European Shock-Tube for High Enthalpy Research: Design and Instrumentation, Manufacturing, and Acceptance Testing

M. Lino da Silva[*] and R. Ferreira[†] and J. Vargas[‡] and R. Rodrigues[§] and B. Carvalho[¶] and L. L. Alves[‖] and B. Gonçalves[**]
Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa,1 Av. Rovisco Pais, 1049–001, Lisbon, Portugal

A. Smith[††] and J. Merrifield[‡‡] and S. McDowell[§§] and D. Evans[¶¶]
Fluid Gravity Eng., The Old Coach House, 1 West Street, Emsworth, Hampshire, PO10 7DX, UK

P. Reynier[***]
Ingénieurie et Systèmes Avancés, Bordeaux, France

V. F. Villace[†††] and L. Marraffa[‡‡‡]
ESA-ESTEC, Flight Vehicles and Aerothermodynamics Engineering Section TEC-MPA, Keplerlaan 1, 2200AG Noordwijk, The Netherlands

We discuss the design, manufacturing, and qualification of the ESTHER shock-tube and its associated instrumentation. ESTHER is a new generation shock-tube funded by the European Space Agency and developed by an international consortium led by the Institute of Plasmas and Nuclear Fusion, an associated laboratory from the Instituto Superior Técnico of Lisbon. This facility aims at improving the European predictive capabilities for Spacecraft planetary entries, providing support for the next generation European exploration endeavours. The main drivers for this facility design have been (in no particular order) performance, repeatability, and cleanliness. These are enforced through an innovative design encompassing a laser-ignited, H_2/He/O_2 combustion driver capable of reaching pressures up to 600bar, and strict tolerances for the shock-tube interior surface state. A significant effort has also been put into setting-up state-of-the-art diagnostics. Besides the traditional streak-camera/spectrometer setups for carrying emission spectroscopy in the visible range, an additional VUV capable streak-camera/spectrometer setup is under development, complemented by a fast camera/MWIR spectrometer setup. ESTHER will be capable of carrying optical measurements in the extended 150nm–4.5μm range. Finally an in-house developed interferometer will be deployed for providing time-resolved electron density measurements.

I. Introduction

We discuss the design, manufacturing, and qualification of the **E**uropean **S**hock-**T**ube for **H**igh **E**nthalpy **R**esearch (ESTHER), a facility for the support of future European planetary exploration missions, developed at Instituto de

---

[*] Assistant Researcher, mlinodasilva@tecnico.ulisboa.pt

[†] Ph.D Candidate, ricky_charizard@hotmail.com

[‡] Ph.D Candidate, joao.f.vargas@tecnico.ulisboa.pt

[§] Chief Engineer, rafael.b.rodrigues@tecnico.ulisboa.pt

[¶] Assistant Professor, bernardo@ipfn.ist.utl.pt

[‖] Full Professor, llalves@tecnico.ulisboa.pt

[**] Principal Investigator, bruno@ipfn.ist.utl.pt

[††] Researcher, Retired, arthur.smith@fluidgravity.co.uk

[‡‡] Researcher, james.merrifiel@fluidgravity.co.uk

[§§] Researcher, steve.mcdowell@fluidgravity.co.uk

[¶¶] Researcher, david.evans@fluidgravity.co.uk

[***] Researcher, Philippe.Reynier@isa-space.eu

[†††] Researcher, victor.villace@esa.int

[‡‡‡] Researcher, Retired, lm.esa.retired@gmail.com

Plasmas e Fusão Nuclear (IPFN), a research unit from the Instituto Superior Técnico, under funding from the European Space Agency (ESA).

The previous facility that provided support for European planetary exploration mission since the 90's, the TCM2 shock-tube located in Marseilles, France, was only capable of reaching shock velocities of about 8-9km s^{-1}. This was enough for supporting missions such as the Huygens Titan entry (5.15km s^{-1}) or Mars exploration missions, but insufficient for reproducing Earth superorbital flows (11–12km s^{-1}). This was not a significant issue since no plans existed for such mission profiles at the time, however renewed ambitions for planetary exploration since the beginning of the Century (as for example the Mars Sample Return mission), made this shortcoming more critical, ultimately leading to the issuing of a competitive invitation to tender by ESA, which was awarded in 2010 to an international consortium comprised of IPFN, Fluid Gravity Eng. (FGE), Université de Provence, Ingénieurie et Systèmes Avancés, and Instituto de Soldadura e Qualidade.

Another question that warranted major updates was the selection of an up-to-date instrumentation. Previous measurements carried out in TCM2 resorted exclusively to optical emission spectroscopy in the visible range, which made up for most of the radiation for these shock velocities (to the exception of Mars entries). However, as shock velocities increase, radiation tends to move towards the UV-VUV region, and further Mars entries have specific radiative heating properties with emphasis on the MWIR [1]. Accordingly, two companion contracts were awarded to the consortium for the development of respectively, an optical spectroscopy setup in the VUV region and another in the MWIR region.

