

# Development and Test of XR-150, a New High-Thrust 100 W Resistojet

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**Abstract:** Nowadays low power resistojets are interesting for orbit control on Low Earth Orbit small missions with low to moderate delta-V, where they outperform the other technologies in terms of cost and system integration simplicity. At the same time they could be used on bigger platforms for attitude control, e.g. despin of reaction wheels, where they can efficiently replace cold gas or hydrazine systems. At present date, low power resistojets operating on xenon show Isp performance up to 50-55 s which is slightly too low for present and future applications. On the other hand, the use of xenon as propellant would be an advantage if the satellite carries on board another xenon electric engine creating the possibility of sharing the propellant tank and part of the related feeding system. The objective of the present paper is the documentation of the design, manufacture, and testing of a new concept 100 W resistojet, named XR-150, with thrust level between 70 and 250 mN. The thruster was tested in Alta and then, independently, in ESA EPL laboratory with direct thrust measurement. The performance comparison between Alta and ESA tests was more than satisfactory. The measured Isp on Argon was of 90 s at 215 mN of thrust and higher for lower thrust levels, and, for Xenon, of 65 s at 100 mN of thrust, corresponding to an efficiency over 55%.

## Nomenclature

$C_p$	=	specific heat at constant pressure
$DTM$	=	direct thrust measurement
$EPL$	=	ESTEC Propulsion Laboratory
$Isp$	=	specific impulse
$LEO$	=	Low Earth Orbit
$SW$	=	SoftWare
$TS$	=	Thrust Stand
$TU$	=	thruster unit

## I. Introduction

The recent trend in telecommunication satellites is to use electric propulsion to perform orbit raising and all station keeping functions. In these architectures, due to the low thrust levels of the electric propulsion systems, there is a need to embark auxiliary thrusters to perform rate damping and safe mode maneuvers. The use of resistojets has been considered to this regard, due to the limited power they need to operate and their intrinsic

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robustness. Moreover, the use of xenon as operating gas is an advantage if the satellite carries on board another xenon electric engine due to the obvious synergy in terms of propellant tank and feeding system that could be shared by the two subsystems.

For what concerns instead LEO small missions, with low to moderate delta-V, resistojets could be used for orbit maneuvers, where they outperform the other technologies in terms of performance, cost, or system integration simplicity.

At present date, low power resistojets operating on xenon exhibit performance with Isp up to 50-55 s which is slightly too low for present and future applications<sup>1-4</sup>. Raising the Isp performance well above 60 s would make the xenon resistojet competitive with respect to nitrogen cold gas thrusters, and also advantageous from several points of view compared to monopropellant engines.

On the other hand, if the resistojet is used on Earth, e.g. in a vacuum chamber for several kind of different tests, it could be better to characterize the engine with argon. Argon shows better Isp performances up to 100 s even though having a volumetric Isp decreased to 35% of the corresponding value for xenon (Table 1). On Earth, for testing purposes and with no Delta V requirements, argon is a better and less expensive choice.

During the last few years Alta S.p.A. developed a set of low power resistojets to be fed with xenon. The explored power range is between 25 W and 100 W with dedicated designs directed from case to case toward redundancy, ruggedness, high-trust level, or high specific temperature (i.e. high Isp). In the last couple of years, Alta co-operated in this field with the European Space Agency that provided also the possibility of independent Direct Thrust Measurement in ESTEC EPL laboratory.

## II. ALTA XR resistojet family

The first prototype, realized during 2004 and shown in Fig. 1, had a body in metal or graphite with diameter of 40 mm, an embedded big area-ratio nozzle, weight around 100 g, two redundant heaters to be powered with the satellite bus unregulated voltage. The maximum power was of 50 W with a nominal thrust level of 50 mN and an effective Isp in Xenon around 50-55 s and around 75 s in argon.

