VEGA Evolution Zefiro 40 Solid Rocket Motor: From a Technological Demonstrator to a Flight Stage

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Abstract

On the base of the agreement reached during the 2014 Ministerial Council for space activities the VEGA Evolution Program foresees the first stage propellant increase from 80 tons class to about 120 tons class and the second stage propellant increase from 23 to about 40 tons. The second stage solid rocket motor is therefore named Zefiro 40. Zefiro 40 studies have a background of about four years within an Avio S.p.A. self-financed program aimed to develop a technological demonstrator to introduce new materials and technologies to increase the propulsive performance of VEGA Launcher reaching a capability of greater payloads insertion in higher orbits. Zefiro 40 represented therefore the means for Avio S.p.A., to develop innovative solutions with the primary target to increase the motor mass fraction. But at the time being Zefiro 40 has to be not only a technological demonstrator, but first of all a flight stage: system analyses performed by ELV, Prime Contractor of VEGA Launcher, are ongoing to definitively frozen Zefiro 40 requirements. On this base the more efficient choices in terms of design, materials and technologies will be taken. This paper reports the current status of Z40 development: an overview of the performed activities is presented as well as the planned activities for the completion of the Zefiro 40 flight solid rocket motor development, qualification and flight.

1. Introduction

VEGA Launch Vehicle (LV) is the small European expendable launcher developed by the European Space Agency. It is designed to deliver from 300 to 1500 kg payloads into Polar and low Earth orbits. VEGA is a single body launcher (136 tons of weight, and 36 m in length), which consists of three solid rocket stages, the P80 FW first stage (97 tons of weight, 3.05 m in diameter and 11,7 m in length), the Zefiro 23 second stage (26 tons of weight, 1.9 m in diameter and 8,5 m in length), the Zefiro 9 third stage (11.5 tons of weight, 1.9 m in diameter and 4,4 m in length), and a liquid rocket upper module called AVUM (see Figure 1).

VEGA qualification maiden flight and other three flights have been successfully performed on February 13th 2012 and between 2013 and 2015 respectively from Guyana Space Center of Kourou.

In the frame of VEGA Consolidation and Evolution Program several launcher architecture changes were investigated in order to improve the launcher performance, the payload comfort and to reduce the launch cost. In particular the first stage propellant increase to about 145 tons and the second stage propellant increase to about 40 tons will represent a new lower composite to add (together to a new liquid based upper stage) versatility on multiple payload market.

Avio S.p.A. set up a developmentprogram, taking benefits from the self-financed previous one, and, in co-operation with ELV, defined a series of functional requirements for a 40 tons propellant Solid Rocket Motor (SRM), named Zefiro 40, to be used as second stage motor of VEGA Evolution Launcher (see Figure 2) and prototype for new technologies introduction.

Primary target of the project is to have an high mass fraction (ratio between propellant and total mass): this parameter is directly linked to payload mass orbit insertion capability of launcher and is therefore one of the most important design driver of Zefiro 40 SRM, that will be the larger solid rocket motor ever produced in Avio facilities.

Zefiro 40 represented the means for Avio S.p.A., leader in solid space propulsion and responsible of design and production of Zefiro 23 and Zefiro 9 SRMs, as well as P80 Loaded Motor Case, to develop innovative solutions with

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the primary target to increase the motor mass fraction, a high performance carbon-epoxy own pre-preg production, a self-protected nozzle flexible joint.
In the frame of the technological demonstrator performed by Avio as a self-financed activity, on December 2012 Z40 Preliminary Design Review (PDR) phase (Phase B) has been performed. The project includes several design and technological improvements with respect to the VEGA SRMs:

- an high performance internal thermal protection
- an high performance carbon-epoxy filament wound composite case as for the VEGA SRMs but implementing own producted pre-preg;
- a propellant formulation with reduced chemical compounds risk class and nozzle throat erosion;
- an undercut casting design to optimise the filling ratio of combustion chamber and to further reduce the SRM inert mass;
- a low torque self-protected Flexible Joint (FJ) with:
  - synthetic rubber layers to achieve more stable mechanical properties with respect to the natural one
  - composite shims instead of metallic ones to strongly reduce the mass of this piece;
- a carbon rope solution as thermal barrier for the chicane between loaded motor case and igniter, as well as the one between loaded motor case and nozzle (already implemented in P80 SRM) to avoid the use of chicane filling with grease that leads to complication of the integration process;
- a chicane shape that avoid the risk of chicane opening during SRM pressurization
- the automatic tape laying of the tape prepreg on the skirts instead of the manual deposition process;
- a nozzle initial part of the divergent produced with the Liquid Resin Infusion (LRI) technology to reduce the occurrence of wrinkle defects.

The trade-off of materials and technologies has been completed and two insulated motor cases development models realization for the validation of the winding process and of the new pre-preg test at full scale has been manufactured.
But at the time being Zefiro 40 has to be not only a technological demonstrator, but first of all a flight stage: system analyses performed by ELV, Prime Contractor of VEGA Launcher, definitively frozen Zefiro 40 requirements. On this base the more efficient choices in terms of design, materials and technologies have be taken into account in the design of the second stage of Vega C launcher, adapting design and technological choices to the program contraints.
This paper reports the current status of Z40 development: an overview of the performed activities is presented as well as the planned activities for the completion of the Zefiro 40 flight solid rocket motor development, qualification and flight.

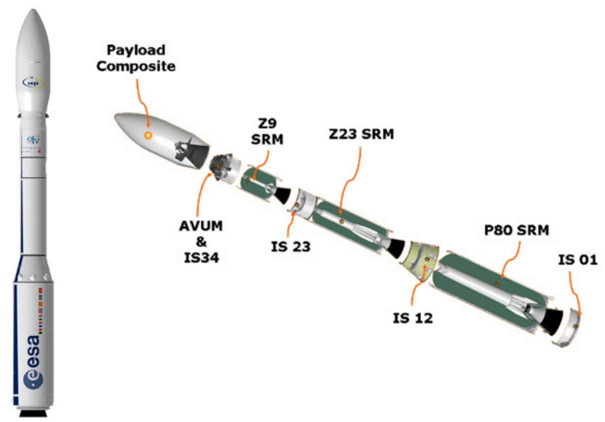


Figure 1: VEGA launcher configuration

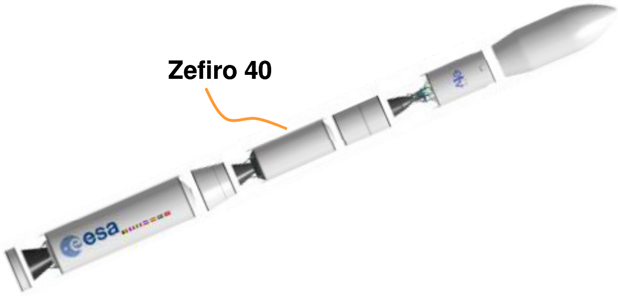
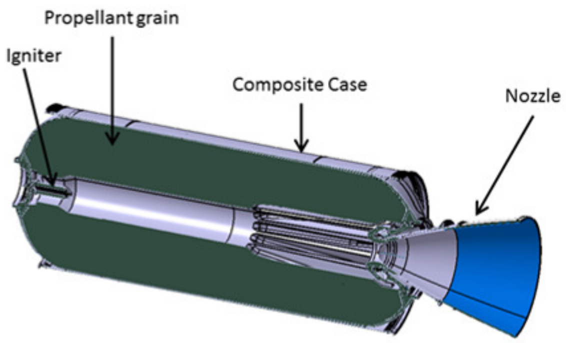


Figure 2: VEGA Evolution Launcher configuration

2. ZEFIRO 40 SOLID ROCKET MOTOR OVERVIEW

Zefiro 40 SRM is a high mass fraction motor with about 36 tons of HTPB composite propellant (see main characteristics and performance summarized in Figure 3).
Zefiro 40 length and maximum thrust is comparable with Zefiro 23 ones, while diameter and combustion time will be greater.
Synergy with Z23 SRM is made for the igniter, that will be adapted for Z40 with a specific connection flange to the motor polar boss interface dimensions and longer combustion time.



