



Evaluation of a Single-Stage Light-Gas Gun Facility in Malta: Business Analysis and Preliminary Design

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Abstract

Impact testing is a critical activity for many aerospace activities. Data on impacts can be employed to evaluate materials survivability, operations safety, and, if possible, to plan prompt maintenance. A classical impact testing facility usually employs Light-Gas Guns (LGGs) to evaluate the effect of collisions in a controlled laboratory environment. In particular, single stage LGGs are relatively simple in their working principle, as they consist in a pressurized gas reservoir and a barrel with a projectile placed in front of the experiment target. When the shot command is executed, the gas from the reservoir accelerates the projectile through the barrel; in first approximation, its velocity is related to the reservoir pressure, the barrel geometry, and the projectile velocity. In this context, The Malta College of Arts, Science and Technology (MCAST) and the Centre of Studies and Activities for Space CISAS “Giuseppe Colombo” of the University of Padova have started a collaboration to develop a single stage LGG impact facility in Malta. In this paper, the conceptual evaluation and the development of the facility is introduced. First, the potential application of such facility in the framework of Malta aviation market as well as the business opportunities in the emerging space sector are presented. In a second part of this work, the LGG main design drivers are defined and a preliminary evaluation of the achievable projectile velocities is performed.

Keywords Light-Gas Gun · Hypervelocity impacts · Space debris · Aerospace structures

1 Introduction

To ensure safe operations, understanding the properties of materials subjected to impact conditions is critical in various aerospace applications. To address this issue, specific tools are necessary to assess the impact damage on structures and systems [1].

With respect to the aeronautical sector, impacts usually include bird strikes and hail collision and, in case of military applications, high-velocity impactors such as projectiles and missiles. Therefore, dedicated facilities shall be able to work with different impactors, from soft bodies (useful for bird strike simulations), to ice (to replicate hail), to metallic and

plastic materials currently used or under investigation in the aeronautical sector.

In a similar way, spacecraft components and materials require advanced testing under different impact conditions, due to the ever-growing threat to spacecraft from man-made orbital debris. In fact, spacecraft are commonly designed to be protected from debris collisions and are provided with shields or dedicated structures to mitigate the effect of collisions. Most modern materials used in these shields are tested on ground to establish if they can withstand specific impacts. Novel materials and manufacturing strategies are currently under investigation to improve the survivability to the impact, such as additive manufactured shields [2], and to detect in-situ the collision event [3].

In this context, Light Gas Gun (LGG) facilities can be employed to simulate a range of different scenarios in a safe and controlled laboratory environment. Common types of light-gas guns are the single-stage LGG, two-stage LGG, and the shock tube. Single-stage LGG are relatively simple in concept, consisting of one pressure reservoir that accelerates a projectile through a barrel to the target; despite their simplicity, they employ a cutting-edge technology that

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presents unique mechanical challenges [4] that can be further developed for the more complex two-stage LGGs [5]. A single-stage LGG is capable of propelling projectiles up to 200 m/s and beyond, while a two-stage LGG can reach velocities up to 5–6 km/s [6, 7]. Both configurations require the presence of a testing chamber, able to contain the debris from impacts and adaptable to house the studied targets.

In this framework, a research collaboration between The Malta College of Arts, Science and Technology (MCAST) and the Centre of Studies and Activities for Space “G.Colombo” (CISAS) of the University of Padova is evaluating the development of a single-stage light-gas gun to test materials for impact resistance. For this activity, the projectile velocities achievable by the LGG are defined in function of the driving gas species, the reservoir pressure, and the barrel lengths. In parallel, a preliminary evaluation of the research and business opportunities is performed considering the rapidly growing aviation market and the emerging space sector in Malta.

In this paper the evaluation results are presented. Section 2 depicts the preliminary business analysis of the aviation sector in Malta, as well as possible future developments. Section 3 focuses on the gas-dynamic model and simulations, introducing an overview of the facility layout and a preliminary concept of the sabot stopping system.

2 Aviation Sector in Malta

Prior to investigating the conceptual evaluation of a single-stage LGG facility in Malta, a situational study was performed taking into account a number of external macro forces that may have an impact on the project's development. Following the assessment of these external factors, the internal strengths and weaknesses are examined.