ESTHER has underwent a long development cycle which is finally coming to its term in 2019, with the completion of assembly operations and the moving to the qualification and testing phases. This unusually protracted cycle can be traced to the decision (at PDR) to move directly for a two-stage design (optional in the proposal), as single-stage performance was deemed too marginal. The decision to move away from the previous TCM2 design (free-piston driver) to a piston-free, combustion driver, also was deemed as a high risk, high reward approach, capable of mitigating issues like shock-tube recoil and enabling additional performance (with driver pressures up to 600bar. However, there was limited experience with this driver technology at European level, and the decision was made to manufacture and test a scaled driver, an operation that underwent from late 2012 to early 2017 [2]. This bombe test program allowed implementing a laser ignition system for the combustion driver that negates many shortcomings of the combustion driver technologies (namely cleanliness), and validated the driver performance predictions from the design phase.

This article provides an outlook on this almost decade long development cycle and presents the frozen design for the shock-tube (Section II), the outcomes of the scaled driver test campaign (Section III), the outcomes of the parts reception, metrology and assembly (Section IV), and finally the design for the instrumentation setup (Section V).

II. Design and Performance of the ESTHER Shock-Tube

The ESTHER shock-tube implements a set of novel technologies, which enable enforcing a key set of Specifications and Requirements that were defined by ESA as critical for a new generation facility that may effectively support the European ambitions for planetary exploration in the 21^{st} Century, namely:

- **Reliability, repeatability, safety, and high performance**. This is achieved through the design of a $H_2/He/O_2$ combustion driver, operating in deflagration mode. The design strategy further includes the addition of a second stage compression tube and an area change between driver/compression tube and compression tube/test section. Shock-tube operation using a deflagration combustion driver ensures reliability and repeatability (when compared for example to detonation or arc-heated drivers). Safety is achieved through a remote handling, ATEX compliant control system, in a semi-buried building specifically tailored for this facility. Finally high-performance is ensured thanks to the aforementioned two-stage design, which allows exceeding superorbital entries above 12km/s for the case of an Earth return.
- **Cleanliness**. this is achieved by the selection of a low-carbon super-duplex steel, with high-vacuum pumping, which prevents significant carbon wall pollution in the test-section walls. A Nd:Yag laser ignition system of the driver (a first in shock-tube technologies) further ensures cleanliness, through the removal of the ignition system outside of the shock-tube, therefore avoiding further contamination (which stems from other ignition techniques such as hotwire or spark-plug).
- **Low-cost, high turnaround**. The facility is automated to a large extent, allowing operation by a two-person team. A high-performance vacuum system is implemented, hastening deep vacuum cleaning operations of the test section. Finally, diaphragms are due to be produced onsite, furthering reducing costs. A range of 2–4 shots per day is expected.

