Test Trials of the ESTHER Shock Tube

The ESTHER Team

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10th Radiation of High Enthalpy Gases in Atmospheric Entry Workshop, Oxford, 9-12th Sep. 2024

Development and Qualification of the European Shock Tube for High Enthalpy Research

Public Presentation of the Doctoral Thesis
Prova Pública de Doutoramento
24th of April 2024, Lisboa, Portugal

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Driver Qualification campaign

High-pressure combustion

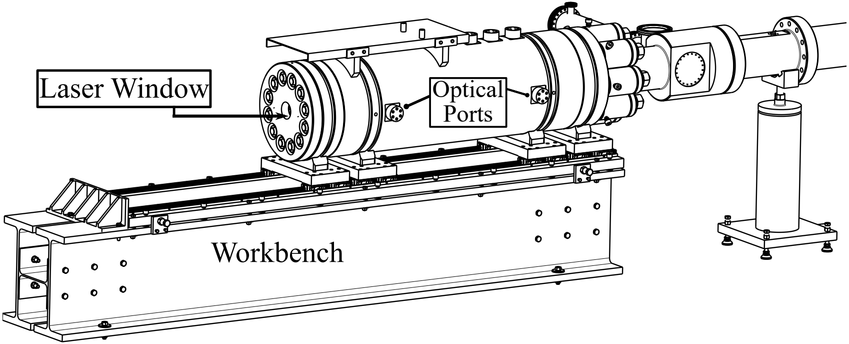
Driver performance

ESTHER operational mixtures

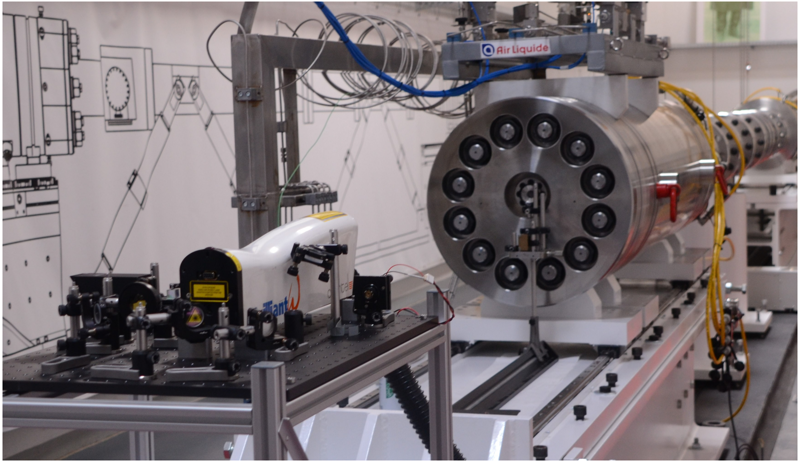
Expected shock wave speed

Driver Qualification - Combustion Chamber

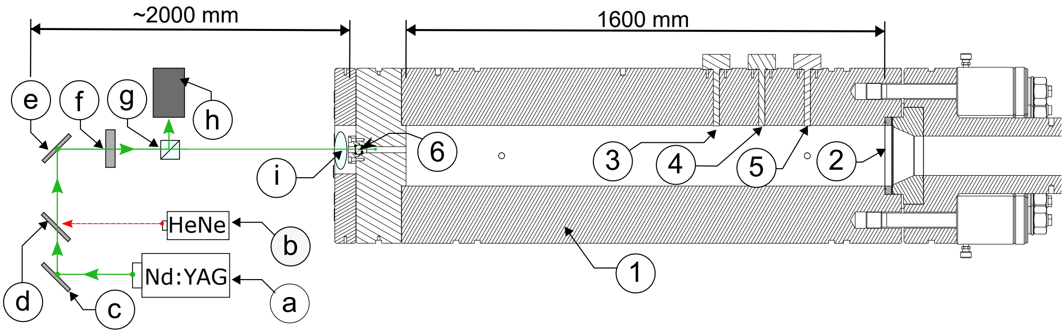
- 50 L $He/N_2{:}H_2{:}O_2$
- Filling pressure up to 100 bar
- Laser ignition (1st of its kind)
- $He{:}H_2{:}O_2 \simeq 8{:}2{:}1.2$
- $N_2{:}H_2{:}O_2 \simeq 10{:}2{:}1.4$



ESTHER experimental Hall
Combustion chamber and Laser Ignition System

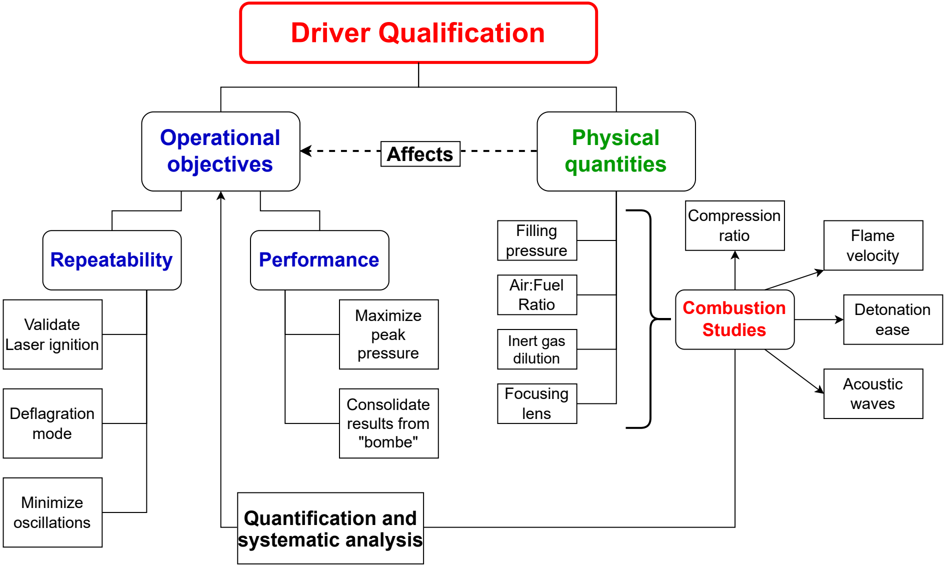


Driver Qualification - Laser Ignition System



- a High-power Nd:YAG laser 1064 nm 5 ns 200 mJ
- b Red diode laser
- c 45º mirror
- d 45º mirror
- e 45º mirror
- f Half-wave plate
- g Beam splitter cube
- h Beam dump
- i Bi-convex focusing lens 100 mm
- 1 Combustion chamber
- 2 Diaphragm/blank
- 3 Gas input port
- 4 Gas output port
- 5 Kistler gauge
- 6 Sapphire Optical Window

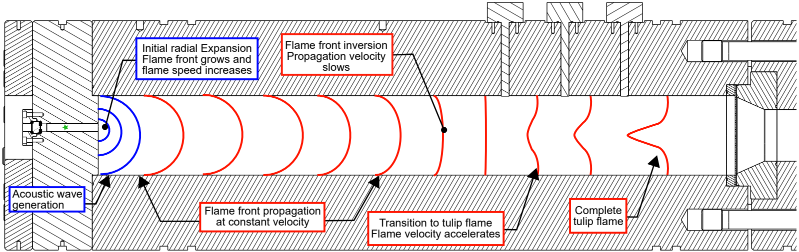
Driver Qualification - Objectives



Driver Qualification - 100 Shots

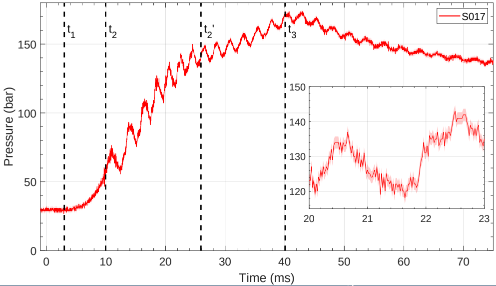
	Helium diluted shots	**Nitrogen diluted shots**
Number of shots	65	35
Filling pressure (bar)	5–100	10–100
Peak pressure (bar)	35–660	40–550
Inert gas dilution (%)	54–76	56–78
Air:fuel equivalence ratio	0.45–2.04	0.75–1.38
Focused ignition	58	32
Unfocused ignition	7	3

Driver Qualification - Combustion Evolution



Flame front propagation inside combustion chamber.