2.1 External Macro-forces Analysis

The analyses of the external context are carried out using a framework that takes into account political, economic, social, technological, environmental, and legal factors that may have an impact on the project's implementation.

2.1.1 Political Factors

Malta experiences a stable political situation and benefits from being a member of the European Community in terms of access to community resources [8].

The country offers a variety of ways to gain access to fiscal advantages, such as those offered by Malta Enterprise, which will make it easier to set up activities in Malta. Furthermore, tax incentives are available to companies that invest in R&D.

These extensive investments and incentives have been contributing, for example, to the fast growth of a cluster of enterprises working in the aviation sector. Furthermore, contributing to this, there is also the fact that Malta ratified the Cape Town Convention (CTC), i.e. an international agreement which provides legal certainty to owners, aircraft operators and parties in transactions such as leasing. International interests have full legal force and effect in Malta and take a prior ranking over national security interests.

Also, other industries such as automotive, semiconductors and pharmaceutical have been benefitting from these policies and incentives. This preliminary study is mostly centred around specialised industrial areas designed to provide secure facilities for the aerospace industry, particularly within the Maintenance, Repair and Overhaul (MRO) sector.

2.1.2 Economic Factors

Facilitation of access to soft loans, loan subsidies, or loan guarantees for an organization looking to establish itself in Malta is a significant financial aspect.

Another strength of Malta's economy is its well-developed logistics sector, which allows operators to work with Just-In-Time (JIT) patterns, eliminating the need to stock huge quantities of raw materials or finished goods.

A collection of infrastructures, like as the Malta International Airport and the Freeport, support the logistics sector, allowing local and foreign direct investment (FDI) businesses to compete effectively with low-cost operators in the Far East.

Furthermore, to facilitate the successfully implanting of new FDI's, through the vocational education and training (VET) system, it is possible to engage quickly a knowledgeable workforce.

In fact, in this scheme the apprentice is attached to an employer, receiving a wage from the employer and an allowance from the government. Social insurance costs are covered by the employer and the apprentice. Employers cover also the costs of materials and tutors. However, the employers are incentivized to the implementation of these national strategies as they can benefit from tax incentive instruments [9].

The Malta Securitisation Act, in force since 2006, scopes in a wide variety of assets that may be securitised including aircraft, helicopters and space assets.

Special tax deductions are allowed in securitisation transactions that enables tax efficient structuring. It is also possible to set up cell companies whereby assets and liabilities of each cell are protected from those of other cells within the same company.

2.1.3 Social Factors

The good level of the education system in Malta is a strong support for the fast development of the local economy.

Following the compulsory school cycle, post-secondary education includes both the academic route and the vocational education and training (VET) route [10].

The VET setup in Malta makes a difference in the local economy, as it is providing students with the right skill sets to work immediately in the industry, using the apprenticeship and work-based learning (WBL) strategies.

2.1.4 Technological Factors

Maintenance, repair, and overhaul (MRO) for both fixed wing and rotary aircraft, flight training, component manufacture, R&D and innovation on unmanned aerial vehicles, back-office support and call center operations, and ICT for the aviation industry are just a few of the important players in the aviation industry based in Malta.

The global pandemic caused by Covid-19 has destabilized the aerospace industry to its core, and recovery is addressing both pre-existing conditions like congestion, carbon footprint, and economic sustainability, as well as new issues posed by increased awareness of pre-existing challenges and challenges presented by new technology and evolving markets.

In addition, the automotive, semiconductor, and pharmaceutical industries all have significant foreign direct investment (FDI) setups.

2.1.5 Legal Factors

Malta's government policies are aimed at attracting foreign direct investment through a series of tax incentives and the provision of space in its industrial estates.

It is important to note the country's rapid expansion of its aircraft registry, which is aided significantly by a flexible and competitive legal structure. Malta has a multitude of legal advantages that encourage aircraft registration.