A. Design Summary

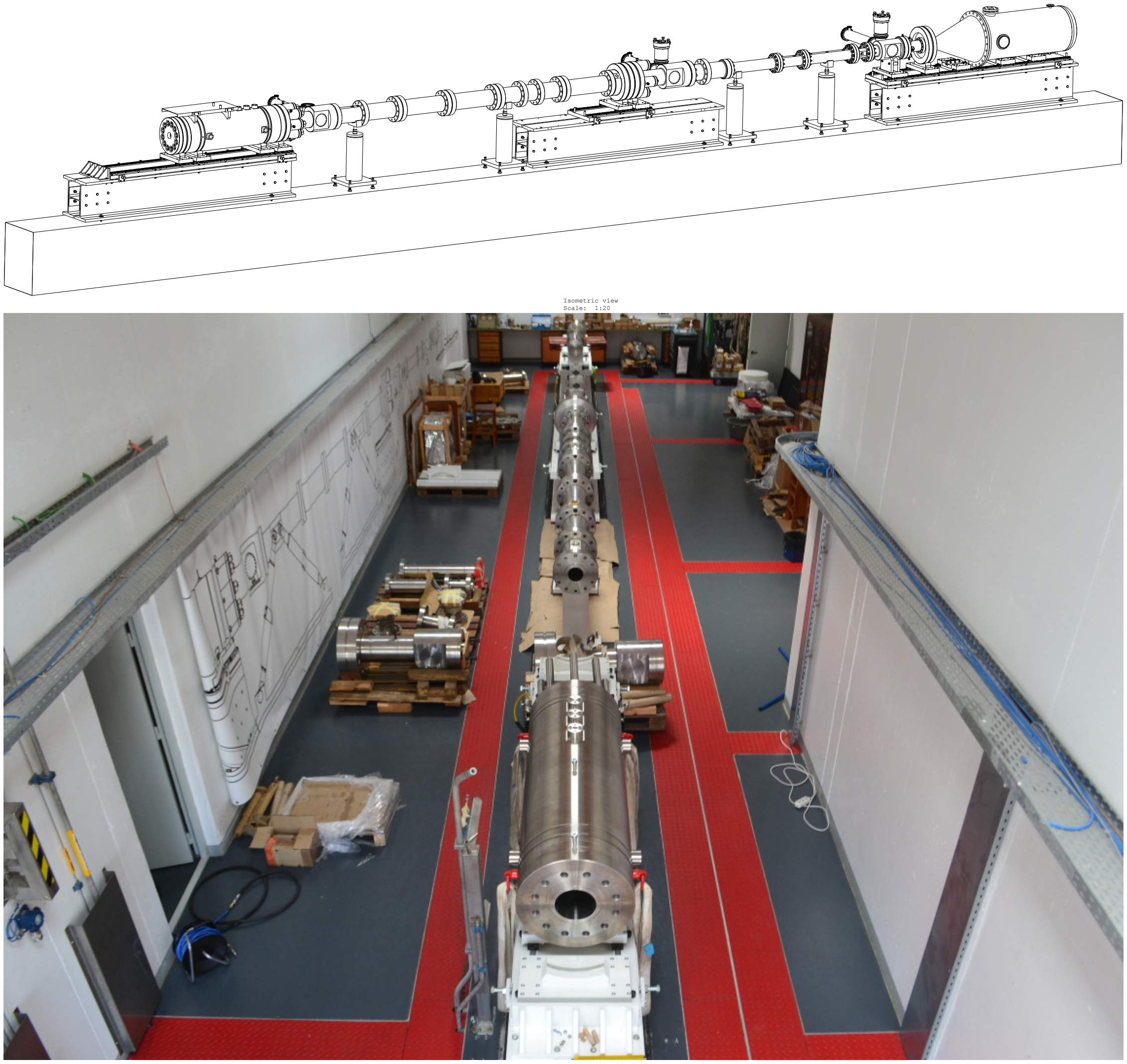

Fig. 1 CAD view of the ESTHER shock-tube (top) and view of the assembly (ca. May 2019).

The ESTHER shock-tube assembly is composed of a 47l combustion chamber (He/H_2/O_2 mixtures) at initial pressure up to 100bar and a final pressure of 600bar. The facility is nominally operated in a deflagration (subsonic combustion) mode; however, detonations (supersonic combustion) may occasionally occur, giving reflected transient pressures of the order of 2.4kbar. Ignition is achieved through an Nd:Yag laser, which shoots a ns pulse. As discussed in the previous paragraph, the combustion chamber is made using low carbon super-duplex steel, which has high mechanical strength and is indicated for hydrogen containment because of minimized adsorption. The combustion chamber has an internal diameter of 200mm. The length of the combustion chamber has been calculated to avoid having the reflected expansion wave overtake the primary shock wave before it reaches the test section [3].

An intermediary compression tube is connected to the combustion chamber through a diaphragm designed to burst at a predetermined pressure. The compression tube is filled with He gas at pressures of about 0.01–1bar. The shock-wave propagates in this section leading to transient reflected pressures of 70bar. The tube end sections are made in super-duplex stainless steel, while the middle sections are made in duplex stainless steel, which also has a low rate of Carbon, limiting adsorption. The compression tube section has an internal diameter of 130mm.

The compression tube is connected to the shock-tube test section through a second diaphragm designed to burst at a predetermined pressure. The shock-tube is filled with a test gas at pressures of about 0.1mbar. The shock-wave propagates in this section at velocities that can exceed 10km s^{-1}, leading to transient reflected pressures of no more than

20bar. The tube is manufactured in duplex stainless steel. The shock-tube section has an internal diameter of 80mm. Pressure sensor stations are located at different stages of the shock-tube, detecting the rise of pressure in the wake of the shock-wave. This allows for developing a triggering system initiating high-speed (10–100MHz rated), time-dependent spectroscopic measurements at the test-section windows (25mm diameter) of the radiation emitted and absorbed in the wake of the shockwave.

A 1,000l dump tank recovers all the gases flowing in the wake of the shock-wave. The H_2O liquid phase is drained off, while the remaining contaminated He mixture is evacuated by the pumping system, after which the shock-tube can be opened for cleaning operations and the replacement of the diaphragms.

The final CAD design of the facility, along with pictures of the partially assembled facility, are presented in Fig. 1

B. Performance

The general design for ESTHER (combustion driver, two-stage) was defined as the outcome of a review of previous facilities capabilities (specifically, combustion shock-tubes such as the Convair shock-tube in the US [4]; TH_2 in Aachen, Germany; and VUT-T in Moscow, Russia), and particularly performance predictions using FGE's in-house analytic code **S**hock-**T**ube **A**nd **G**as **G**un (STAGG) code. The code solves an updated expression of the shock-tube equation (see Eq. 1 and schematic figure above[*]) for a variety of scenarios (variable area, two-stage geometries, frozen and equilibrium chemistry, and rarefaction effects [5]).

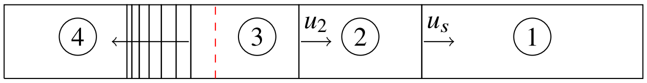

Fig. 2 Flow in an one diaphragm, constant area shock tube after diaphragm breaking [not at scale].

$$\frac{P_4}{P_1} = \frac{P_2}{P_1}\left[1 - \frac{(\gamma_4 - 1)\frac{a_1}{a_4}\left(\frac{P_2}{P_1} - 1\right)}{\sqrt{2\gamma_1}\sqrt{2\gamma_1 + (\gamma_1 + 1)\left(\frac{P_2}{P_1} - 1\right)}}\right]^{-\frac{2\gamma_4}{\gamma_4 - 1}} \tag{1}$$

A database for the calculation of equilibrium chemistry properties (post-combustion p, T, γ, etc...) was created for the combustion driver, accounting for selected $He/H_2/O_2$ mixture ratios considered in our facility. this was carried out using NASA's CEA equilibrium code[†].