The first generation of XR-50 resistojets was developed in 2006 with the aim to increase specific impulse while reducing the thrusters dimensions and weight. Also in this case the thruster, shown in Fig. 2, was equipped with two redundant heaters to be powered with the unregulated bus voltage, with target power of 50 W and thrust up to 100 mN, a stainless steel body of 16 mm of diameter

**Table 1. Typical limit merit parameters of different propellant for resistojets.**

Propellant	Molecular weight	Typical Isp	Storage Phase	Storage Density	Volumetric Isp
[-]	[amu]	[s]	[-]	[kg/m <sup>3</sup> ]	[kNs/m <sup>3</sup> ]
H <sub>2</sub>	2	800	Gas	19	149
He	4	400	Gas	42	165
NH <sub>3</sub>	17	250	Liquid	600	1470
H <sub>2</sub> O	18	150	Liquid	1000	1470
N <sub>2</sub>	28	110	Gas	280	302
N <sub>2</sub> H <sub>4</sub>	32	300	Liquid	1000	2940
Ar	40	80	Gas	440	345
Xe	131	65	Gas	1600	1019



**Figure 1. Alta's first xenon resistojet prototype designed for 50 mN of thrust at 50 W.**



**Figure 2. Alta's XR-50 first generation resistojet, optimized for low weight (60 g).**

embedding a miniaturized nozzle with area ratio of 81 for a total weight below 60 g. In this case the specific impulse was also increased at the 50 mN level by about 5 s both for argon and Xenon.

During 2008, the specifications for the XR-100 thruster (Fig. 3) were defined as follows, in order to increase furthermore the specific impulse and move from engineering models towards qualification models<sup>5</sup>.

- Target thrust level of  $125 \text{ mN} \pm 10 \text{ mN}$ .
- Maximum power level of 100 W,
- Functioning with unregulated 28 V bus.
- Two 50 W redundant heaters.
- Target specific impulse @ 100 W and 125 mN of 90 s for argon and 60 s for xenon.



**Figure 3. Alta's XR-100, dry mass 150 g.**

The thruster shall be compatible with feeding pressure up to 10 bar.

- Total dry mass below 200 g.
- Thruster maximum diameter below 50 mm.
- Thruster design and material selection shall be performed in order to provide the maximum ruggedness in view of vibration and shock tests.

The final XR-100 performance assessment showed a maximum needed power of 80 W, a dry mass of 150 g and a measured specific impulse of 105 s in Argon and 63 s in Xenon. The revised internal path allowed to increase the thruster efficiency up to 60%, although some care had to be devoted to the internal materials also to limit impact on the heaters due to internal radiation. Table 2 shows a summary of the XR series performance, including the new model XR-150.

**Table 2. Performance summary of Alta XR resistojet family.**

Propellant	XR-50		XR-100		XR-150	
	Xenon	Argon	Xenon	Argon	Xenon	Argon
Power	≤50 W		≤80 W		≤95 W	
Bus	28 V unregulated		28 V unregulated		28 V unregulated	
Thrust	100 mN		125 mN		250 mN	
					100 mN	
Specific impulse	55 s	85 s	63 s	105 s	65 s*	90 s
					65 s	100 s
Thrust efficiency	≤50%		≤55%	≤60%	≤50%	≤60%
Lifetime	100 hours		100 hours		200 hours	
Total Impulse	≤36000 Ns		≤45000 Ns		≤180000 Ns	
Thruster mass	50 g		150 g		220 g	
Thruster Size	Ø 16 x 60 mm		Ø 23 x 65 mm		Ø 27 x 80 mm	
TRL	5		5		5/6	

\* Estimated

### III. XR-150 design and development

The possible application to telecommunication satellites was the main driver toward the design and development of the XR-150 thruster. The main requirements were direct towards having a higher thrust level, desirable for high mass spacecraft, a slightly higher available power level, and a more rugged design for very long (15 years) intermittent operation (tens of thousands cycles).

#### A. Requirements

The additional functional requirement that led to the major design review was the aim to minimize the start-up duration for cycling operation: both for the XR-50 and XR-100 thrusters the time needed to reach the maximum performance is of several tens of minutes when starting firing from cold conditions. It is possible for both thruster to start operating in hot conditions, i.e. turning on the heaters before starting the propellant flow, so to reach the thruster thermal steady state in advance, but this operation mode tends to limit the operative life because is more rough on the internal redundant tungsten heaters. Moving towards high thrust levels while keeping also low power level led to a decreased expected performance in terms of Isp: having to heat a significantly higher mass flow rate imposes to lower the propellant temperature increase. It has to be noted that, due to the much lower specific heat, xenon is less affected by this problem.