The Malta aircraft Registration Act (ARA) introduced rules facilitating the registration of aircraft and provides for a creditor-friendly body of laws meant to allow owners the possibility to grant mortgages and register international interests over aircraft and engines, prevailing over Maltese-registered mortgages, Irrevocable De-Registration and Export Request Authorisations (IDERAs) to be files, and for owner and lessor interests to be registered in the National Aircraft Register.

The Aircraft Registration Act also implemented "Alternative A" to the Cape Town Convention.

2.1.6 Environmental Factors

Due to Malta's small size and significant tourism industry, there has been a growing awareness of the significance of implementing Corporate Sustainability Responsibility (CSR) regulations for businesses operating in the country.

Major participants in the aviation, semiconductor, and pharmaceutical industries are increasingly aware of the issue, and they are adopting stringent policies on climate change, recycling, carbon footprint, waste disposal, and sustainability.

2.2 Internal Weaknesses and Strengths Analysis

Following the assessment of the external macro forces that may have an impact on the preliminary study described in this paper, the internal weaknesses and strengths are evaluated making a situational analysis that takes care of the Strengths, Weaknesses, Opportunities, and Threats (SWOT) aspects, as reported in Table 1.

Malta is home to some well-known Maintenance, Repair and Overhaul (MRO) entities such as Lufthansa Technik and SR Technics which provide D check maintenance services to both narrow-bodied and wide-bodied aircraft and which together employ around a thousand people.

Moreover, Malta hosts the Malta Aviation Conference and Expo, attended by hundreds of experts in the aviation industry for 3 days of panel discussions, keynotes and networking. The aviation sector in Malta has encountered significant growth over the past decade with the Maltese aircraft register listing over 477 aircraft and the number of AOC holders approaching 40.

From a business perspective, the SWOT analysis underlines the general feasibility of establishing a single-stage LGG facility in Malta, which might act as an additional incentive for R&D centers to relocate to the island. Furthermore, the facility's service could potentially serve as a further factor in strengthening the unique competitive space of industries and R&D centers already present on the territory [11].

3 Single-Stage LGG Conceptual Evaluation

In this section the gas-dynamics modelling for a new single stage light gas gun for the MCAST Hypervelocity Impacts Facility is presented; in addition, the preliminary layout of the facility is described.

The starting point for the design of the single-stage LGG takes into account the following objectives, as highlighted in Sect. 2:

Table 1 SWOT analysis for the implementation of single-stage LGG at MCAST in Malta

	Favorable for achieving the objective	Unfavorable for achieving the objective
External origin	<p><i>Opportunities</i></p> <ol style="list-style-type: none"> 1. Extensive FDI in the aviation and space sector in Malta 2. Presence of R&D facilities in the aviation, automotive, semiconductor and pharmaceutical industries 3. Co-operation with foreign universities with expertise in developing hypervelocity impact facilities 4. Providing services to the local industries 5. Possibility to provide a further factor to attract industries to set up in Malta, complementing the already existing financial aids 6. To have a facility in a niche research area, with few competitors in EU 7. To be part of the European Community, with free access to HR and physical resources 	<p><i>Threats</i></p> <ol style="list-style-type: none"> 1. Geographical position, being Malta an island 2. Changes in the favorable local legislation for FDI might halting the fast growing of foreign R&D investments that Malta is observing 3. Competition with other growing economies within the European communities might trigger changes in their legislation and tax regime in order to attract similar investments to the ones on which Malta is focusing
Internal origin	<p><i>Strengths</i></p> <ol style="list-style-type: none"> 1. Personnel, HR factor, qualified academically and with experience in research in the field of aerospace, material and electronics 2. Strong relationship with the major players in the industries of aviation, automotive and construction 	<p><i>Weaknesses</i></p> <ol style="list-style-type: none"> 1. Lack of experience in design and implement a single-stage LGG facility 2. Possible bureaucratic issues, being MCAST a government institution