The STAGG code was firstly calibrated/validated against results from the VUT-1 test campaign previously carried in the scope of an ESA TRP in 2008 [6]. Then, the code was applied to the optimization of the ESTHER design. The critical parameters to optimize were 1) the driver/compression tube/test section areas, examining the tradeoffs between a larger cross-sectional area of the driver (which improves shock velocity) and the resulting driver volume (with negative implications in safety, geometrical clearance, and cost per shot); 2) the compression tube optimal filling pressure. Examples for both these optimizations are presented in Fig. 3, reporting the shock speed dependence on the driver/test section area ratios for a single-stage configuration, and Fig. 4, reporting the optimization of the compression tube/test section area ratio and gas pressure.

The design was therefore frozen to area ratios of 6.25/2.5/1, with compression tube pressures around 10^2–10^3mbar.

The STAGG code has then been ran for different test gas mixtures representing respectively Earth reentries, Mars/Venus entries, Titan entries and Gas Giant entries. The details for this study can be consulted in ref. [3]. Fig 5 summarizes the ESTHER performance envelope for different planetary atmospheres. Tab. 1 reports the maximum shock speeds that are predicted for the selected ESTHER configuration.

From the performance analysis (and the comparison with typical planetary entry profiles, see Ref. [3]), we verify that ESTHER is compliant in terms of performance for most of the entry scenarios, with the notable exception of Gas

---

[*] with 1 and 4 the undisturbed low/high-pressure zones respectively; u_s the shock wave and u_2 the contact wave. The ruptured diaphragm is represented by the dasehd red line

[†] available at `https://www.grc.nasa.gov/WWW/CEAWeb/`

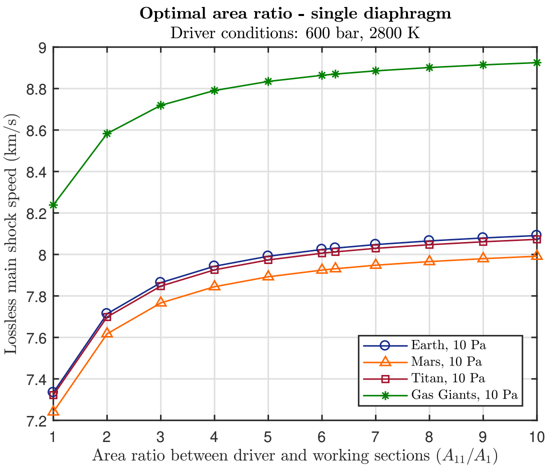

Fig. 3 Effect of area ratio on shock speed (single-stage, P_4=600bar, T_4=2800K, p_1=10Pa, T_1=300K)

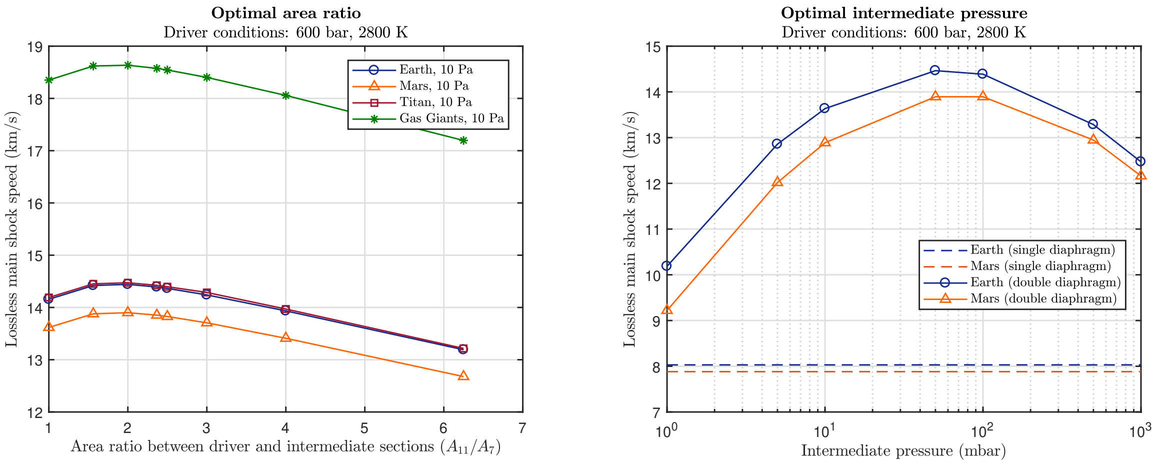

Fig. 4 Optimization of the compression tube size (top) and pressure (bottom) (two-stage, P_4=600bar, T_4=2800K, p_1=10Pa, T_1=300K)