Length	7.6 m
Cylinder diameter	2.4 m
Skirt to skirt length	5.4 m
Combustion time	95.5 s
Maximum pressure	115 bar
Nozzle expantion ratio	37
Specific impulse	293.5 s
Propellant mass	36200 kg
Target inert mass	3252 kg

Figure 3: Z40 SRM main characteristics

2.1 Composite case

The case is the motor component which assures the structural functions, such as the transmission and sustaining of launcher mechanical loads, the withstanding of inner pressure load, the respect of interface with the launcher, the maintaining of adequate stiffness during the flight. In the frame of VEGA program Avio developed and qualified composite cases of great dimensions, produced with the filament winding process.
Main design and technological developments implemented in Z40 are the use of own producted carbon-epoxy composite prepreg and the automatic tape laying for skirt manufacturing ([1],[2] and [3]).

2.1.1 Avio prepreg

A development program was already started in Avio S.p.A. some years ago in order to produce in Italy a carbon-epoxy pre-preg material with improved stability at ambient temperature. A specific resin has been developed and tested, showing an increased glass-transition temperature able to further reduce the thermal protection thickness to be installed inside the composite case. For Z40 program this resin will be applied to a high strength/low weight carbon fibres of last generation, with consequent inert mass reduction.

A large technological and experimental campaign has been performed in Avio premises in order to improve and set up the prepreg facilities and obtain the required characteristics both for the resin system and for the prepreg itself. The pilot prepreg line (see Figure 5) has been fully validated manufacturing different material batches for both tape and tow, sufficient for the parameters set-up, the material characterization and the first massive material batches for the full scale items production.

Figure 5: Avio prepreg production line

A trade-off campaign has been performed for the selection of the fiber and for the first material characterization.

For the tow characterization and trade off the mechanical performances have been evaluated on two different specimens:

- Standard small vessel specimen test (Figure 6): small vessel of 150 mm of diameter used to evaluate the performances decay due to the technological process

- 1:5 specimen test (Figure 7): is a specimen with an internal diameter of one fifth of the final motor and it is used to evaluate the scale factor to be used for a large diameter motor.

In fact, the tow is mainly used to manufacture the vessel body of the motor case that shall be able first of all to substand the SRM maximum expected operative pressure.

For the tape fiber selection the most important feature is its stiffness and the compressive strength; in fact, it is used for the skirt component, facing mainly compressive loads coming from the launch vehicle, requiring adequate safety margins with respect to buckling and compressive strength.

For the trade off tensile, compressive and Short Beam Shear (SBS) test have been performed.

The technological suitability of the winding process and skirt manufacturing with Avio prepreg has been validated on December 2013 on P80 scale (about 3m of diameter) (Fig.8). A further unit, based on the Z9 design (about 2m of diameter) has been manufactured with the Avio prepreg. NDI revealed a defect-free structure. The following testing phase has been successfully completed, passing the acceptance pressure test (1.1 MEOP) and mechanical tests up to the qualification level.