- Establish a facility that can conduct tests for both space and aeronautical sectors. The projectile velocities selected will be suitable for replicating low-speed impacts, such as those seen in GEO orbits [12], as well as testing impacts on aircraft components.
- To develop a facility which can work in conjunction with existing European hypervelocity research centers, such as the one at the University of Padova.
 - o The Centre of Studies and Activities for Space “Giuseppe Colombo” (CISAS) at the University of Padova features a top-level experimental facility for hypervelocity impacts (HVI), which employs a two-stage Light-Gas Gun. CISAS conducted several test programs for customers like ESA, Thales, JAXA and EMI (Fraunhofer). The two-stage LGG is able to launch projectiles up to about 100 mg to velocities up to 5.5 km/s; for heavier impactors (up to 1 g) lower velocities (up to 2.5 km/s) can be reached. The MCAST single-stage LGG facility will expand the operational range for test campaigns, allowing for lower speeds of up to 1 km/s and heavier launch package weights in the range of 15–20 g. Furthermore, the Malta facility could have an impact testing chamber capable of hosting targets with larger dimensions than the one in Padova, enhancing experimental flexibility. This will facilitate a more

thorough investigation of new materials for aviation and space applications.

- The installation and maintenance of an LGG facility can be expensive, so one of the key goals is to define the main parameters to design a high-performance, high-frequency, and low-cost experimental setup.

In the following subsections the analysis of the targets will be performed by varying the main LGG parameters. Moreover, a possible design for a configuration of the LGG’s sabot stopping system will be described.

3.1 Overview

The investigation of gas dynamic aspects for a new single stage LGG for the MCAST Hypervelocity Impacts Facility is described in this paragraph.

The study’s main focus is on the projectile’s velocity when it hits the target [13], with a specific attention for the effect of initial loading parameters on the projectile’s velocity as it exits the launch tube.

The simulations started with the analysis of a single stage Nitrogen gas gun with a 1 m long launch tube. The velocity of the projectile is affected by initial parameters such as pressure and compressibility of gas, and the theory indicates

that there is a nonlinear relationship between initial pressure and velocity upon exit from the barrel.

As a result, a specific model in Matlab™ Simulink™ was created with the goal of modelling the performance of the light gas gun; obtained data will drive the design the dimensions of the first stage reservoir, of the pump tube length, and of the sabot containing the projectile.

The model is based on traditional gas-dynamic equations that have been integrated over a designated time interval. It is possible to evaluate the system’s performance by modifying the model’s parameters, such as the reservoir pressure.

The core components of a single-stage LGG are shown in Fig. 1. A first-stage reservoir stores a light gas, such as Nitrogen (N₂) or Helium (He), at high pressure; downward, the pump tube is employed to accommodate the launch package, consisting of a protective sabot and the projectile, and accelerate it with the high pressure light gas from the reservoir. A sabot stopping system allows the projectile to be separated from the sabot after the acceleration phase; details on this system are reported in Sect. 3.3. In the launch tube the projectile continues on its path towards the target, and its velocity is measured by two laser blades; last, in the impact chamber the projectile strikes the target.

3.2 Gas-Dynamic Simulations

The first set of gas-dynamic simulations will now be described, using a zero-dimensional model developed with Simulink™ software. The numerical model will be described in the next subsection; a preliminary evaluation of the LGG performance in function of different parameters variation will follow, leading to the identification of the main design drivers that shall be considered in the detailed design.

3.2.1 Numerical Model

To simulate the unsteady gas-dynamic processes involved in the first stage of the light-gas gun, as well as to calculate the pressure created by the launch package compression stroke, a zero-dimensional numerical code was utilized. The model was developed in MATLAB™ Simulink™ symbolic language, with macro-blocks representing all the main modules of the LGG; it is based on simplified models and formulas employed in literature on light-gas guns design [14] and implements the equations developed by Milora et al. for the “Quickgun” code [15].

Figure 2 shows the MCAST single-stage light-gas gun in the form of a logic block diagram, which was employed to define the main components of the LGG gas-dynamic model and the interactions among them. Five main elements were identified, three of them acting as “virtual” reservoirs (first stage, with constant volume, pump and launch tubes, with variable dimensions), the shot valve commanding the mass flow between the first stage and the pump tube, and the launch package, which is propelled by the pressure acting on its bottom and which position coordinates affect the size of the pump tube equivalent reservoir.

