoretical and numerical modelling ranging from microscopic processes taking place in plasma up to circuit modelling of the periphery of thrusters, the development of new plasma and plume diagnostics, the development of novel propellants for ion thrusters providing an alternative to rare and costly xenon, electronics development, novel concepts for miniaturized thrusters, issues of spacecraft – EP interaction, issues of electro-magnetic compatibility, and, of course, still the development of ion thrusters and ion sources, in particular, of the RIT type. To be competitive, Justus-Liebig University and Airbus DS have signed a cooperation agreement in 2015 to promote the further development of RIT-technology. Furthermore, Justus-Liebig University of Giessen and the DLR Institute for Aerodynamics and Flow Technology have signed a treaty to cooperate in the development and use of their test facilities, e.g. the JUMBO tank in Giessen and the STG-ET at Göttingen. A professorship for "spacecraft" in 2012 and a honorary professorship for "electric propulsion" in 2015 have been established at Justus-Liebig University in the course of these treaties to further support activities in this field.

III. Brief description of ongoing and future research ideas

The involvement of more research groups in the research related to EP offers several opportunities. On the one hand, for the whole consortium to tackle a wider range of scientific questions, in particular, interdisciplinary questions, and, on the other hand, for each individual research group to be more focused on questions related to its scientific expertise. The research ideas, which have been identified by the consortium as being of interest in the future can be divided into three groups: (A) general EP issues, (B) issues specifically relevant to RIT technology, and (C) related space physics issues as well as outreach projects into other research fields such as plasma medicine or plasma/ion-deposition or treatment technologies in material sciences.

A. General EP issues

The general issues which have been identified make use of the complementary expertise of the research groups involved in tackling specific issues.

For example, numerical models of the microscopic processes of plasmas in ion thrusters are developed based on the strength of the groups in theoretical physics.[2] Such models yield a full 3D description of the plasma in discharge chambers of realistic dimensions and can be used to predict plasma parameters such as electron temperatures, ion temperatures as well as the 3D spatial distributions of charged and neutral particles. These microscopic models are complemented by 3D models treating the plasma and its interaction with the electro-magnetic fields on the basis of conservation laws for charge, mass, and energy complemented by a coupling to Maxwell's equations.[3-5] This model forms the link between the physics of the plasma and electric engineering, i.e. electric circuit theory, yielding amongst others a description of the plasma behavior in terms of electric circuit components. Furthermore, this model allows one to predict thruster performance in the sense of fast virtual prototyping. It is also used by the groups in engineering to develop peripheral components of thrusters, e. g. new concepts for RFGs in case of RIT thrusters[6-8].

New plasma and beam diagnostics are developed by the groups working in plasma physics.[11-13] In addition, to conventional diagnostics such as Faraday cups and RPAs for beam diagnostics or Langmuir probes for plasma characterization inside the thruster's discharge vessel the development of optical spectroscopic characterization tools is emphasized. These efforts include the use of optical fiber probes as well as conventional laser absorption and emission spectroscopy of the plasma inside the discharge vessel, but also of the plume.[13] Using this variety of characterization tools, allows one to access the same plasma or beam parameters generated by the same thruster simultaneously. This approach will show differences between the diagnostic methods and, thus, be a valuable check of the reliability of the diagnostic techniques. In addition, it provides experimental data for the verification of the theoretical and numerical models.

Another research direction deals with the challenges of miniaturization.[14-17] Many of the conventional thruster concepts cannot be miniaturized much further without approaching technological limits. The trend towards even smaller satellite size (e.g. femtosatellite) requires a careful consideration of suitable propulsion systems. In close cooperation physicists, material scientists, and chemists are working on the long-term development of such miniaturized propulsion systems with a high degree of integration. One approach comprises the microfabrication of colloid emitters made of the photoresist SU-8 by 3D-lithographic techniques and MEMS technology.[14,15] These emitters shall employ ionic liquids as propellant. Ionic liquids consist of anions and cations of roughly the same molecular weight. Employing these as propellants will allow one to operate the micro-thruster with alternating extraction voltages extracting periodically positive and negative ions and thus not requiring a conventional neutralizer to avoid charging of the satellite. A second approach assesses the suitability of solid-state ion-conductors as ion emitters, i.e. thrusters.[16,17] First experiments indicate that such an approach is feasible. As positive and negative solid-state ion-conductors are available, a suitable combination of both should allow one to abandon neutralizers, if a dual beam mode, i.e. simultaneous or alternating expelling of positive and negative ion beams, is realized. Another interdisciplinary research field is the quest for alternative molecular propellants to replace xenon.[18] Increasing number of satellites with EP systems in addition to competing technologies such as Xe-based light technologies will increase the price of xenon even further. Thus, cheap alternatives become of interest. This research subject is clearly interdisciplinary and requires input from chemistry, atomic and molecular physics, plasma physics and engineering in almost equal measure.