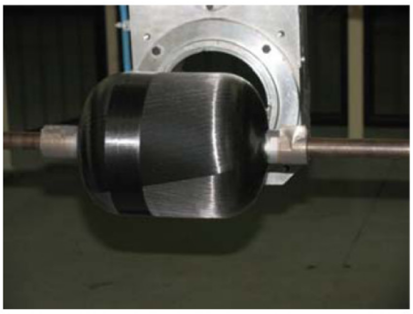


Figure 5: Small vessel specimen

Figure 6: 1:5 scaled item

Figure 7: Avio prepreg winding on P80 scale

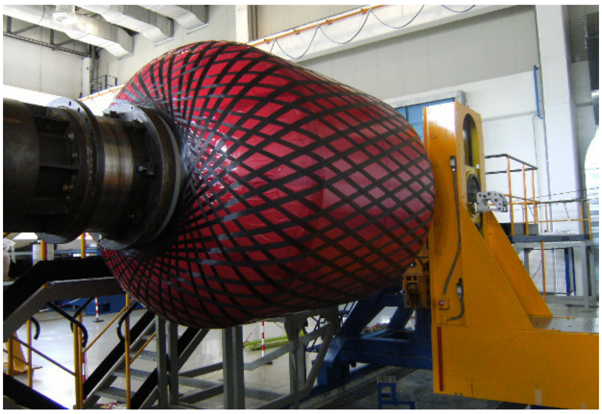


Figure 8: Avio prepreg winding on Z9 scale

2.1.2 Automatic tape laying of skirt manufacturing

In the frame of process improvements activities, the possibility to reduce the defect linked to skirt manufacturing is undertaken. The first Z40 IMC DM00 unit has been manufactured, for the first time, with a fully automated process for both body and skirts. The manual deposition of carbon epoxy tape (see Figure 10), currently used on the Vega motor cases for skirts lay-up, has been substituted by an Automatic Tape Laying (ATL) process, allowing to dramatically increase the quality of skirt manufacturing and to reduce the production cycle time, due to the implementation of robotic arms (put beside the filament winding machine) able to assure high precision in tape layers deposition and cutting (Figure 11).

Figure 10: Manual deposition of tape

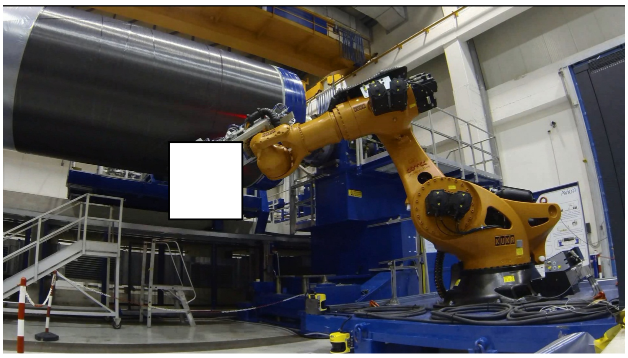


Figure 11: ATL machine sketch

The DM00 unit has recently successfully completed its cycle of tests (last test on 3rd of June, 2015), during which the behaviour under pressure (up to 1.1MEOP) and mechanical loads (traction and compression) have been thoroughly tested. In particular, very high compressive and tensile fluxes (2000 KN/m under compression and 1000 KN/m under tension) have been sustained by the structure, practically doubling the actual maximum capabilities experienced by the Z23 IMC (1200 KN/m under compression and 500 KN/m under tension). The item has been equipped, before polymerization, with an embedded system of measurements constituted by Fiber Bragg Grating sensors, for the evaluation of residual strain after curing and for the mechanical tests monitoring. This part of the activity is a step of a wider program for the setup of an health monitoring system of the composite structure.

Figure 12: Z40 DM00 motor case on test bench

2.2 Loaded motor case

Propellant grain is the motor element which generates, once combustion is activated, the thermal energy able to produce thrust, when converted in kinetic energy by the nozzle.

Main design and technological developments implemented in Z40 is a new propellant formulation.

2.2.1 New propellant formulation

Z40 propellant grain will maintain the same configuration of Zefiro 23 and Zefiro 9 motors (finocyl shape), while some improvements have been introduced for propellant formulation in order to reduce the chemical compounds risk class.

The trade off has been completed for the propellant formulation and composition selection, with particular attention to “low erosion rate of the nozzle throat” criteria. The selected one show a low viscosity of the mixture.