Pressure signal example



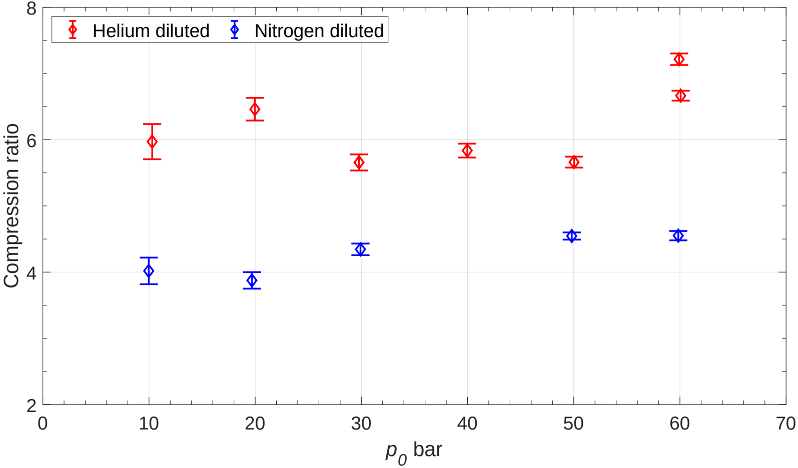
Pressure Signal

- Laser firing $t = 0$
- Combustion start t_1
- Flame front hits wall t_2
- Second slope t_2'
- Tulip flame transition
- End of combustion t_3
- Cooldown phase

Driver Qualification - Pressure Effects

Increasing pressure

- Similar compression ratio
- Increased acoustic oscillations
- More Detonation prone

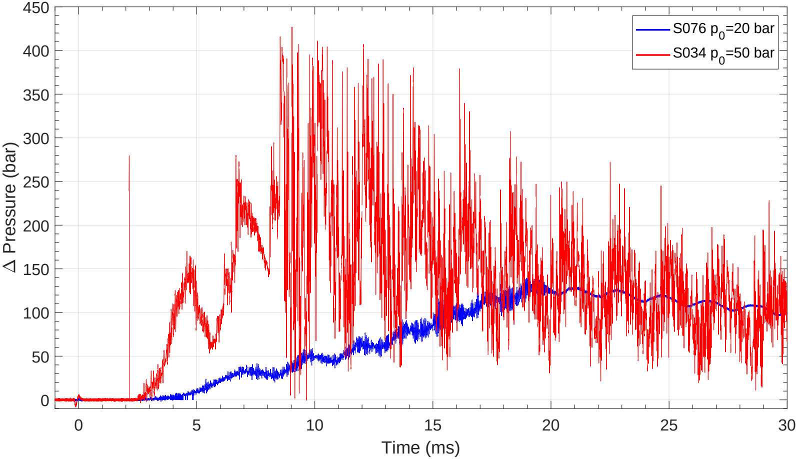


Compression ratio comparison for the "typical" [X:H2:O2] 8:2:1.2 shot at different filling pressures.

Driver Qualification - Pressure Effects

Increasing pressure

- Similar compression ratio
- Increased acoustic oscillations
- More Detonation prone

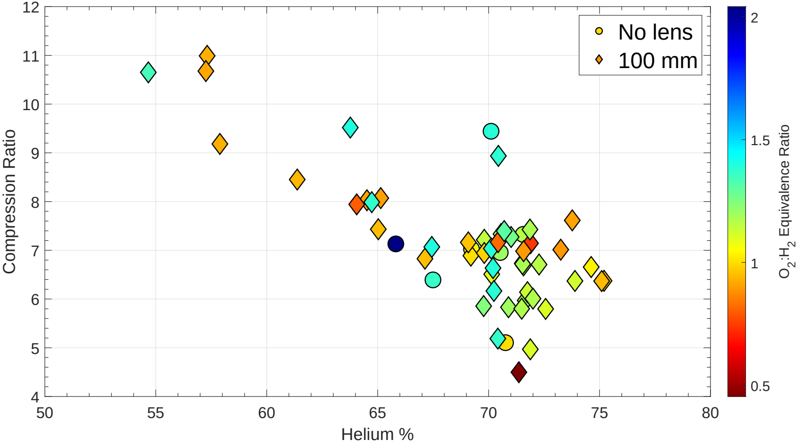


Variation in pressure signal comparison for S034 (p_0=50 bar) and S076 (p_0=20 bar), X_{He} = 64%, λ=1.40.

Driver Qualification - Dilution Effects

Increasing dilution:

- Lowers compression ratio
- Weaker acoustic oscillations
- Less Detonation prone
- N_2 shots lower compression ratio
- N_2 combustion is more unstable



Scatter plot of compression function of helium dilution, O_2:H_2 equivalence ratio in color-axis, focal lens distance in markers symbol.

Driver Qualification - Dilution Effects

Increasing dilution:

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- Weaker acoustic oscillations
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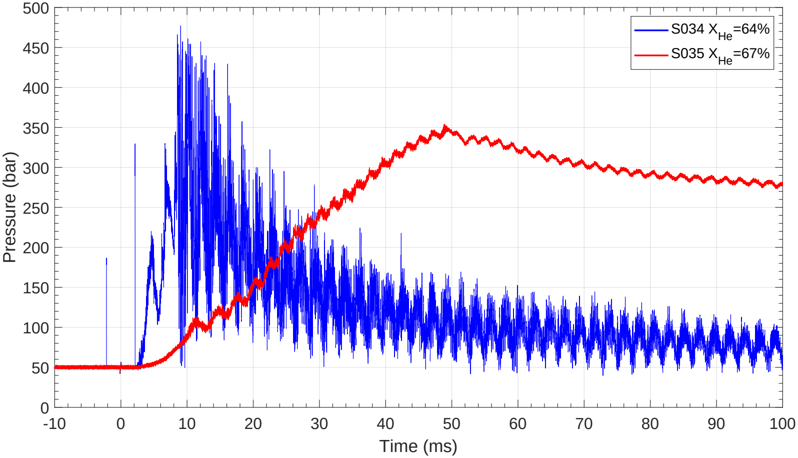
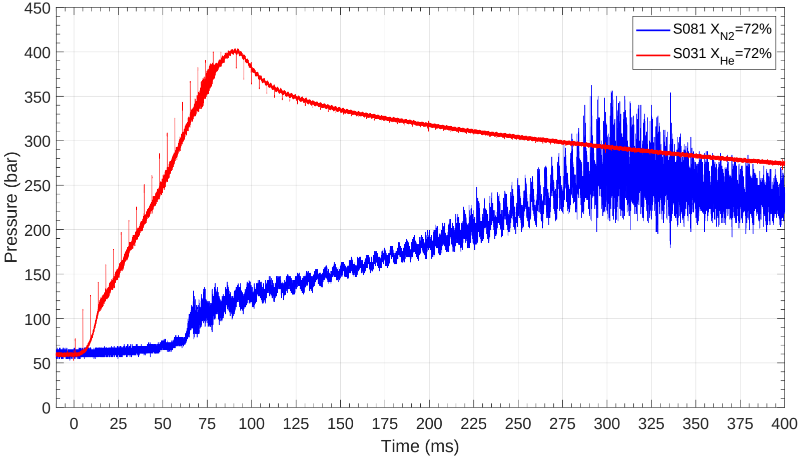