In more detail, the valve is simulated in this model as in the “Quickgun” code: its flow area changes during valve operation, taking a linear variation from zero to the open value during the net opening time, which is defined as the time between when the obturator starts moving and when it stops its motion; a similar approach was employed to model the closing phase. In addition, the response time can be included in the valve simulation by adding a time delay between the activation signal and the moment the obturator begins to move.

Fig. 1 Schematic of a Single-Stage Light Gas Gun

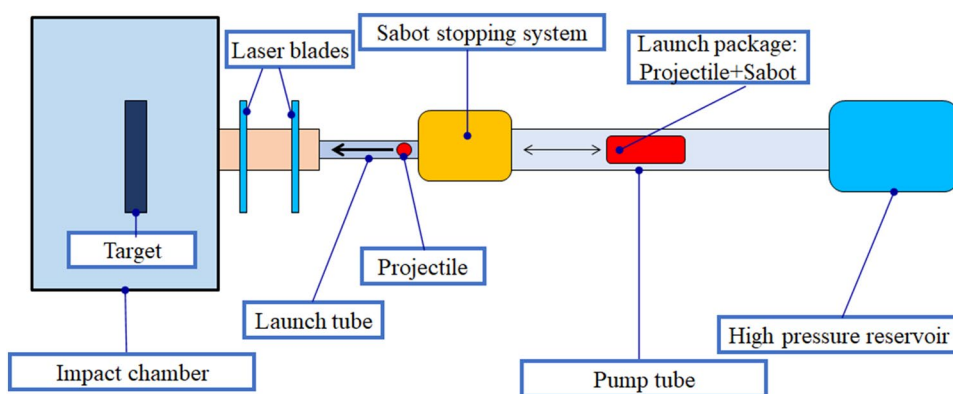
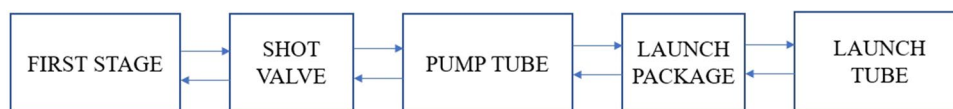


Fig. 2 Block diagram of the main single-stage LGG sub-systems



Last, in the model, the investigated working fluids (Nitrogen and Helium) are considered to follow the ideal laws of perfect gases.

3.2.2 Initial Setup

The starting point for these simulations is based on the following constraints:

- The facility shall be developed targeting a cost-effective approach;
- The prior experience in LGG design shall be employed, especially in the definition of the simulations starting point and in the comparison of potential design solutions;
- The range of velocities and mass of the launch package shall be compatible for both space and aviation applications;
- The LGG pressure values shall be included within the operational ranges of standard industrial fittings.

Table 2 Initial LGG parameters

Parameter	Value
Pump tube length	1 m
Pump tube initial pressure	1 bar
Pump tube inner diameter	30 mm
Launch package mass (sabot and projectile)	40 g
Reservoir initial pressure (Nitrogen gas)	40 bar
Reservoir Volume	$9.4e-04 \text{ m}^3$

Following these considerations, the Simulink™ model includes the following initial parameters, as shown in Table 2:

The simulations are based on three different scenarios related to the valve's opening time and the launch package clearance. In the first case, represented by the red curve in Fig. 3, an ideal valve operating instantaneously is considered (Case 1); the curve can be compared to the one of a pneumatic valve with a supposed opening time of 10 ms ($1e-2 \text{ s}$, Case 2, black curve in Fig. 3). Last, a realistic situation also considers a radial clearance (Fig. 4) between the launch package and the pump tube; in this case, the evaluated value is 1 mm ($0.1e-3 \text{ m}$, Case 3, green curve in Fig. 3).