Table 1 ESTHER maximum speed for different gas mixtures

	10Pa	100Pa	Comments
Earth/Titan	14.5	11.7	OK All scenarios
Mars/Venus	13.8	10.8	OK All scenarios
			No Go Jupiter
Gas Giants	18.4	15.3	OK Saturn/Uranus/Neptune
			with Gas substitution

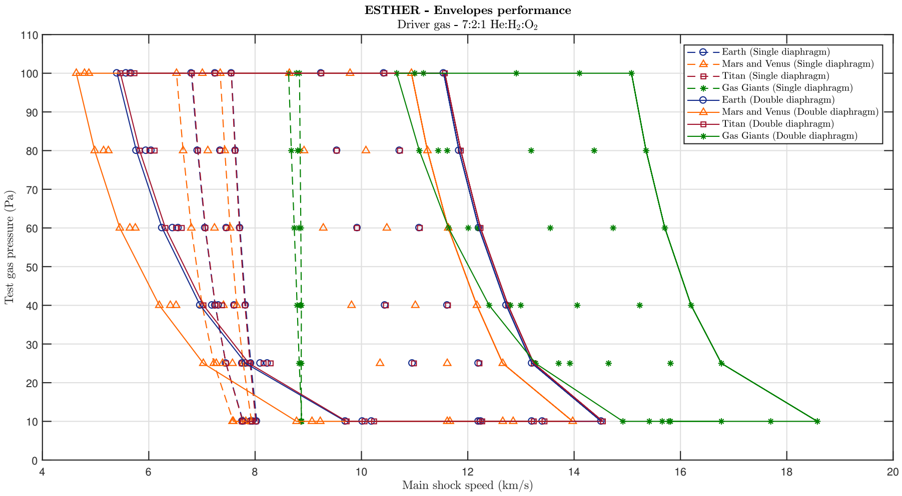

Fig. 5 Pressure vs. speed performance envelope for the ESTHER facility (Earth, Mars, Venus, Titan and Gas Giants)

Giant entries, owing to the large mass of these bodies. Nevertheless, while the reproduction of a Jupiter entry conditions is outside of the possibilities for the ESTHER facility, one may still reproduce the entry conditions for the other Gas Giants resorting to the gas substitution technique [3, 7]. In this case, instead of reproducing the shock speeds, one simply reproduces the post-shock temperatures, which remains a relatively accurate simulation of the real entry conditions [7].

The performance analysis further shows that, as a facility specifically tailored for speed, ESTHER has some difficulties in reaching lower ($<5\,\mathrm{km\,s^{-1}}$) shock velocities, even if the compression tube stage is run at non-optimized pressures. One alternative possibility is to consider the facility as working in single-stage mode. As such, single-stage performance is also reported, but purely as an exercise. While the design for ESTHER allows for the compression tube to be decoupled and the test section connected directly to the combustion driver[‡], in practice the team does not expect to use this configuration. If lower velocities are required, the He dilutant in the driver will be replaced with nitrogen[§], making the driver gas heavier, and hence slower. Then lower shock waves might be reached in the test section.

III. Scaled driver test trials

Although the sizing of the main combustion chamber was frozen very early into the design phase, the risks for designing and manufacturing an untested ignition system were deemed too high, and a pragmatic approach of designing a "bombe" scale model of the combustion chamber was favored also in the early stages of design. This provided the advantage of being able to fully design and test the facility gas supply system, the ignition system, the pressure measurement setup, and also evaluate the mechanical behavior of the "bombe" test model. An early testing and validation of such key components allowed an expedited setup of the whole shock-tube facility later on, since these are some of the most critical components (safety-wise) of the facility.

The design and setup of the gas filling system/bombe experiment spanned for the period of Feb. 2012–Jul. 2015, with a test campaign spanning for the period Jul. 2015– May 2017. The 3l bombe was used to test the gas filling system[¶] in operation. The initial ignition system design was composed of a hotwire (described in detail in Ref. [2]). This system evidenced a few shortcomings, such as brittleness of the MACOR electrical insulator ceramics in the case of a detonation, and the accretion of wire residue to the combustion chamber walls, increasing the risk of pollution for extended operations of the shock-tube. Ultimately, an alternative ignition system comprised of an Nd:Yag laser ignition system and a thick window for accessing the bombe interior was designed and successfully tested. It was possible to offset one of the shortcomings of such a laser system, which is the localized deposition of energy in a single point, as opposed to the distributed heat deposition throughout the whole hotwire length, through the careful tailoring of

---

[‡] there is also the possibility of assembling the compression tube after the test section, acting as an expansion tube

[§] And optionally in the compression tube

[¶] Developed by Air Liquide

the combustible gas stochiometric mixtures, with an oxygen-rich mixture having been found out to avoid the onset of detonations (which are undesirable since they negatively affect the repeatability of the facility). A grand total of 177 shots were carried out from lower (10bar) to higher (100bar) filling pressures. A maximum of 625bar post-combustion has been achieved, for a filling pressure of 98bar (see Fig. 6).