Pressure signals for different diluent molar fractions, S034 64% (blue) and S035 67% (red). p_0=50 bar, λ=1.40 and lens focal distance 100

Driver Qualification - Dilution Effects

Increasing dilution:

- Lowers compression ratio
- Weaker acoustic oscillations
- Less Detonation prone
- N_2 shots lower compression ratio
- N_2 combustion is more unstable



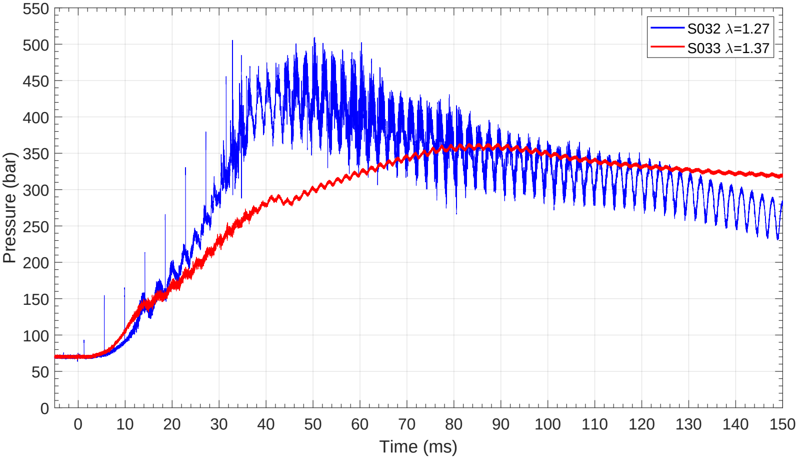
Pressure signal comparison for different diluent gases, helium in S031 (blue) and nitrogen in S081 (red). p_0=60 bar, λ=1.20 and lens focal distance 100 mm.

Driver Qualification - Air:Fuel Ratio

Leaner mixtures:

- Slight reduction in compression ratio
- Lower acoustic oscillations
- More stable combustion

$$\lambda = \frac{n_{O2}}{n_{H2}} \Big/ \left(\frac{n_{O2}}{n_{H2}}\right)_{stoichiometric}$$

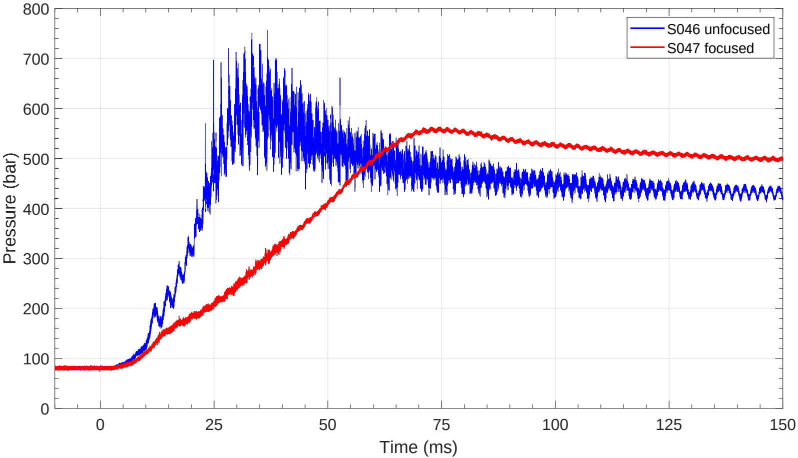


Pressure signal comparison of shots at p_0=70 bar, X_{He}=71%, S032 (blue) and S033 (red) and lens focal distance 100 mm

Driver Qualification - Focal Lens Effects

Unfocused ignition

- Only for $p_0 > 30$ bar
- Irrad. $\sim 10^8 \ll 10^{10}$ W/cm^2 (min in literature)
- Similar compression ratio
- Increased turbulence
- Shorter combustion
- Slightly higher detonation prone



Shots S047 and S046 pressure signal comparison, p_0=80 bar, λ=1.39 and X_{He}=70%

Driver Qualification - Resume

	Compression ratio	Flame speed	Acoustic wave	Detonation ease
$\mathbf{p_0} \uparrow$	$\simeq$	$\downarrow$	$\uparrow$	$\uparrow$
$\mathcal{X}_{\mathbf{He}} \uparrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
He $\rightarrow$ $\mathbf{N_2}$	$\downarrow$	$\downarrow$	$\uparrow$	$\downarrow$
No Focus lens	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$

ESTHER Driver operational parameters:

Filling pressure p_0 (bar)	**10**	**50**	**60**	**70**	**80**	**100**
Mixture He:H_2:O_2	8:2:1.2	8:2:1.2	8:2:1.2	8:2:1.3	8:2:1.4	8:2:1.4
Peak Pressure p_{peak} (bar)	61.5	334	400.5	425	528	660
Mixture N_2:H_2:O_2	10:2:1.4	10:2:1.4	–	–	–	–
Peak Pressure p_{peak} (bar)	38	190	–	–	–	–

ESTHER Vacuum Systems

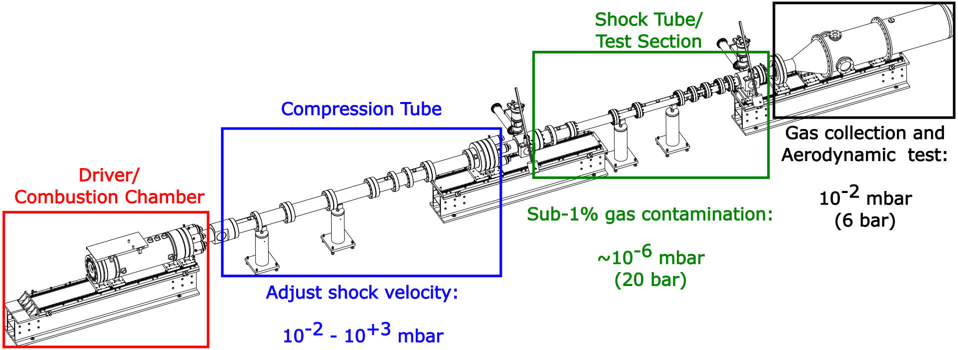
ESTHER vacuum requirements

Vacuum equipment

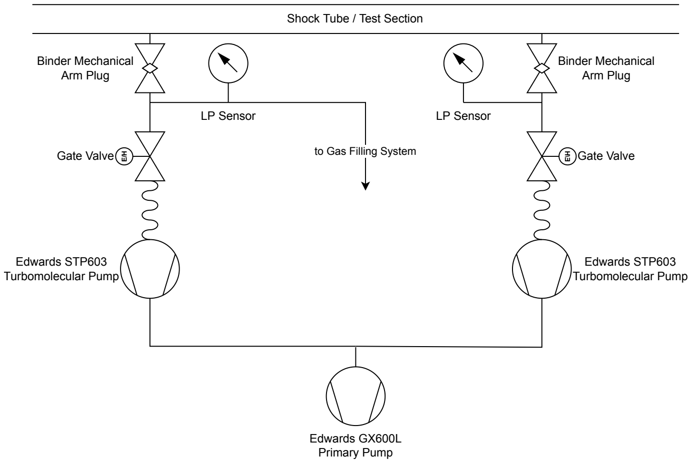
Vacuum test campaign

Vacuum overview

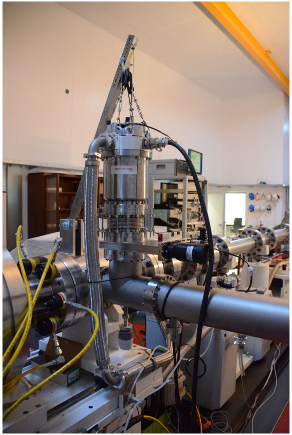
ESTHER vacuum pressure and overpressure requirements:



Shock Tube - Vacuum System



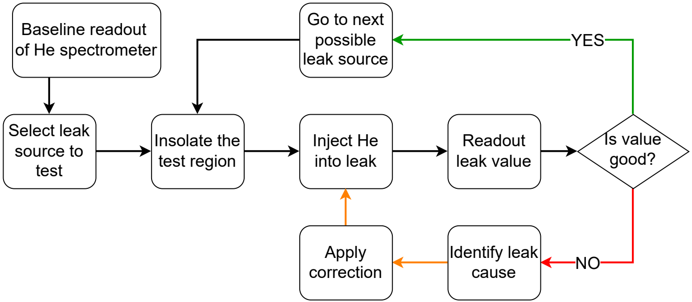
PID Scheme for Shock Tube vacuum system

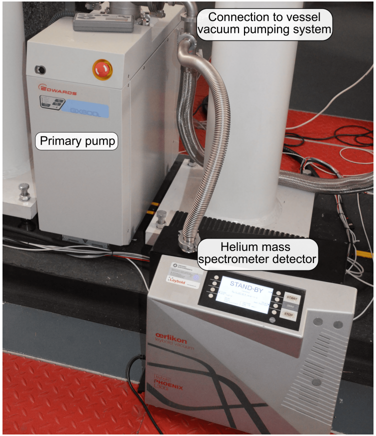


Shock Tube vacuum system - partial photo

Shock Tube - Leakage Test

Helium Leakage Test Methodology:





Helium leak detector setup

Common problems/limitiations:

- Cleaning and outgassing
- Surface state
- Copper ring ductablity
- Bitten O-ring
- Insufficient torque
- Cross-threaded bolt

ESTHER Vacuum Systems - Achievements

Date	$p_{ultimate}$ CT side (mbar)	$p_{ultimate}$ DT side (mbar)	$\dot{p}$ (mbar/s)
12th May	3.70×10^{-6}	2.12×10^{-4}	9.99×10^{-5}

Sub-Assembly	Limitation	Correction
Diaphragm holder	Clamping diaphragm	Re-design
ST7-1 Plug	Copper ring did not plastically deform	Annealing the ring at 450 ºC
Gauge DT side	Leakage at O-rings	Replace O-ring
Tee arm DT side	Debris from threaded holes Surface state Bitten copper ring	Re-Threading and cleaning Polishing surface Replacing the ring
Inner tube surface	Oils Outgassing	Surface cleaning System held under vacuum

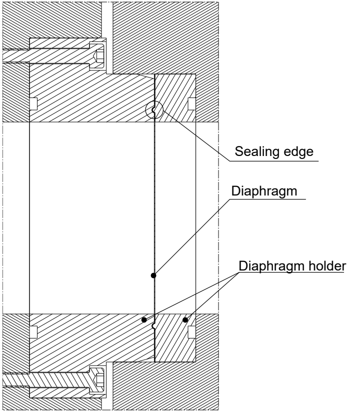
Date	$p_{ultimate}$ CT side (mbar)	$p_{ultimate}$ DT side (mbar)	$\dot{p}$ (mbar/s)
25th July	9.89×10^{-7}	1.33×10^{-6}	1.31×10^{-6}

Vacuum - Diaphragm material test

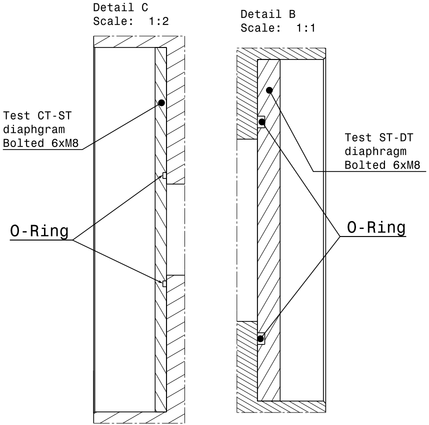
Test diaphragms for shock tube section

- Aluminium 0.3 mm (top right)
  1. Shear cut
- Tin 0.1 mm (top left and bottom right)
  1. Shear cut
  2. Buckling
  3. Plastic deformation
- Tin 0.3 mm (bottom left)
  1. Buckling
  2. Plastic deformation

Vacuum - Diaphragm holder

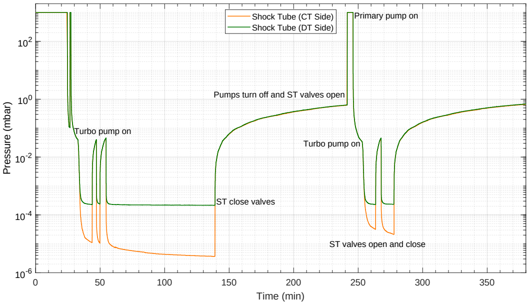


Current diaphragm holder design for the ST-DT section, similar to CT-ST section.

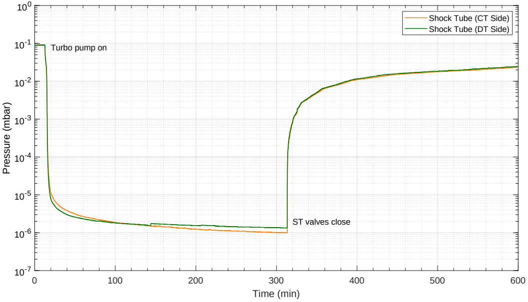


CAD of the blank and shock tube assembly for the vacuum test using O-ring sealing, based on University of Queensland design.

Vacuum - Pressure signal



Pressure time evolution for vacuum tests after correction of small leak sources (03rd of July 2023).



Pressure time evolution for vacuum tests after correction of leak sources in the tee section (25th of July 2023)

ESTHER Vacuum Systems - Main Achievements

Operation of helium mass spectrometer leakage detector

Major leak sources identified and correct

- Copper ring annealing
- Surface state treatment
- Outgassing

Sub-1% gas contamination rate

Reduction of leakage rate by two orders of magnitude

ESTHER Diagnostics

Emission spectroscopy

Compact microwave diagnostic

ESTHER Spectroscopy - Requirements

VUV and Visible Spectrographs and Streak cameras

- 100-300 + 200–850 nm wavelength
- Spectrograph ⇒ wavelength separation
- Streak camera ⇒ time separation

CRT TV does not have blur or lag, works similar to a streak camera

IR Spectrograph and High-speed camera

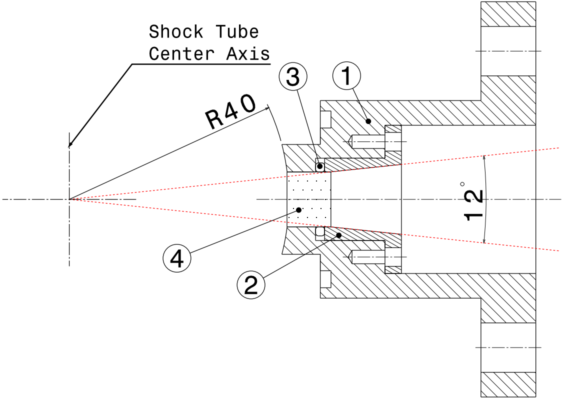
- 1-5 μm wavelength
- No photocathode IR radiation
- Cannot use streak camera
- Blur due to integration time

Integration time on CCD camera causes the blur

ESTHER Spectroscopy - Fast VUV Optics

Requirements:

- To be mounted in ST8
- Hold a sapphire window
- Guarantee the 12º light cone
- Ensure vacuum seal $\sim 10^{-6}$ mbar
- Handle 3500 N of instant force
- O-Ring to DN100 ConFlat seals adapter



❶ ST8 Plug
❷ Window adapter
❸ O-Ring
❹ Sapphire Window

ESTHER Spectroscopy - Fast VUV Optics

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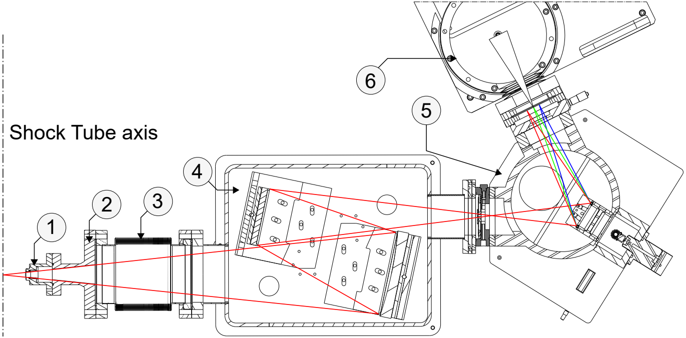
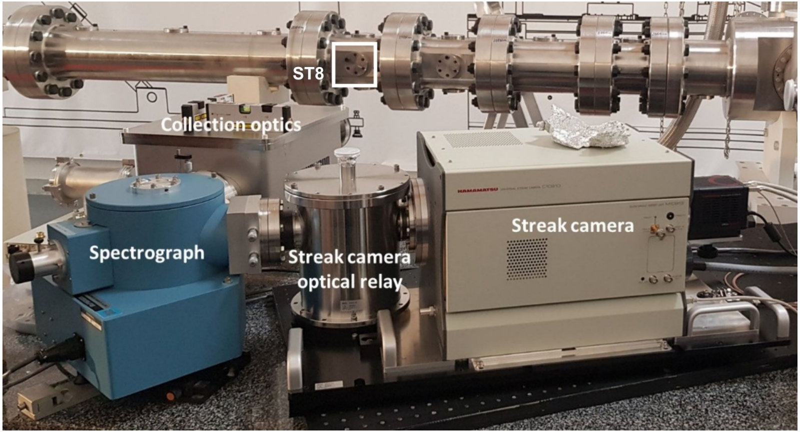


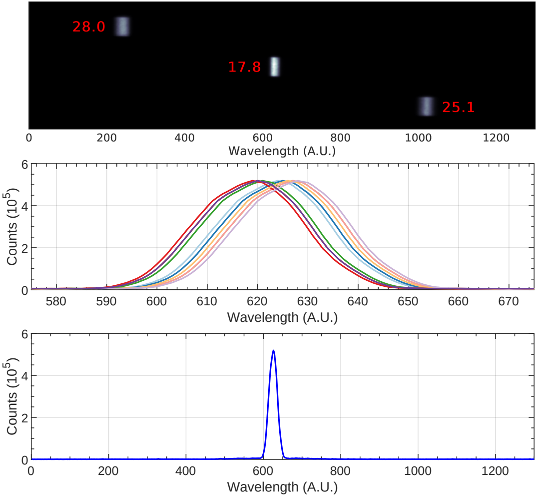
❶ ST8 Plug Assembly
❷ O-Ring to DN100CF adapter
❸ Vacuum bellow
❹ Optics box
❺ Spectrograph
❻ Streak Camera

ESTHER Spectroscopy - Fast VUV Qualification



VUV Spectroscopy setup assembled and tested Nov 2019

ESTHER Spectroscopy - Fast VUV Qualification



Validation tests using the 1200 gr/mm grating and Hg 254.65 nm line

Wavelength Resolution:

- Center Position:
  628 px
- Dispersion:
  0.0128 nm/px
- Full scale range:
  17.19 nm
- Resolution:
  0.36 nm - left
  0.23 nm - center
  0.32 nm - right

Five measurements of peak location:

- Accuracy:
  4.5 px

Peak intensity to noise standard deviation:

- Signal-to-Noise:
  3425

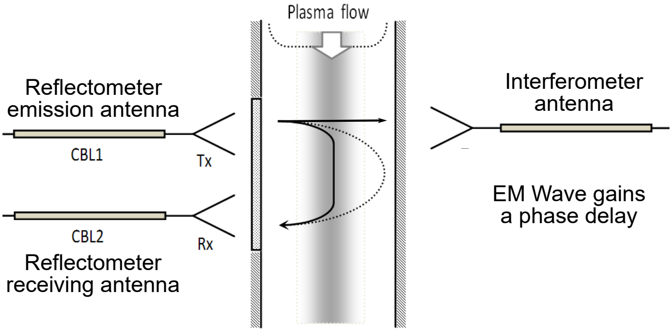
ESTHER Microwave Interferometry - Principles

Principles :

- Minimum frequency for EM wave propagation
  - $f > f_{pe}$ - Wave crosses
  - $f < f_{pe}$ - Wave reflects back
- For non-magnetized plasmas
- $f_{pe} = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{m_e \varepsilon_0}}$

Equipment requirements:

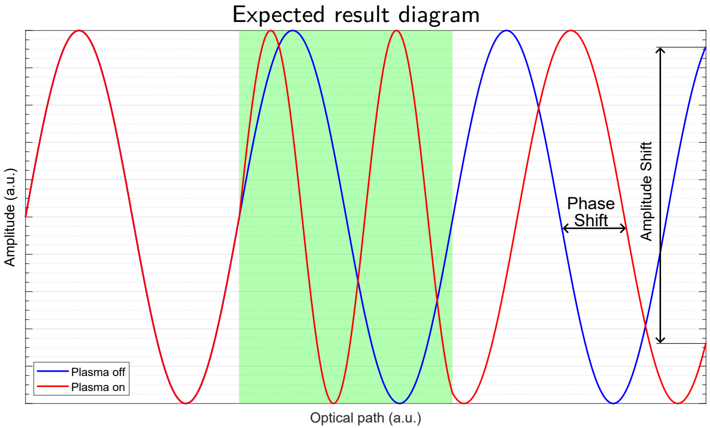
- Light & compact dimensions
- Off-shelf components
- Adequate for space environment
  - Launcher shock/vibrations
  - Work under vacuum
  - Thermal resistant



Colaboration with CupidoTech and IPFN reflectometry group

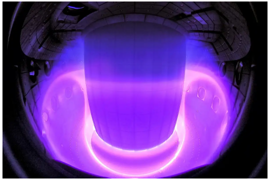
Interferometry/Reflectrometry - Working principle of interferometry

- When the plasma is on, a slower wave propagation in the plasma
- An amplitude (phase shift) change is the detected by the diagnostic
- Detector measures the amplitude value
- Needs to convert from amplitude to phase shift



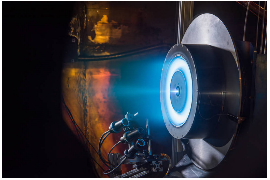
Interferometry/Reflectrometry - Reflectometry *vs.* Interferometry

- Varying/sweeping frequency
- Used on fusion tokamaks
- Suited for large devices
- ✓ Differential signal
- ✓ Complete spatial profile
- ✘ Probing $f \sim f_{pe}$
- ✘ Requires complex algorithms



TCV fusion reactor in Switzerland - Curdin Wüthrich/SPC/EPFL

- Fixed probing frequency
- Used on Hall thrusters
- ✓ Can measure $f_{pe} < f$
- ✘ Signal is integrated over space
- ✘ Requires a reflecting surface or two face-to-face antennas
- ✘ Profile needs an Abel-inversion to be recreated