The results of the simulations using the starting set of parameters indicate that the projectile will enter the

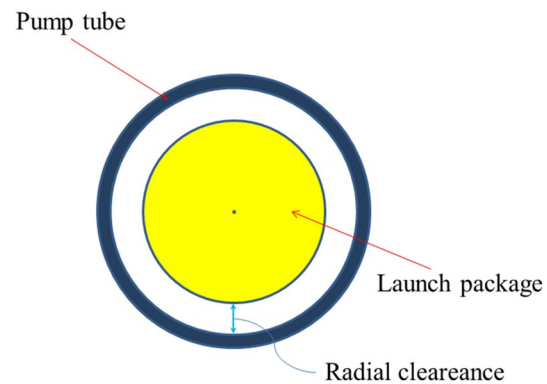


Fig. 4 Schematic representation of the radial clearance between the pump tube and the launch package

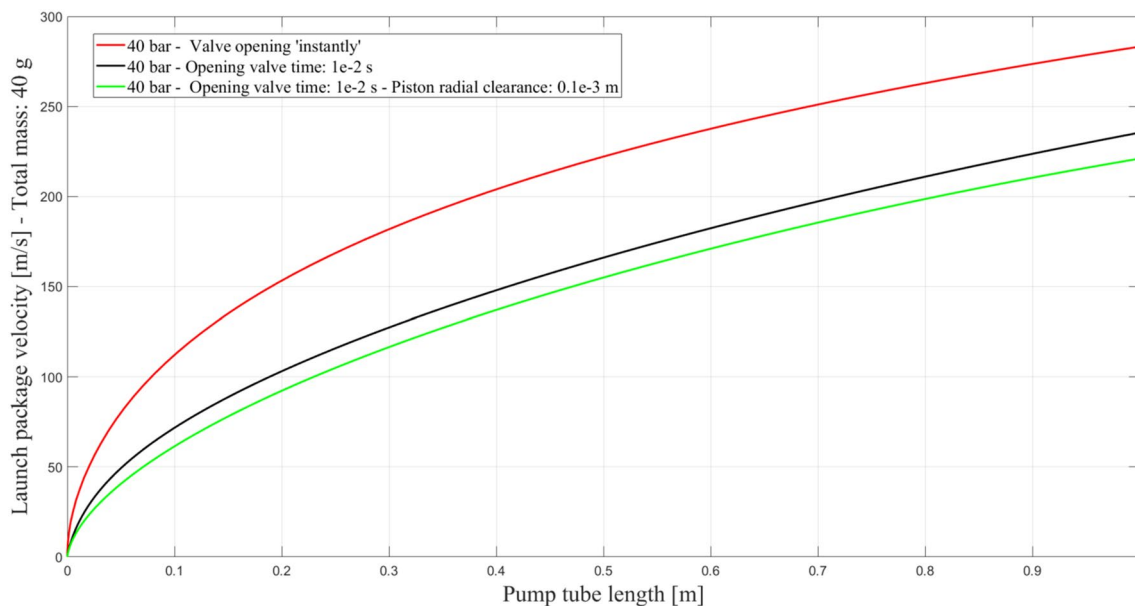


Fig. 3 Results of LGG simulations using the default settings

impact chamber at a final velocity between about 220 m/s (Case n.3) and 240 m/s (Case n.2). In the following subsections the other parameters of the model will be varied to better understand the most important design drivers for the LGG.

3.2.3 Reservoir Pressure

Different pressure values can be considered for the reservoir. Figure 5 shows simulation results respectively for 40, 100, and 250 bar in the reservoir, considering the configuration with an opening valve time of $1e-2$ s and a piston radial clearance of $0.1e-3$ m.

It can be noted that, as expected, the launch package velocity increases non-linearly with the reservoir pressure. It can be seen that the launch package is 1.4 times faster at 150 bar than at the initial LGG configuration (40 bar).

3.2.4 Pump Tube Length

To improve the LGG performance, in addition to increasing the reservoir valve, it is possible to increase the length of the pump tube. Figure 6 illustrates the effect of this design choice.

It can be noted that the velocity increases with tube length. The launch package, in particular, is 1.5 times faster with a 3-m long pump tube.

3.2.5 Performances with Different Gases

Figure 7 shows the comparison between the use of Nitrogen gas (N_2) and Helium gas (He).

Considering a pump tube length of 1 m, the utilization of Helium provides for a 10% gain in performance.

3.2.6 Performances in the Impact Chamber with Different Pressures

Figure 8 shows simulations at different impact chamber pressures (1000 mbar, 500 mbar, and 5 mbar).

The performance improvement is negligible under these conditions; nevertheless, tests for space applications may require the LGG to shoot in vacuum conditions.