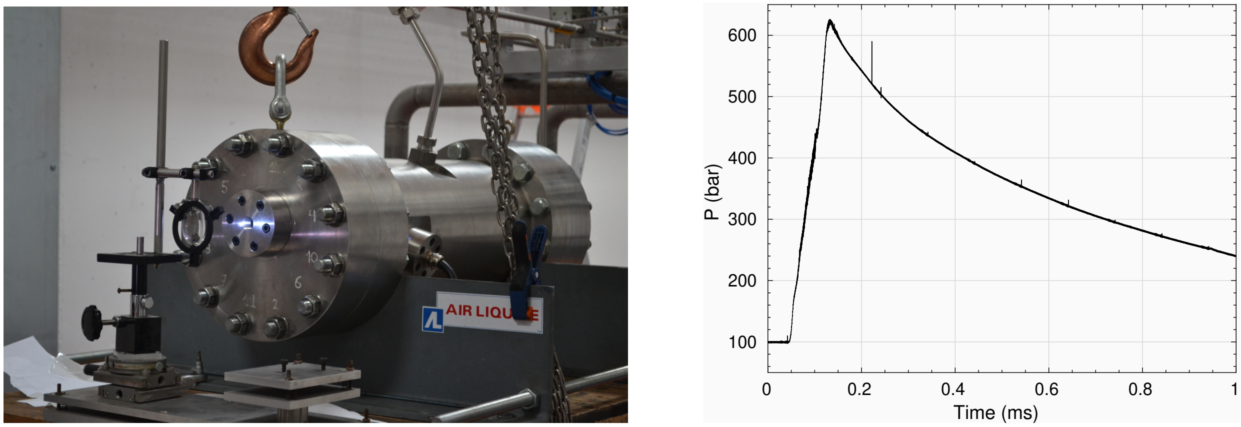

Fig. 6 View of the bombe during laser operation (left) and laser-ignited shot ♯177 (01/03/2017), Peak pressure is 625bar **(right)**

The test-campaign achieved two objectives: 1) Demonstrating the viability of a laser-ignition system without transition to detonation and 2) achieving (and slightly exceeding) maximum pressure requirements for the driver (above 600bar). The findings of this experimental campaign were then put into the fine-tuning of the driver design.

IV. Parts reception, metrology, assembly, and qualification

Starting on the second half of 2018, final parts of the shock-tube have been receptioned, and assessed metrologically. Critical dimensions have been probed by laser metrology, and surface state has been assessed using surface metrology. Specifications and requirements mandated a surface state of Ra0.8 for the driver and compression tube, and Ra0.5 for the test section. The requirements have been met and exceeded for all the parts. Sample metrology assessments are presented in Fig. 7 for a compression tube part (CT3–1) and a test section part (ST7).

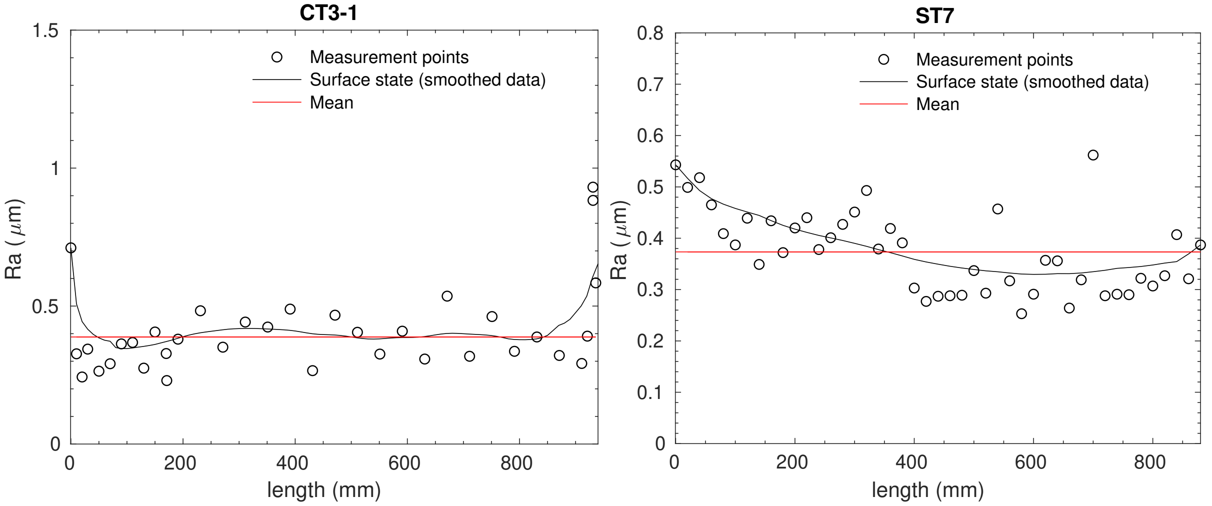

Fig. 7 Surface state of the compression tube CT3–1 (top) and test section ST7 parts (bottom)

Pressure and vacuum qualification tests are currently being set-up. The pressure test includes qualification of the driver section around 1,400–1,500bar using a water pump, and the compression tube and test sections at lower pressures (since these will experience much lower overpressures than the driver section).