Another truly interdisciplinary research issue comprises the wide field of spacecraft – electric propulsion interaction ranging from damage of peripheral components such as solar panels by the thruster plume to issues of electro-magnetic compatibility.[19-21]

B. Issues especially relevant to RIT-technology

In the framework of the cooperation treaty between the Justus-Liebig University and Airbus DS, the joint research and development of RIT-technology is paramount.[22] One issue is, of course, the promoting of the existing thrusters to higher TRL, their employment in science missions and in commercial applications. The corresponding tasks are clearly divided up between the partners. Justus-Liebig University will be mainly responsible for the fundamental scientific issues whereas Airbus will take the lead in engineering aspects of the thrusters. The electrical engineering groups from University of Applied Sciences at Giessen will also be involved and help to bridge the gap between the two partners. Joint research subjects which are currently addressed or will be addressed in the near future comprise the use of alternative propellants in RITs, the development of new grid systems as well as first steps towards the development of larger thrusters, e.g. RIT-35. The RIT development will, of course, strongly profit from the advances made on the general EP issues discussed in (A) and vice versa, i.e. all new techniques will first be tested on RIT technology.

C. Related space physics issues and outreach projects

The PK-4 experiment on the ISS deals with complex plasmas, one of our research groups is involved in this experiment.[23] However, ion and plasma technologies are also of interest in other disciplines such as medicine and materials science. As the field of EP can profit from knowhow in materials science as discussed in (A), the same also holds vice versa. Variations of ion thrusters may be reliable ion sources for material deposition as well as material processing.[24,25] Furthermore, low-energy plasmas have become of interest for sterilization issues, e.g. in hospitals, or even for the treatment of wounds or skin diseases. The consortium actively seeks such application fields and the contacts to corresponding companies involving also research groups in medicine at Justus-Liebig University.

IV. Description of the status of the test facilities

A major aim of the cooperation between the Justus-Liebig University and the DLR Institute of Aerodynamics and Flow Technology in Göttingen is a concerted operation of their test facilities providing a high standard test environment for EP research and development as well as commercial tests. In order to achieve such a high standard, we are conducting comparative studies of the test chambers in order to identify their best use. The equipment will be developed further to offer the best possible test environment for industrial customers. For example, we will provide a high standard of conventional diagnostic tools in Giessen and Göttingen whose reliability is tested and verified by comparative measurements of the same thruster. Furthermore, we will develop and provide highly specialized diagnostic tools such as the optical diagnostics described in (A) at the smaller test chambers in Giessen, which are offered to external costumers for addressing and answering non-standard questions concerning the performance of their thrusters.

Altogether five test chambers are available. One, the largest chamber STG-ET is located in Göttingen,[25] a medium sized test chamber JUMBO as well as three smaller ones are located in Giessen. The parameters of the chambers and the diagnostic tools installed are listed in table 1.

Table 1: *Description of the test facilities in Göttingen and Giessen*

name	*location*	*dimensions*	*pump volume*	*diagnostics*
STG-ET	Göttingen	cylindrical shape length 12 m, diameter 5 m, volume 236 m^3	turbo and cryo pumps 90 000 liter/s	thrust balance Faraday cup and RPA scanner
JUMBO	Giessen	cylindrical shape length 6 m, diameter 2.6 m, volume 30 m^3	turbo and cryo pumps 120 000 liter/s	quadrupole-mass spectrometer, Faraday cup and RPA (under reconstruction); optical diagnostics (under construction)
BigMac	Giessen	cylindrical shape length 1.2 m, diameter 1.6 m, volume 2.4 m^3	turbo and cryo pumps 2500 liter/s	Faraday cup and RPA scanner
iPott	Giessen	cylindrical shape height 0.68 m, diameter 1.20 m, volume 0.76 m^3	turbo and cryo pumps 15 000 liter/s	90°-dipole magnet system for ion-beam mass analysis
DoubleCube	Giessen	two cubic diagnostic chambers (cube edge length 0.4 m)	turbo pumps 3000 liter/s	emittance measurement setup, optical emission spectroscopy, Faraday cup and RPA scanner

V. Conclusion

The RITSAT-project has promoted the activities in the field of EP at Giessen. About 10 research groups from physics, chemistry, material sciences and electric engineering are now working in an interdisciplinary fashion on research subjects related to the field of EP. This cooperation embeds the EP research into the research and teaching activities of Justus-Liebig University and of the University of Applied Sciences at Giessen. The cooperation treaties with DLR and Airbus DS further support these activities and prepare the location Giessen, home of the RIT, well for future challenges.

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