Due to the above considerations, the requirements for the XR-150 were finalized as follows:

- Target thrust level of  $250 \text{ mN} \pm 10\%$ .
- Maximum power level of 120 W.
- Functioning with unregulated 28 V bus.
- Target specific impulse @ 120 W and 250 mN of 85 s for argon and 55 s for xenon (target 50% efficiency).
- Target specific impulse @ 100 W and 250 mN of 80 s for argon and 50 s for xenon (target 50% efficiency).
- Thruster designed to start firing in hot conditions.
- Thruster designed for short start-up time
- Thruster to be compatible with feeding pressure up to 15 bar.
- Total dry mass below 250 g.
- Thruster maximum diameter below 40 mm.
- Thruster design and material selection performed to provide the maximum ruggedness in view of vibration and shock tests.

#### B. Design

The main development in thruster design was the choice of a completely different heater setup: instead of using the standard approach with two redundant tungsten-wire based heaters, a single more powerful and rugged heater was chosen for the thruster.

Preliminary performance tests allowed to verify that the new heater can work proficiently also at lower power level, therefore covering the function of one single wire heater of the previous versions, and outperforms a single wire-heater in all types of functioning tests in terms of ruggedness and lifetime.

The only two drawbacks of the new approach are the obvious lack of hardware redundancy for the thruster and the fact that the new heater is forced to operate at a lower temperature at the propellant-interface with respect to the traditional ones, leading to a lower performance if a very high temperature thruster is desired.

An additional advantage of the new design is the possibility to operate the thruster with any kind of propellant, including oxygen based propellants and/or propellants with possibility of liquid droplets entering the heater.

#### C. Manufacturing

Two slightly different thruster models were manufactured, with the only differences being the internal flow path and nozzle throat diameter: the reason was the comparison of two possible designs in terms of optimization of propellant heating efficiency. The two thrusters, labeled XR-150-A and XR-150-B, are shown in Fig. 4 along with information about dimensions and the mechanical interface. Thruster XR-150-A has a dry mass of  $220 \pm 2 \text{ g}$ , while thruster XR-150-B has a dry mass of  $200 \pm 2 \text{ g}$ . The thruster maximum diameter is, for both thrusters, 24 mm, while the mechanical interface has a diameter of 40 mm. In both cases, the interface is constituted by 3 holes for M3 screws, placed on a circle with diameter of 32 mm. Both thrusters are equipped with a laser welded control thermocouple, giving the temperature of the tip region, as close as possible to the nozzle.

The nominal pressure level, i.e. the one needed to reach 250 mN of thrust, was identified around 7 bar for XR-150-A and 12 bar for XR-150-B.

Preliminary performance tests allowed to verify that, for both thrusters, the actual maximum power level is around 95 W.