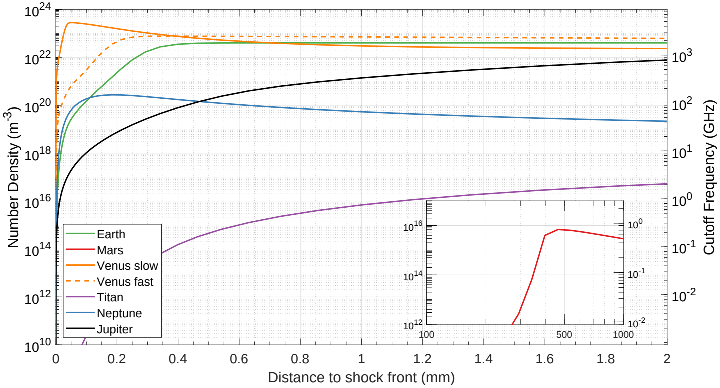


NASA Glenn's Hall Thruster

ESTHER Microwave Interferometry - Working Frequencies

Shock tube plasma

- 1D axial-symmetric
- Small size (1-2 cm)
- Short time frame (1-10 µs)
- Very high peak density above 10 km/s (10^{23} m^{-3})
- Relative low density below 6 km/s (10^{18} m^{-3})



Electron density in shock tube for typical entry conditions in different atmospheres

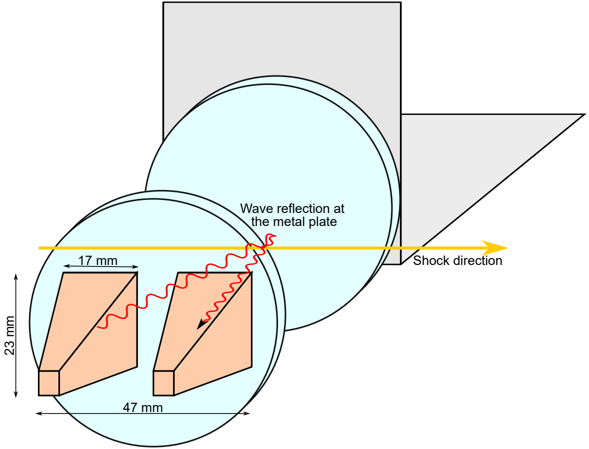
Interferometry/Reflectrometry - Functional requirements and challenges

Requirements:

- One optical windows
- Fast acquisition system
- *À priori* estimation of n_e/f_{pe} range

Challenges:

- Needs large enough optical window
- Face-to-face windows work better than reflecting at the tube wall
- High-speed shocks ⇒ very high n_e/f_{pe} ⇒ new tech (THz)
- Probing frequencies need to be well suited
  - Too low ⇒ reflect back
  - Too high ⇒ small phase deviation



ESTHER Microwave Interferometry - IPFN compact microwave diagnostic

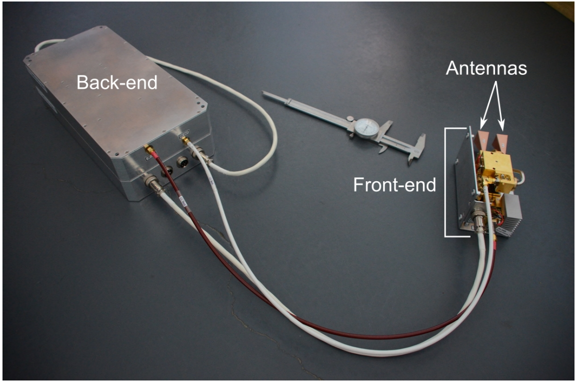
Back-End

- Voltage controlled oscillator
- 8-12 GHz (or 12-18 GHz) oscillator
- Digital arbitrary waveform generator
- Controlled via a TCP/IP connection

Front-End

- Frequency multiplier (6 factor)
- 70.8–112.8 GHz (NATO W bands)
- Dedicated waveguides
- Two side-by-side horn antennas

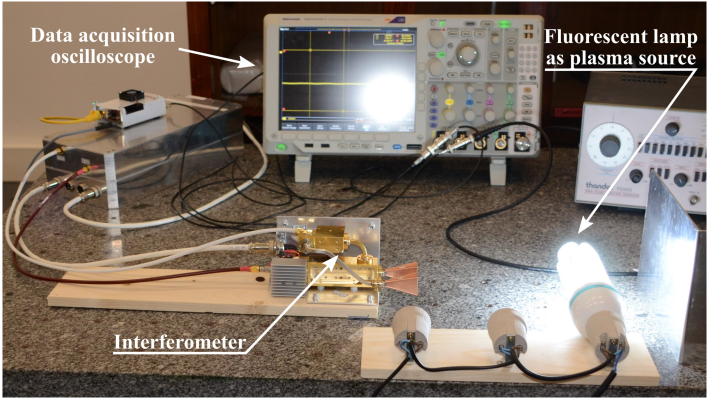
IPFN compact interferometer/reflectometer (70.8–112.8 GHz)



ESTHER Microwave Interferometry - Proof-of-concept experiment

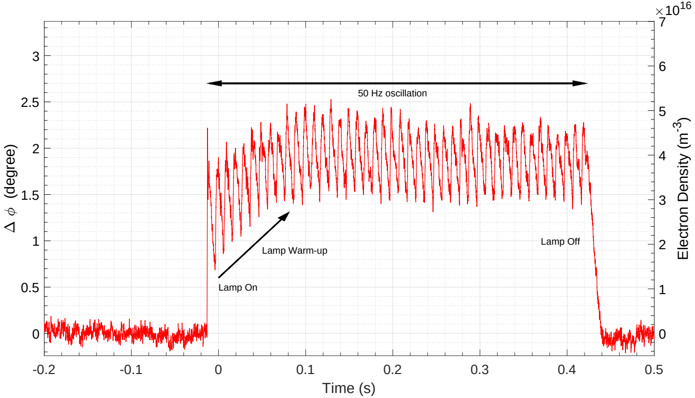
- Interferometer mode fixed f=70.8 GHz
- Fluorescent lamps as plasma source
- Reflection on the metal plate
- Fast oscilloscope for data acquisition

Setup for proof-of-concept experiment



ESTHER Microwave Interferometry - Proof-of-concept experiment

Average electron density $\bar{n}_e \approx 4 \times 10^{16}$ m^{-3}



- Similar results to Liu $\bar{n}_e = 0.8 - 5.3 \times 10^{17}$ m^{-3}
- Partial reflection of waves on the glass
- Difficult alignment of antennas, lamp and plate
- Polished plate works better as a reflector

Testing @ VKI minitorch

- Promising results
- Frequency pulsation of the torch measured by the interferometer
- Spatial limitations: Only one location could be observed, question on how much phase shift was being measured (φ?φ+2π? φ+4π?)
- Probably very high electron densities, a larger frequency multiplier (ours is 6x) would have been more adequate.