The vacuum tests will be carried out with a setup comprised of a primary EDWARDS GX600 pump, connected to two turbomolecular pumps EDWARDS STP603, in charge of ensuring a “deep” vacuum of over 10^{-4}mbar in the test section, allowing outgasing of contaminants prior to filling with the test gases. Two additional pumps are included in the setup: An additional GX600 pup for vacuuming the dump tank, and a smaller EDWARDS iXL120 pump for vacuuming the compression tube.

These initial qualification tests will be followed by diaphragm opening testing and the first shots (with a “blind diaphragm” of the driver, operating in “bombe” mode). These will be followed by the first test trials at lower velocities in the third and last quarters of 2019, during which the pressure sensor and fast triggering systems will be optimized.

V. Instrumentation setup

ESTHER is an unique facility also in terms of instrumentation. A grand total of 8 25mm window ports are available for measurements (2x4 windows in North, South, East, West orientation). The instrumentation setup, developed in the scope of two companion ESA contracts (ESA Contract 4000108651/13/NL/HB: “Characterization of Radiation for High Speed Entry”, and ESA Contract 4000118059/13/NL/HB: “Standard Kinetic Models for CO_2 Dissociating Flows”), will be comprised of a visible streak-camera and spectrometer (refurbished from the older TCM2 shock-tube facility), a VUV streak-camera/spectrometer setup for fast entries (see schematics in Fig. 8) developed by Hammamatsu/McPherson and to be setup in October 2019, and an IR fast camera/spectrometer setup for Martian-type entries (tailored for CO_2 radiation measurements). The overall spectral range covered by the ESTHER facility instrumentation is presented in Fig. 9.

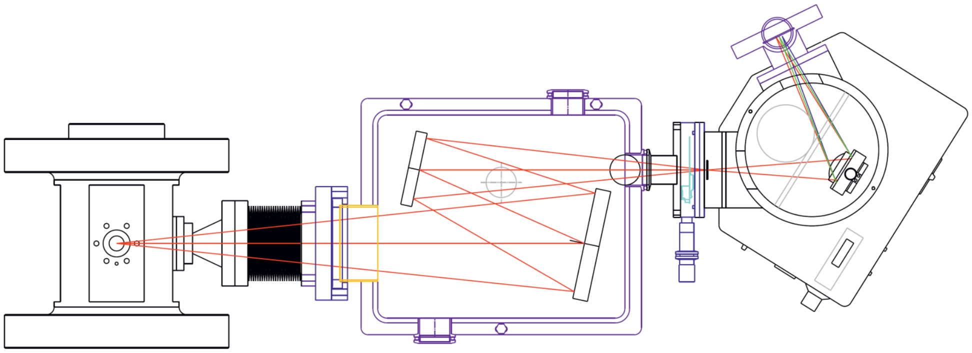

Fig. 8 VUV instrumentation schematics

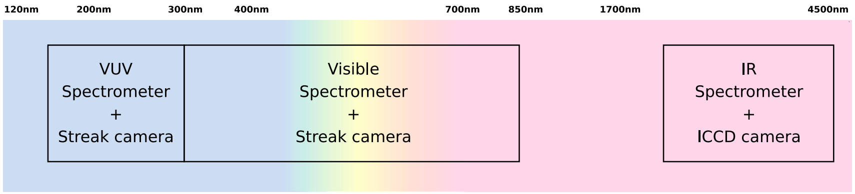

Fig. 9 ESTHER instrumentation spectral range coverage

The VUV spectroscopy setup has underwent successful acceptance tests in the end of November. A picture of the setup is presented in Fig.

Last but not least, a fast and compact (15x15cm, 200g) Frequency Modulated Continuous Wave Radar (FMCW) interferometer/reflectometer is being developed “in-house” for the measurement of electron densities. The reflectometer