An extensive characterization campaign shall be performed to deeper investigate on the induced throat erosion, and to define its chemico-physical, thermo-physical, ballistic and mechanical behaviour as well as, for the first time in Avio, its dynamic characteristics.

2.3 Nozzle

The nozzle is the motor component which accelerates the combustion gas products in order to generate thrust.

Main design and technological developments implemented in Z40 nozzle are a self-protected flexible joint and a forward divergent thermal protection manufactured by liquid resin infusion ([4]).

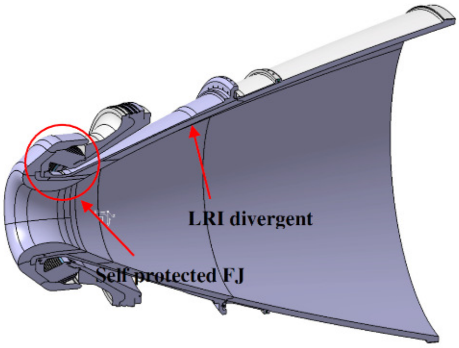


Figure 14: Z40 nozzle scheme

The FJ consists of two interface rings (one fixed and the other one movable) and a series of thinner rings (shims) alternated with synthetic low module rubber layers. Synthetic rubber has been chosen because it shows more stable mechanical properties if compared with natural one (actually used on Zefiros nozzles).

Very stringent requirement on FJ stiffness and component led to choose a composite shims configuration in replacement of the metallic ones used on Zefiros nozzles: it allows to strongly reduce FJ mass also because self-protected FJ avoids manufacturing and integration of dedicated thermal protections by protruding composite shims beyond rubber pads in order to withstand thermal loads coming from SRM combustion gas (see Figure 15). In fact, due to necessities to withstand simultaneously high mechanical loads on low diameters and high thermal loads in aggressive combustion chamber environment in higher diameters, Z40 reinforcement shims are made by hybrid composite: layered carbon–epoxy and glass-epoxy in low diameter zone in order to stiffen and strengthen most mechanically loaded area; glass-epoxy in contact with hot gas.

A spherical configuration has been chosen to reduce stress on reinforcements when pressure and actuation act simultaneously. Anyway this geometrical configuration is the most “volume consuming” in terms of nozzle envelope and involve substantial decrease of stiffness when FJ is pressurised.

Z40 FJ design fulfil the following requirements:

- low FJ stiffness (<3000 Nm/°): reached by acting on rubber modulus and pad thickness
- thermal resistance for 100 sec
- mechanical resistance to loads induced by max pressure of 100 bar and max actuation of 7°
- mechanical stability at high pressure

From the technological point of view both composite shims manufacturing and FJ manufacturing processes have been investigated.

Hybrid composite shims shall be manufactured by manual stratification of stripes of fabric pre-preg and curing in autoclave. Tow winding technology feasibility has been evaluated but problems in achievable fibres angles and shims thickness tolerances discarded this possible solution.

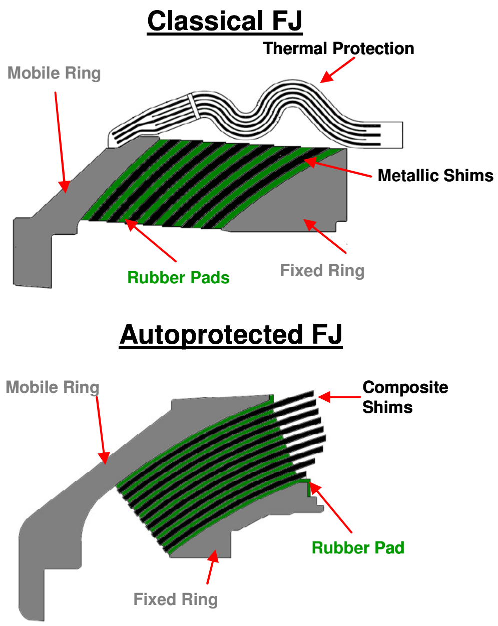


Figure 15: Autoprotected FJ design

Different prototypes have been preliminary produced at Z23 scale in order to set up and optimise manufacturing process (see Figure 16), after that a set of full scale shims has been produced in order to manufacture the first Z40 FJ.