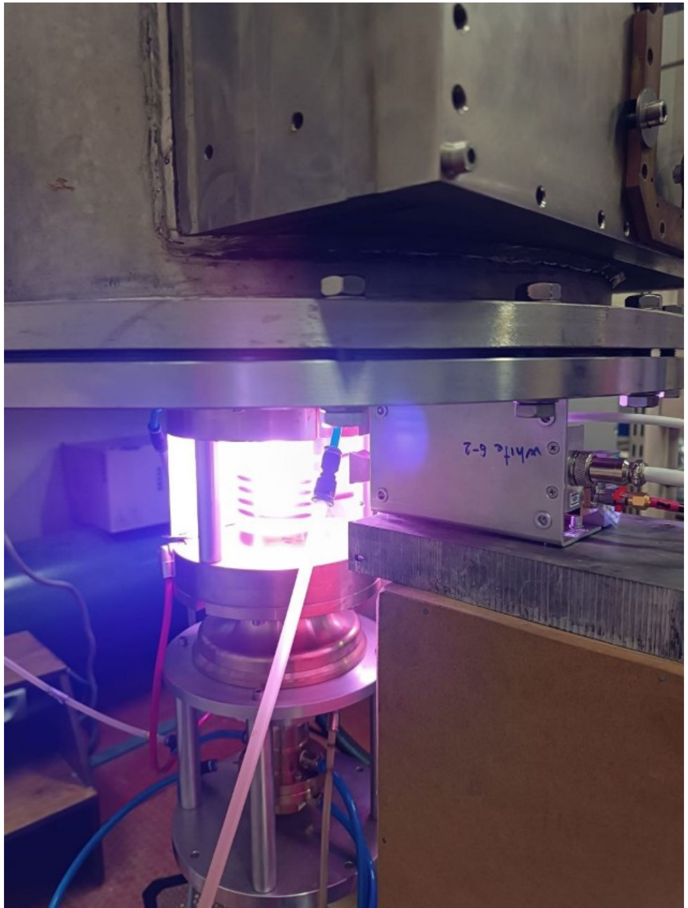
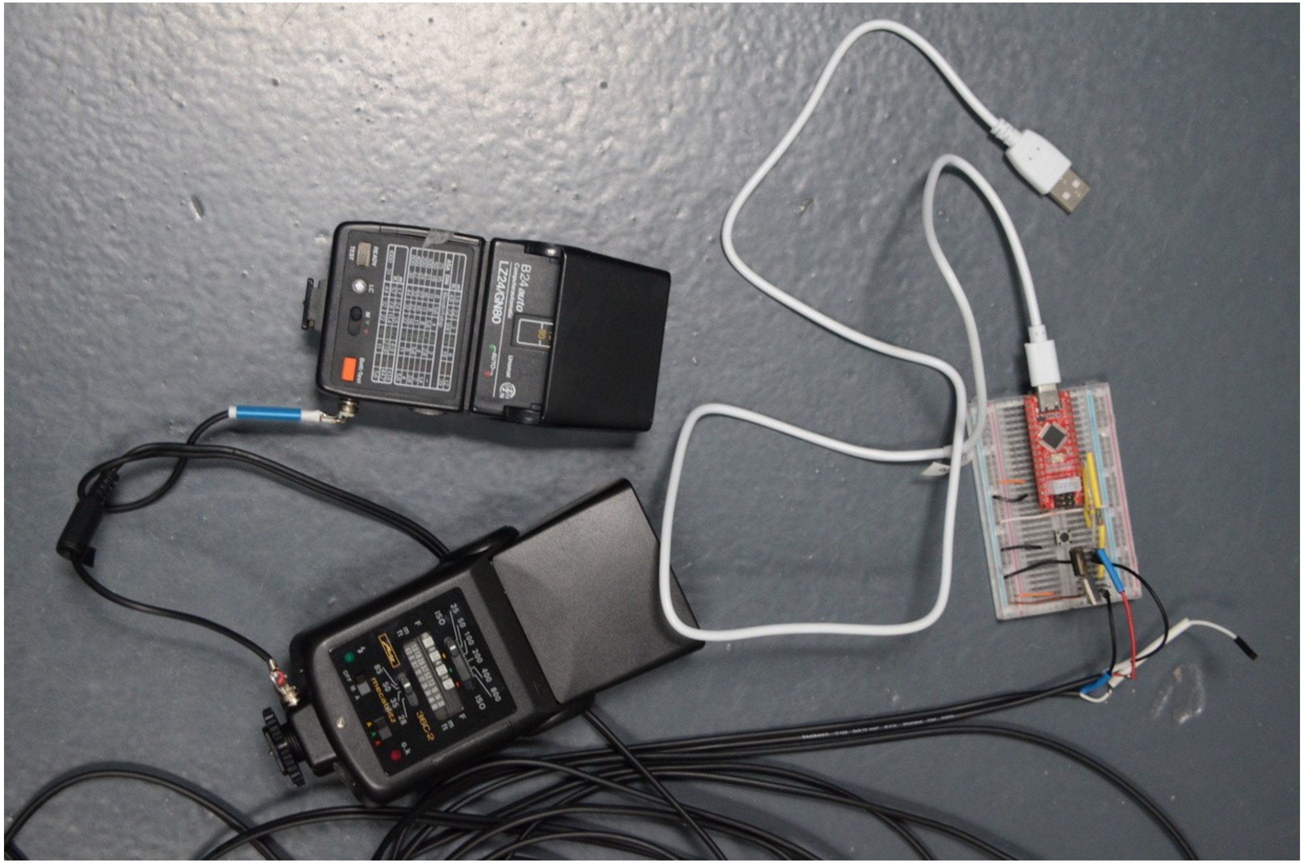
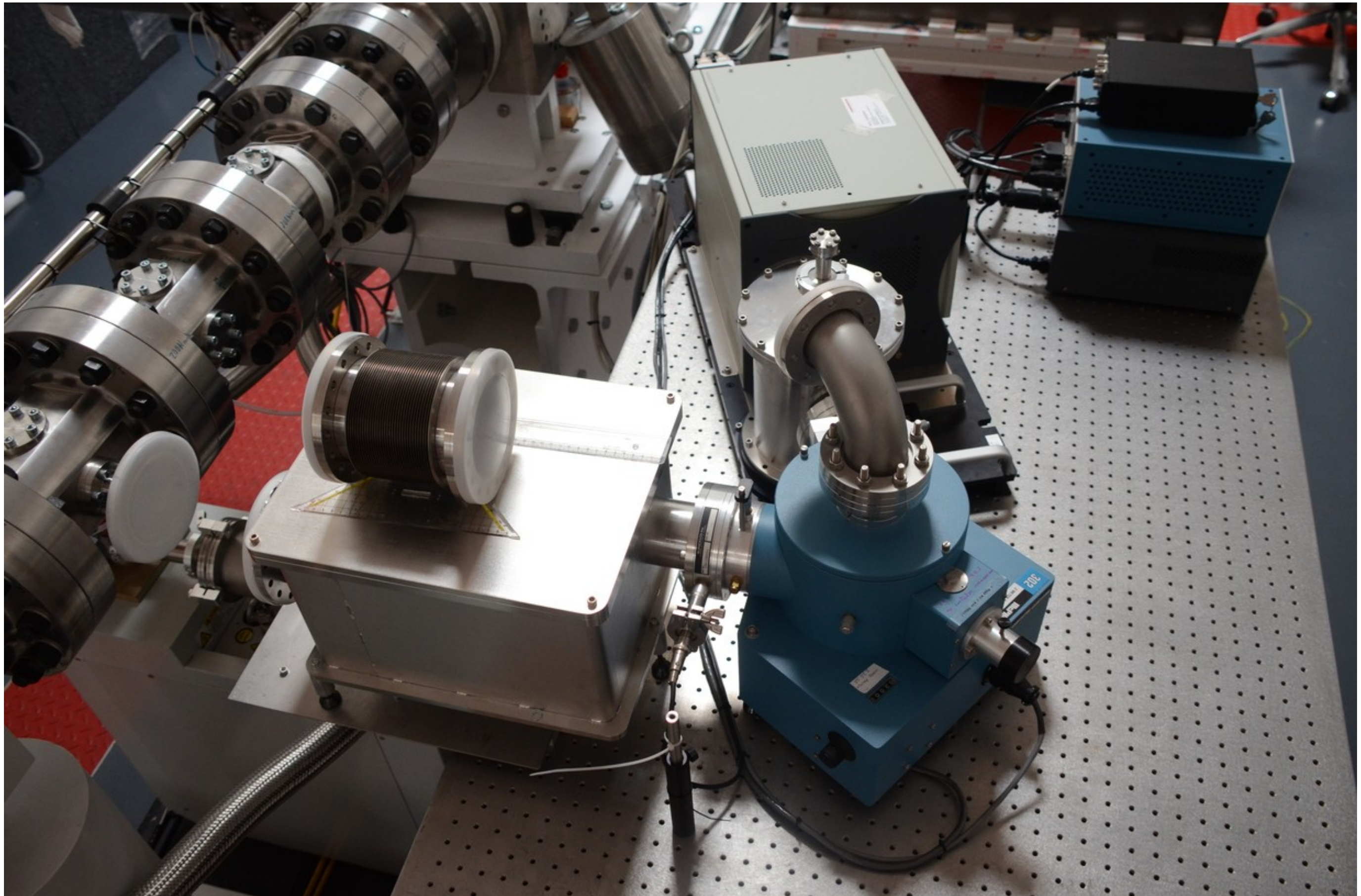