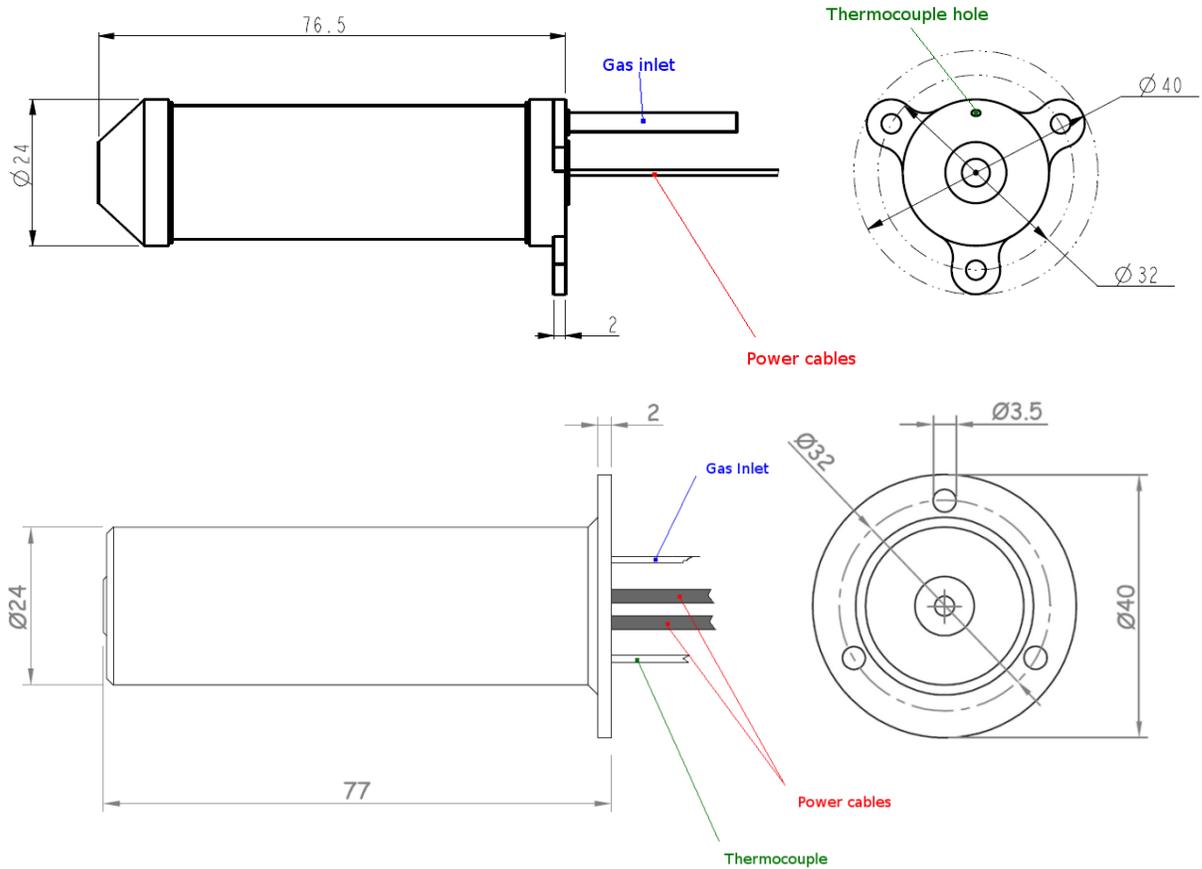


Figure 4. Alta's XR-150-A (top) and XR-150-B (bottom).

#### IV. Performance test

##### A. ESTEC Propulsion Laboratory

The EPL<sup>6</sup> is an operational facility at ESTEC (Fig. 5) in the spacecraft propulsion testing field<sup>7</sup>. The EPL provides test services to the ESA Propulsion and Aerothermodynamics Division, which is responsible at European Space Agency for research and development activities and support to projects in the areas of chemical propulsion, electric and advanced propulsion and aerothermodynamics. The main effort of EPL is directed towards the



Figure 5. ESA Propulsion Laboratory at the European Space Agency in the Netherlands.

performance, endurance and assessment testing of propulsion systems for ESA missions. Moreover, the EPL increases its collaboration with international industry and Academy in the field of space propulsion research, development and testing.

The testing of propulsion systems requires facilities capable to simulate space conditions and which are designed for this scope. In some cases such as electric propulsion components (thrusters and neutralizers) the vacuum conditions must be better than  $10^{-9}$  mbar. The European Space Agency has invested in the ESA Propulsion Laboratory to allow the Agency to assess the special characteristics of the electric and cold gas propulsion thrusters and components in the last decades. Lately, the laboratory has expanded its fields of application to other chemical propulsion activities such as testing of propulsion components (valves, injector, etc).

The domain of competence of the EPL includes ISO 17025 accredited procedures for the direct and indirect measurements of thrust, mass flow and electrical power related to propulsion systems operation in specific ranges.