3.3 Sabot Stopping System

A design for the configuration of the LGG's sabot stopping system will be introduced. This system is key in the design of the full LGG system, since its role of interface between the first stage accelerating the launch package and the projectile impacting on the target at the end of the process.

The system described is mechanically decoupled in the interaction with the impact chamber and the pump tube. This to avoid damages in case of failures, moreover it allows easier operations during the pre and post-test phases.

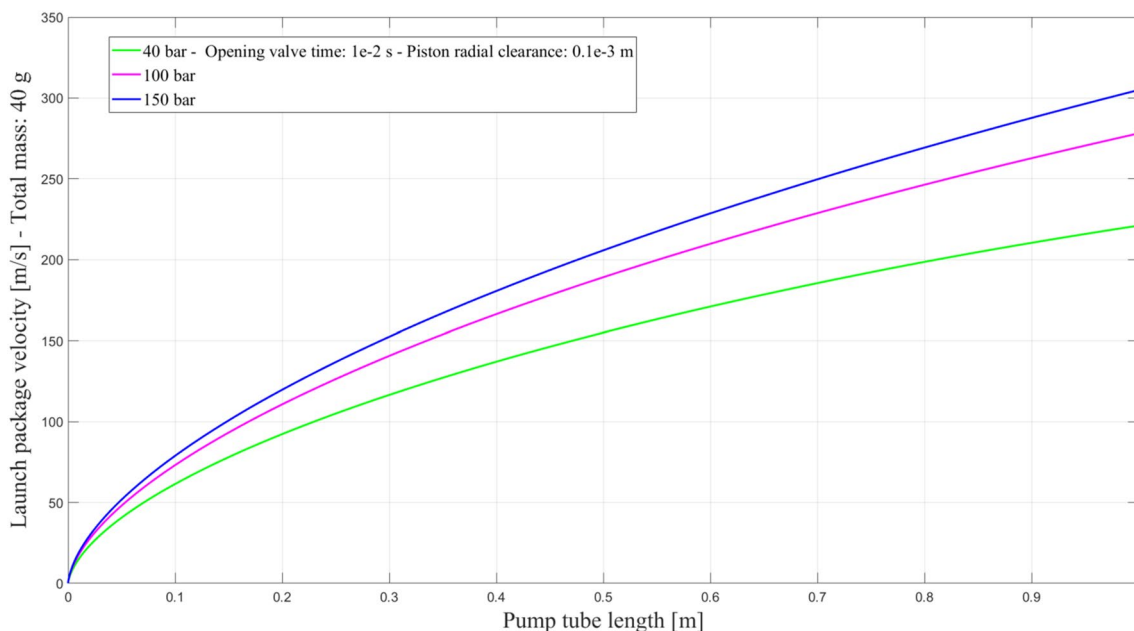


Fig. 5 Plot representing the velocities values increasing the pressure in the reservoir