For FJ manufacturing, rubber transfer molding is considered the baseline because this is the process used at the moment for Zefiro FJ.

Composite and rubber post-cured bonding is considered a backup process. Technical and cost problems can arise due to necessity of several equipment to ensure correct and centered adhesion between rubber pads and composite shims and need to test correct adhesive agents based on cold or hot bonding process. Preliminary rubber transfer molding has been successfully executed on Z23 FJ where two composite shims have been used in order to assess the applicability of this technology on the composite shims instead of metallic one.

Figure 16: Prototype of hybrid composite spherical reinforcement shims at Z23 scale

Thermo-ablative behaviour of self-protected FJ will be tested in the next future with a small scale motor (see Figure 16), in which the purpose to verify the thermal protection efficiency of the selected configuration.

2.4 Inner interfaces

Z40 internal interfaces (between loaded motor case and igniter as well as between loaded motor case and nozzle) main design and technological developments comprehend a carbon rope solution as thermal barrier and a "Z" chicane shape.

2.4.1 Carbon rope solution

A carbon rope solution as thermal barrier is already employed on P80 SRM, first stage of VEGA Launcher, and on Pressure Oscillation Demonstrator (POD-X) for Ariane program ([5]) but not on Zefiro 23 and Zefiro 9, for which grease filling solution is still employed, with great complication of integration process (see Fig.18).

The carbon rope, working as thermal protection inside the chicane, is able:

- to sustain the extreme temperatures reached during SRM firing, without loss of integrity;
- to drop the incoming gas temperatures to acceptable levels to O-rings, to prevent O-ring damage (including char and erosion);
- to exhibit adequate resiliency/springback, in order to accommodate limited joint movement and manufacturing tolerances;
- to diffuse/spread incoming narrow hot gas jets, in order to reduce the damaging effects on the downstream O-rings;
- to block hot slag (i.e. alumina, etc.) entrained in gas stream from reaching O-rings;

2.4.2 "No volume increase" chicane shape

A different chicane shape with respect to VEGA is applied on Z40. This is already employed on POD-X ([5]). This solution has the advantages with respect to the solution with grease to simplify the integration phase, to relax the dimensional tolerances and required integration precision, to facilitate the O-ring pressurization; moreover, the innovative Z40 configuration, compared with the one currently adopted with carbon rope on P80 SRM, assures that, during the chicane deformation due to SRM pressurization, the carbon rope is compressed between the horizontal and oblique surfaces of the chicane, guaranteeing that the thermal shield is always in touch with IMC-TP surfaces during the entire SRM firing, so no hot gas paths from combustion chamber to O-ring can occur. The disadvantage of this configuration is the more elevated difficult in the manufacturing with respect to the P80 one, in particular at LMC level; preliminary technological tests have been performed, that have supplied good results in terms of manufacturing precision and dimensional requirements satisfaction.