Features of testing facilities at EPL:

- Certification ISO 9001 (Quality Management)
- Accreditation ISO 17025 (General Requirements for the competence of testing and calibration laboratories)
- Cleanroom ISO Class 8 capability (eq. to class 100,000)
- Seismic block for noise isolation
- 7 vacuum facilities dedicated to space propulsion testing
  - o Vacuum chamber reproducing space environment with pressure down to  $10^{-9}$  mbar
  - o Beam target and diffuser reducing on-ground testing disturbances
  - o High speed high resolution data acquisition systems
- 1 flow bench (to be upgraded into water-hammer bench)
- Calibrated commercial measurement instruments
  - o Various electronic equipment for measurements from 1  $\mu$ V/1 nA to 35,000 V / 20 A
  - o Mass spectrometers for residual gas analysis
  - o Infrared Thermocamera
  - o Pyrometer
- Customized measurement instruments with chain of calibration
  - o 5 thrust balances for thrust measurement from microNewton to Newton ranges
  - o 3 beam diagnostics systems for beam divergence and energy distribution measurements

Specific diagnostic systems available at the EPL include two Mettler-Toledo high precision (0.1 mg resolution) electronic load cells customized for micro and milliNewton thrust measurement of cold gas thrusters, two specifically designed thrust balances for milliNewton range electric propulsion thrusters. The design and manufacturing of very specific diagnostics is usually realized in collaboration with external entities. For instance, among others, two balances and several diagnostics (Faraday probes, Retarding Potential analyzers, etc.) were developed by ALTA S.p.A, ICARE designed and developed a retarding potential analyzer and its electronic system able to measure energies of primary and charge-exchange ions, the University of Stuttgart is developing a Langmuir Probe. Nevertheless the EPL has independent capabilities to carry out this kind of activities: lately Langmuir probe and emissive probes are being successfully used in the laboratory to determine the plasma parameters in a Hall Effect Thruster plume. A microNewton thrust balance<sup>8</sup> was developed in the past few years, in collaboration with the National Physics Laboratory (UK) to measure thrust in the microNewton range and noise. This balance is in the process to be validated to perform ISO 17025 accredited measurement for thrust only.

The EPL is capable of designing, preparing and executing performance characterization and endurance tests of low and medium power electric propulsion thrusters and components in its automated vacuum facilities. Performance of components for chemical propulsion may also be measured.

## **B. XR-150 test performance**

### *1. Argon tests*

The thruster performance was assessed in ESA EPL SPF vacuum chamber for both XR-150 models, with personnel from Alta carrying out the operations and providing training to EPL personnel for the successive independent direct thrust measurement tests. The chosen propellant, due to cost reasons, was Argon.

In both cases the test procedure consisted in a cold start with propellant feeding pressure of about 4 bar until a complete thermal equilibrium was reached, as measured by the thermocouples mounted on the EPL thrust balance system. This phase was followed by test at two higher pressure levels, again until thermal equilibrium was reached (in this case starting from hot conditions). The pressure levels (lower than nominal for XR-150-B) were selected to be able to use the standard gas feeding system and bottles in EPL which allowed pressures up to about 10 bar.

No anomalies were identified during both tests. Figures 6, 7, and 8 show the mass flow rate, thruster thermocouple temperature, and Isp histories for thruster XR-150-B as recorded by the thruster control SW, provided by Alta. It has to be noted that, in this case, the Isp is an estimation calculated by the SW basing on each thruster calibration in cold gas conditions carried out in Alta.

Some key element of the tests are summarized below:

- The three pressure levels corresponded to about 120, 210, and 300 mN respectively for thruster XR-150-A and to about 70, 110, and 150 mN respectively for thruster XR-150-B.
- The time needed to reach complete thermal equilibrium starting from cold conditions is about 30 minutes, with 90% of the target Isp reached in 8 minutes.
- The time needed to reach complete thermal equilibrium starting from hot conditions is about 8 minutes, with 90% of the target Isp reached in less than 1 minute, starting from higher values.
- The specific impulse calculated for thruster XR-150-A was 91, 85, and 75 s for the three pressure levels, while it was 93, 89, and 84 s for thruster XR-150-B.
- Thruster model A was found outperforming model B by at least 5% in similar conditions.