Image courtesy of D. Luis, VKI, with permission

Trigger System Testbed

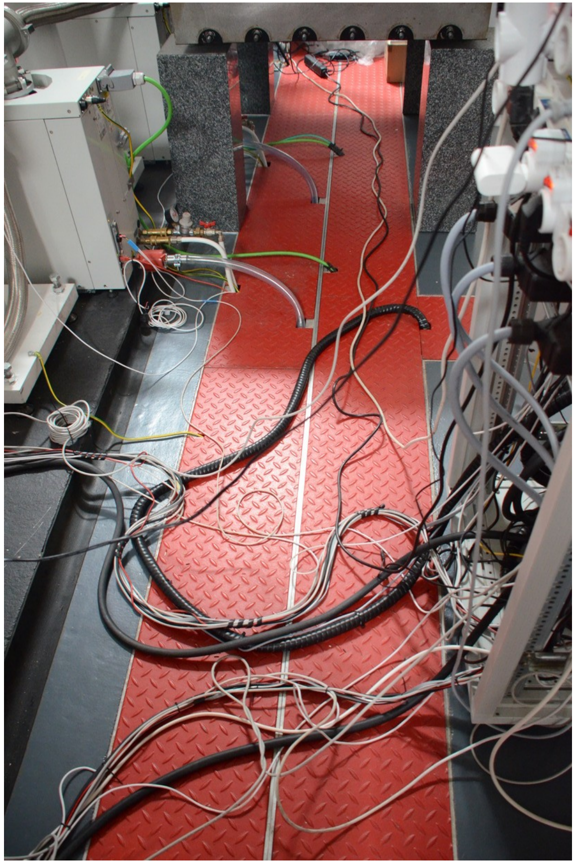


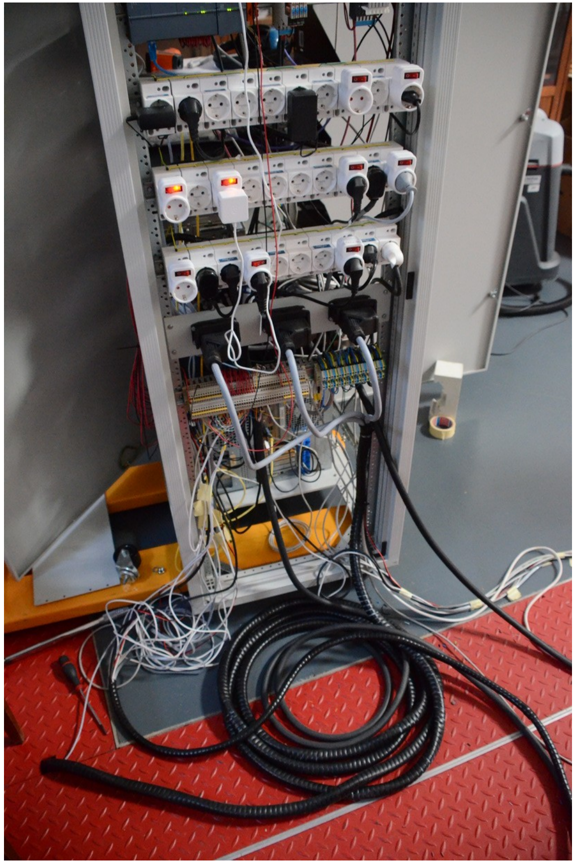
VUV Streak Camera Final Setup



Test Gas Filling System

Cables!





A Series of Unfortunate Events

- 25th July: One turbomolecular pump destroyed due to backflow from primary pump
  - ...at least the restraint system worked and it didn't went flying through the experimental hall
- End of August: 5.3 magnitude Earthquake strikes Lisbon
  - Fortunately no casualties but requires safety inspection of the driver Gas filling system
- Hiring process of an assistant researcher responsible for diagnostics (due to start on 1st October) fell through.

→ We have a brand new opening for a specialist on shock-tube diagnostics @ ESTHER

Beatings will continue until morale improves

- Safety Inspection scheduled for 19th September
- Replacement pump and parts being ordered. 12 weeks delivery time
  - We are improving resiliency of the vacuum & control system to improve resilience
- The “Abel” pumping side is blanked we can still work, just with reduced vacuum performance
  - Purchase of a cheaper (<1k€) - more compact laser (probably from AliExpress)

- First shockwave test postponed to October (?)

Published Works on Driver Qualification

International Journal of Hydrogen Energy 58 (2024) 948–953

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journal homepage: www.elsevier.com/locate/he

ELSEVIER

Short Communication

Unfocused laser ignition of high-pressure He–H_2-O_2 combustible mixtures

Check for updates

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Combustion of High-Pressure Hydrogen Diluted Mixtures in ESTHER Shock Tube

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https://doi.org/10.2514/1.T6963

European Shock Tube for High-Enthalpy Research (ESTHER) is a new state-of-the-art combustion-driven shock tube developed for supporting future ESA planetary exploration missions. Its high-pressure combustion driver sports a unique innovative design where a mixture of He : H_2 : O_2 or N_2 : H_2 : O_2 gases, filled to pressures up to 100 bar, is ignited by a high-power Nd:YAG laser. The qualification of this facility driver has allowed for the detailed study of laser-ignited combustion processes at high initial pressures (in the 5–100 bar range), over a series of 100 shots carried out for different configurations and gas mixtures. The influence of the air-to-fuel ratio, filling pressure, inert gas dilution, and ignition mode have been studied and are presented in this work. The effects of nitrogen vs helium dilution are also discussed. Filling pressure and helium/nitrogen dilutions have the strongest influence in peak pressure, acoustic oscillation, and combustion velocity. The first two increase, whereas the latter strongly decreases with the filling pressure. Nitrogen diluted shots have drastically lower compression ratios and flame velocity when compared to the helium ones. Acoustic perturbations/instabilities are also found to be stronger. This test campaign allowed the definition of a large range of stable and reproducible firing conditions in deflagration mode, yielding postcombustion pressures up to 660 bar.

Published Works on Instrumentation

CEAS Space Journal
https://doi.org/10.1007/s12567-023-00482-3

ORIGINAL PAPER

Reflectometry diagnostics for atmospheric entry applications: state-of-the-art and new developments

R. Grosso Ferreira[1] · J. Vicente[1] · F. Silva[1] · B. Gonçalves[1] · L. Cupido[2] · M. Lino da Silva[1]

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sensors

Article

VUV to IR Emission Spectroscopy and Interferometry Diagnostics for the European Shock Tube for High-Enthalpy Research

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Ricardo Ferreira Ph.D. Thesis

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