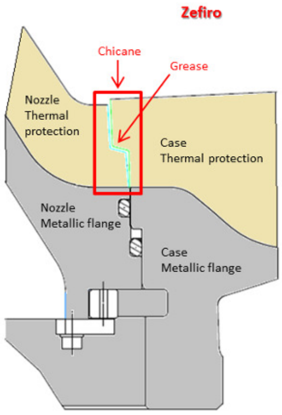


Figure 18: Zefiro chicane with grease

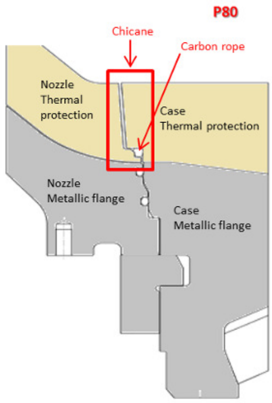


Figure 19: P80 chicane with carbon rope

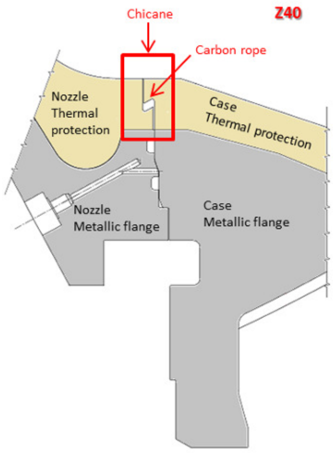


Figure 20: Z40 chicane with carbon rope

Anyway, an hybrid back-up solution is under-investigation (red line in Figure 21), representing a good compromise between the easy manufacturing of P80 chicane and the elevated performance of PoD-X one: it can be easily manufactured (at LMC level the chicane manufacturing is consistent with the P80 one, currently industrialized) and keeps the advantage to guarantee the touching between carbon rope and chicane surfaces during SRM firing.

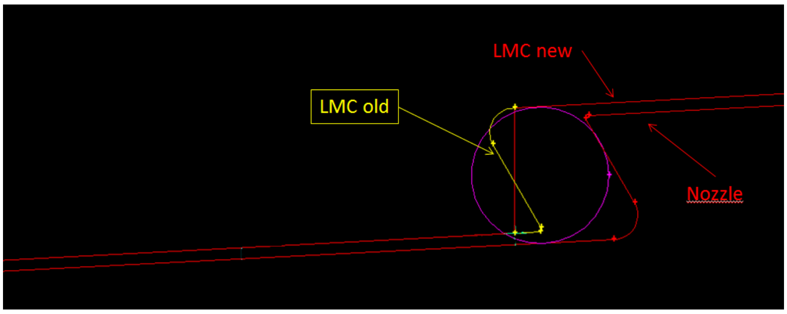


Figure 21: Z40 chicane back-up solution

3. DEVELOPMENT AND QUALIFICATION PLAN

Z40 Solid Rocket Motor Program will be characterised by several development and qualification milestones. The Preliminary Design Review has been performed on December 2012. A delta PDR, to take into account the planning constraints derived from VECEP Program, and in general for the programmatic objective changes (from technological demonstrator to a flight item of next Vega evolution) is foreseen at the end of June 2015.
Avio prepreg material is now on the second phase of characterization: all the effects related to ageing, environmental test and damage tolerance are under investigation.
The DM00 model has completed the first phase of the validation (motor case structural part and internal thermal protection). All the tests at full scale level (tightness, pressure loads, mechanical loads), have been successfully completed.

The DM00 will be used to perform an inert propellant casting (foreseen in 2016) for set up and validation of the casting process, equipment and procedures.
Starting from June 2015 the manufacturing of the DM1 item for the case as well as its casting with active propellant and two full nozzle (the first one for qualification) will be done in order to perform a first motor firing test (Z40 DM model). Moreover the first two prototype of full flexible joint will be manufactured and tested at acceptance loads. At the beginning of 2016, the third motor case item (DM0 model) will be manufactured and tested for mechanical qualification of the structure up to the burst test.
These activities will allow to perform the Critical Design Review (CDR). A second bench firing test (Z40 QM model) and a final Qualification Review (QR) will be completed in the first part of 2018.

4. CONCLUSIONS

Zefiro 40 Solid Rocket Motor program is a key element of the Vega Launcher evolution. It also represents for Avio S.p.A. the means to develop innovative technologies, materials and design solutions, being the first item of a new generation of solid rocket motors.
Summing up, Z40 SRM represents an important technological breakthrough propedeutic for the developments currently ongoing in Avio in the frame of the new launcher activities: P120C SRM for VEGA and Ariane 6 launchers will benefit of the knowledge and TRL achieved during the Z40 development. This experience is important to consolidate Avio position as leader in the solid space propulsion.

5. AKNOWLEDGEMENTS

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