## 2. Xenon tests

XR-150-A was also tested in Alta using Xenon as propellant at the 100 mN thrust level.

The thruster reached a specific impulse of about 65 s, limited by the practical equivalence of the gas temperature to the one of the heater surface. Due to the low  $C_p$  of xenon with respect to argon, the limit temperature was reached using only 25 W of power; the remaining power was dissipated mostly by radiation by the thruster body that became red-hot (Fig. 9). Considering the thruster efficiency in the range of 50-60%, this would imply the possibility to keep the same specific impulse for xenon up to 250 mN.

## C. Direct thrust measurement

The direct thrust measurement test was independently performed by EPL personnel twice, in order to verify the repeatability of the measurements, respectively on 29/08/2012 and 30/08/2012. The results of both tests were very similar.

Alta's 1-axis thrust balance, which is part of the EPL equipment, was used for the tests, with preliminary calibration performed in the range 0-200 mN. Figure 10 presents the evolution of the thrust calculated by XR-150 control SW, thrust measured by the TS, and mass flow rate during the measurements. The first part of the values of the calculated thrust should not be taken into account due to SW preparation.

In a first period the thruster was in cold gas mode at two different inlet pressures: 5.3 and 4.5 bar. Then the

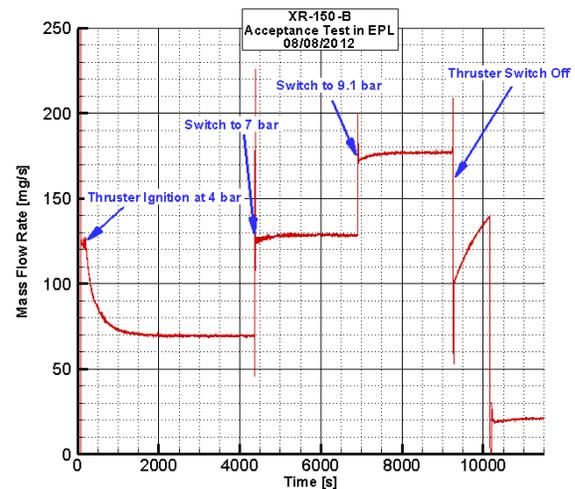


Figure 6. Mass flow rate history.

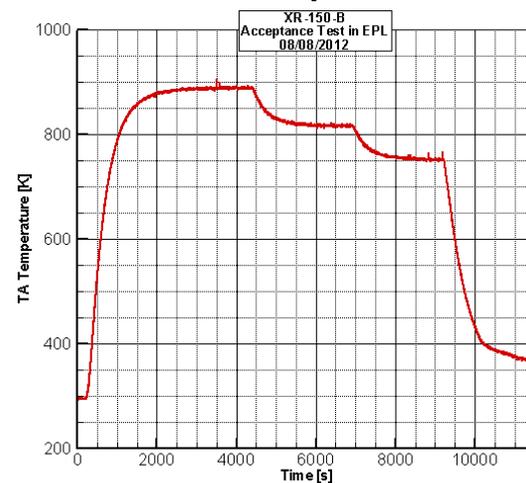


Figure 7. Thruster nozzle temperature.

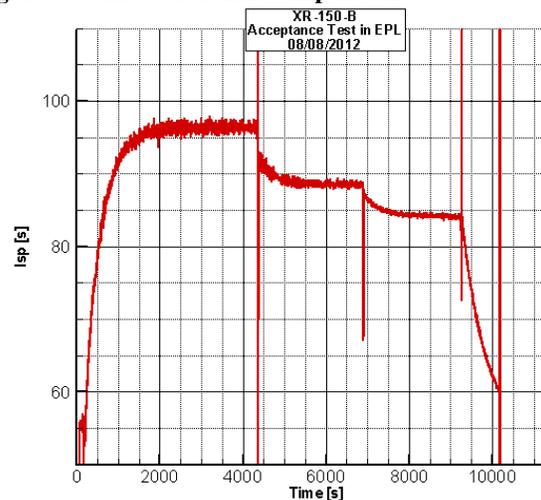


Figure 8. Software estimated Isp.

heater of the TU was turned on and two different inlet pressures were also tested: 4.5 and 7 bar.