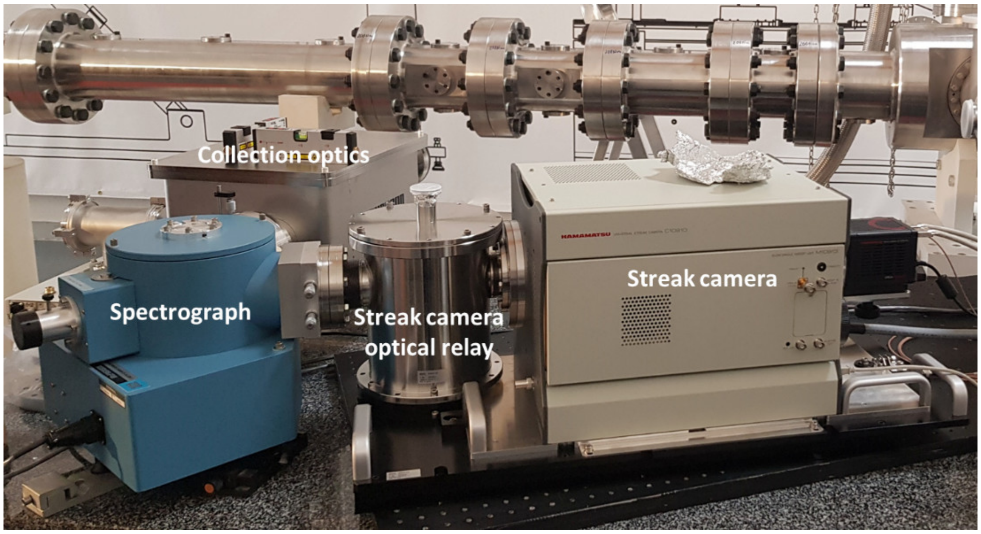

Fig. 10 VUV spectrogrph+streak-camera setup

has an ultrawide band coverage in the 2–140GHz range, allowing for the probing of an extensive range of plasma densities (5×10^{16}–2.4×10^{20}electron/m^3). It is expected that this design might also be useful for deployment in entry spacecrafts for actual measurements of plasma electron densities in the actual conditions of an atmospheric entry.

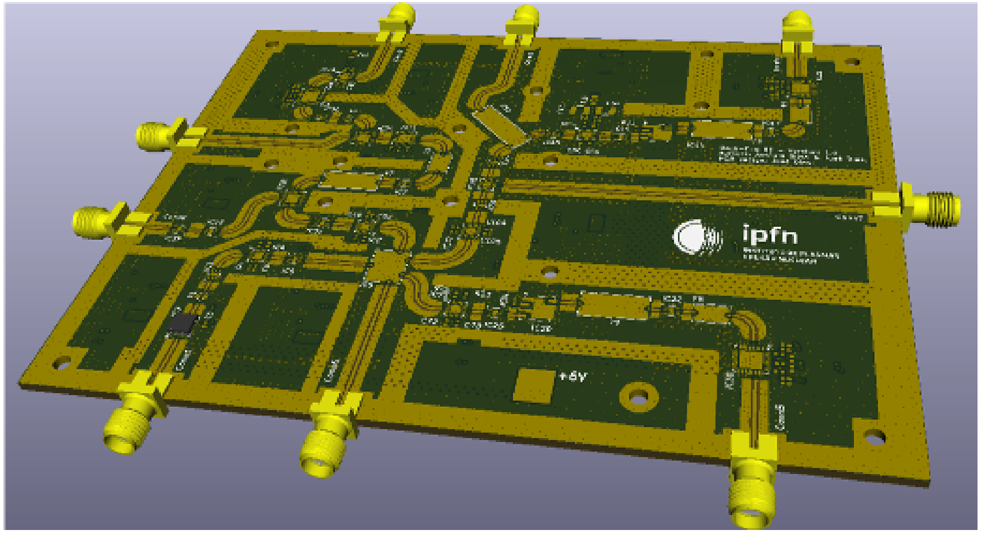

Fig. 11 reflectometer PCB board

Acknowledgments

This work has been conducted under funding from the ESA Technology Research Programme contracts: “Kinetic Shock-Tube for Radiation Database for Planetary Exploration”, European Space Agency Contract 23086, “Characterization of Radiation for High Speed Entry”, European Space Agency Contract 4000108651/13/NL/HB, and “Standard Kinetic Models for CO_2 Dissociating Flows”, European Space Agency Contract 4000118059/13/NL/HB. IST/IPFN manpower has been funded by Fundação para a Ciéncia e Tecnologia through project UID/FIS/50010/2019, grant PD/BD/114325/2016 (PD-F APPLAuSE), and grant PD/BD/142970/2018 (PD-F APPLAuSE).

References

[1] M. Lino da Silva, and J. Beck, “Contribution of CO_2 IR. Radiation to Martian Entries Radiative Wall Fluxes”, *AIAA paper 2011–0135*, 49th AIAA Aerospace Sciences Meeting, Orlando, FL, 4–7 Jan. 2011.

[2] M. Lino da Silva and B. B. Carvalho, “High-Pressure H_2/He/O_2 Combustion Experiments for the Design of the ESTHER Shock-Tube Driver,” *AIAA Paper 2016–4156*, 46th AIAA Thermophysics Conference, Washington D.C., Washington, 13–17 June 2016.

[3] D. Luis, “Mapping of the Aerodynamic Performance of the ESTHER Shock-Tube”, Ms. C Thesis, Instituto Superior Técnico, Universidade de Lisboa, Sep. 2018, available at https://fenix.tecnico.ulisboa.pt/cursos/meaer/dissertacao/1972678479054139.

[4] K. C. Hendershot, *“Development of a Combustion Driven Shock Tunnel,”*, Symposium on Hypersonic Techniques, 20–21 October 1960, University of Denver Research Institute, (Institute of Aeronautical Sciences, New York, 1960).

[5] H. Mirels, “Test Time in Low Pressure Shock Tubes”, *Physics of Fluids*, Vol. 6, No. 9, 1963, pp. 1201–1214.

[6] “CFD Validation in CO_2 Environment”, *European Space Agency Contract 19677*, January 2008.

[7] C. James, “Radiation From Simulated Atmospheric Entry Into the Gas Giants”, *Ph.D. Thesis*, Mechanical and Mining Engineering Department, University of Queensland, Queensland, Australia.

A. Some additional pictures of the ESTHER facility