As can be seen in Fig. 10 the thrust measured by the TS followed very well the decrease/increase of the inlet pressure. When the heater was turned on, as expected, the thrust measured did not change (its variations are only due to the change of the inlet pressure), while the mass flow rate decreased correspondingly to the increase of specific impulse.

Table 3 shows the summary of the results of the DTM tests that prove that the actual performance of the thruster in terms of thrust and Isp is higher to what estimated by the control software. The actual gas-dynamic performance of the TU can be calculated from the cold gas functioning in terms of percentage loss with respect to an ideal axially symmetrical nozzle. The model implemented in the software uses a gas-dynamic efficiency of 95%, while regression from the data in Table 3 shows that the actual efficiency is of 98%. The specific impulse was found to be 96 s around 4 bar, 95 s at 7 bar, i.e. from 3% to 6% more than value estimated by the software and reported in section IV-B.

DTM tests were also performed on the XR-100 thruster, in this case confirming a 95% gasdynamic efficiency; uncertainty budget calculation performed by EPL personnel allowed to determine the uncertainty range in  $\pm 2.1\%$  at the 100 mN thrust level.

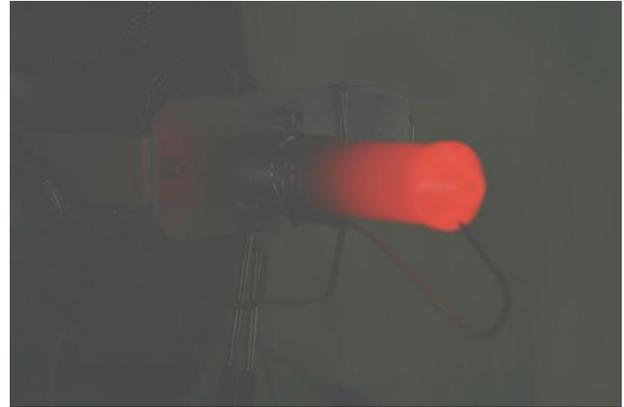


Figure 9. XR-150-A firing xenon at 100 mN.

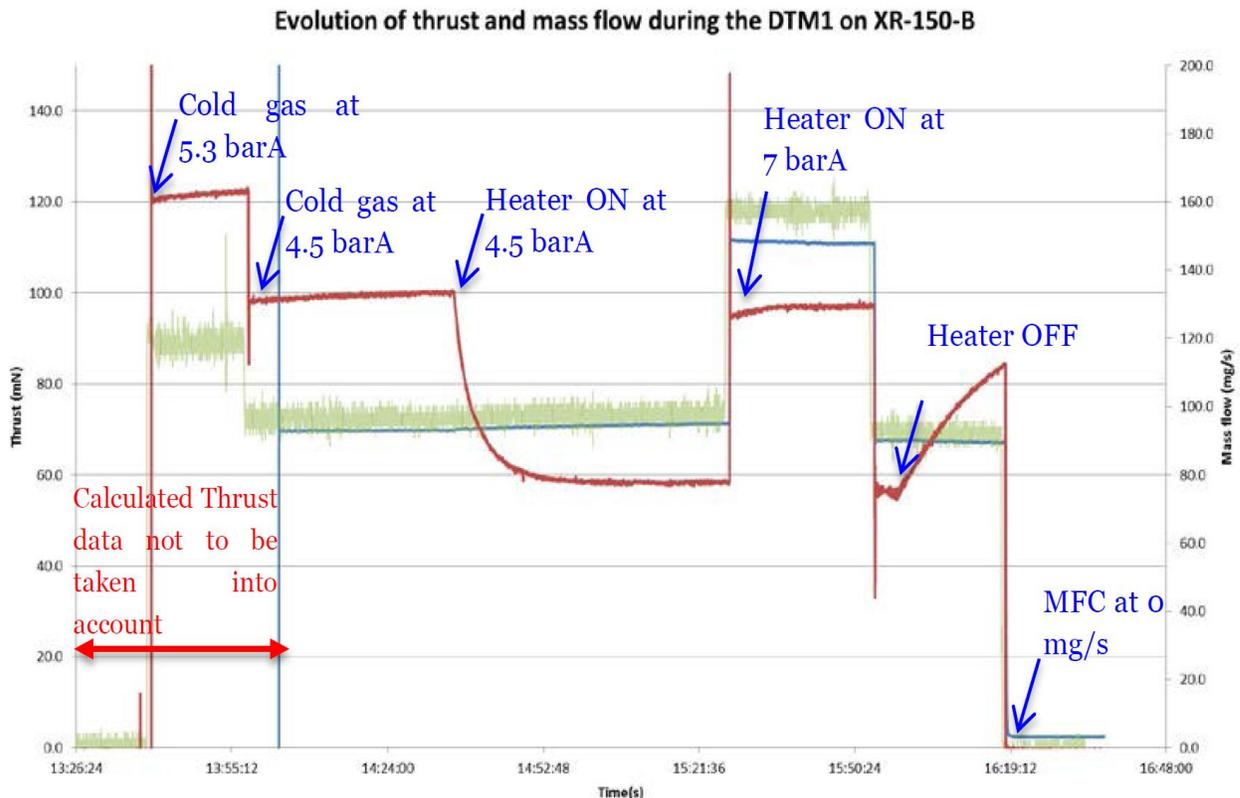


Figure 10. XR-150-B firing during DTM1 test: thrust calculated from the control software (blue), thrust from Direct Thrust Measurement (grey), mass flow rate (red).

**Table 3. XR-150-B firing during DTM1 test: thrust from SW (blue), thrust from DTM (grey), MFR (red).**

	Inlet pressure (barA) – day 1	Calculated thrust (mN) – day 1	DTM (mN) – day 1	Inlet pressure (barA) – day 2	Calculated thrust (mN) – day 2	DTM (mN) – day 2
Resistojet - 4 bar	4.51 ( $\pm 0.004$ )	71.2 ( $\pm 0.1$ )	73.6 ( $\pm 1.8$ )	4.40 ( $\pm 0.004$ )	70.4 ( $\pm 0.1$ )	72.5 ( $\pm 1.6$ )
Resistojet - 7 bar	7.02 ( $\pm 0.004$ )	110.8 ( $\pm 0.1$ )	118.0 ( $\pm 1.7$ )	7.04 ( $\pm 0.004$ )	112.8 ( $\pm 0.1$ )	119.8 ( $\pm 1.4$ )
Cold gas - 4 bar	4.42 ( $\pm 0.004$ )	69.8 ( $\pm 0.1$ )	72.2 ( $\pm 1.4$ )	4.35 ( $\pm 0.004$ )	68.0 ( $\pm 0.1$ )	71.7 ( $\pm 1.5$ )

## V. Future developments

The XR development plan now foresees three major steps, both for XR-100 and XR-150. The first one is represented by preliminary vibration and shock tests to experimentally verify the design robustness and move towards the realization of qualification models. The second one is a general design review directed toward increase of performance for both models in terms of life-time cycling hot and cold start tests. The final one is the review in terms of high temperature performance, needed to properly use the available power with xenon and consequently increase the thruster specific impulse at least up to about 85 s.

## VI. Conclusion

A new low-power resistojet named XR-150 was designed, manufactured, and tested by Alta with the aim to provide high thrust levels coupled with sufficiently high specific impulse. The main modification with respect to the previous models was the use of a new single stage heater, capable to operate with a very short start-up duration and with oxygen based propellants. The new thruster was found to be more rugged with respect to the other versions in all operation modes, while retaining an overall efficiency above 50%.

The XR-150 thruster was tested in ESA-ESTEC EPL laboratory, including completely independent direct thrust measurement tests, that allowed to confirm that the performance is slightly higher with respect to the assessment carried out in Alta.

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