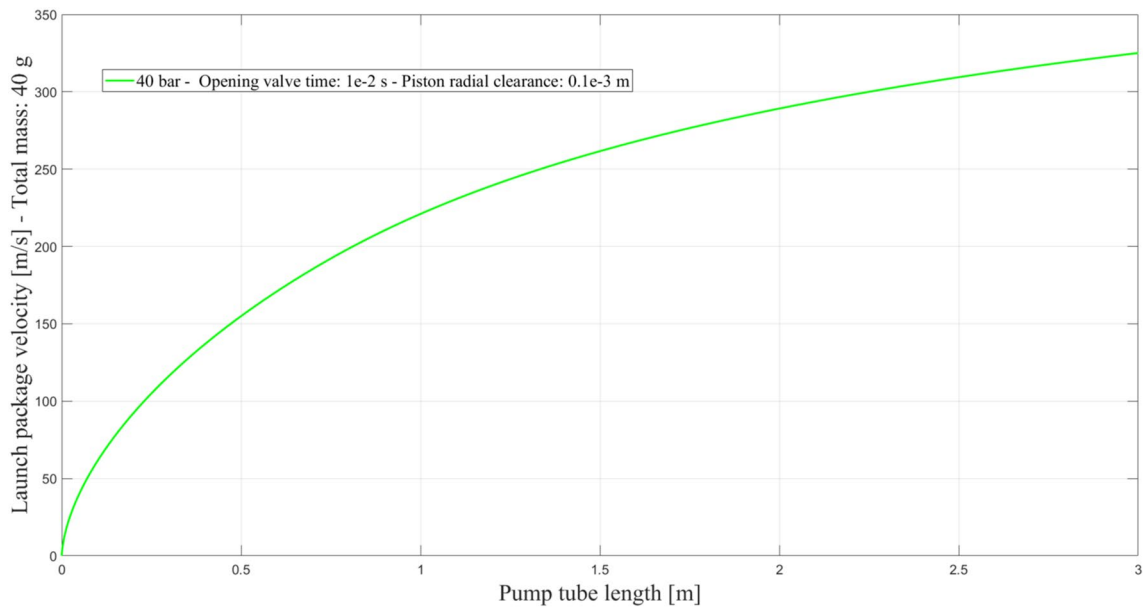


Fig. 6 Comparison of different pump tube lengths

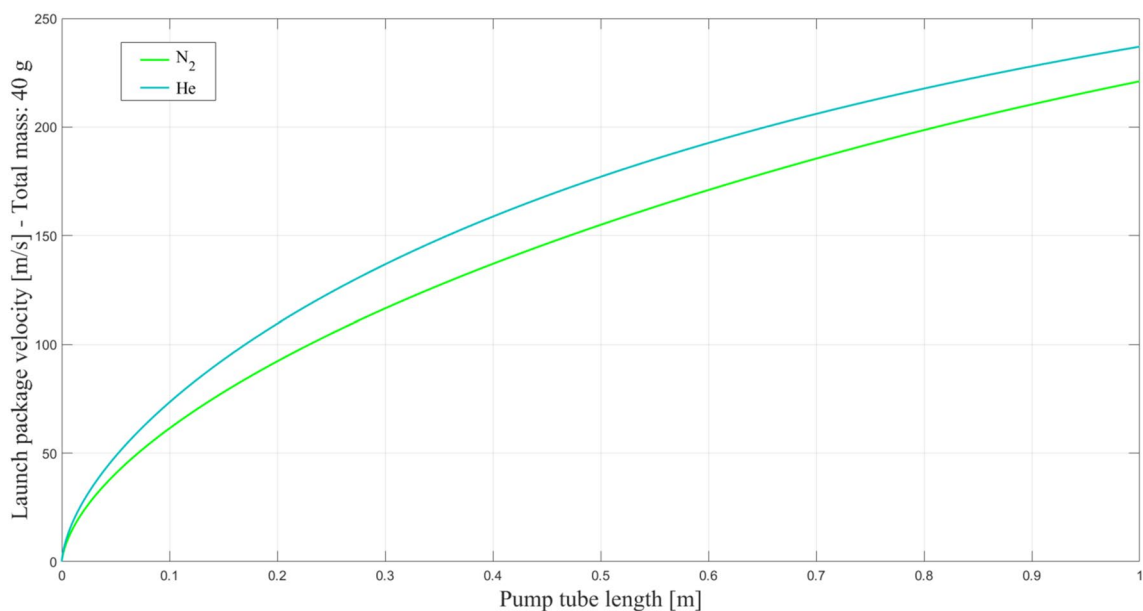


Fig. 7 Helium and nitrogen gas performances

3.3.1 Conceptual Design

A schematic of the system's concept is reported in Fig. 9, showing the dissipation mechanism principle for the impact force; Fig. 10 shows a preliminary layout of the main components. The sabot system includes a holder with the sacrificial impact tube, a rubber disc around it and a rubber cylinder behind it; the impact tube is the main component, in direct contact with the sabot after the shot. The holder

is inserted in a flanged supporting structure, which can be inserted between the LGG pump tube and the impact chamber.

The system working principle is here described. The launch package hits the sabot stopping system and deliver a force to the impact tube, stopping the sabot that is therefore separated from the projectile, which continues its paths till the target. The structure is protected by the transferred momentum by the properties of stiffness and damping of a

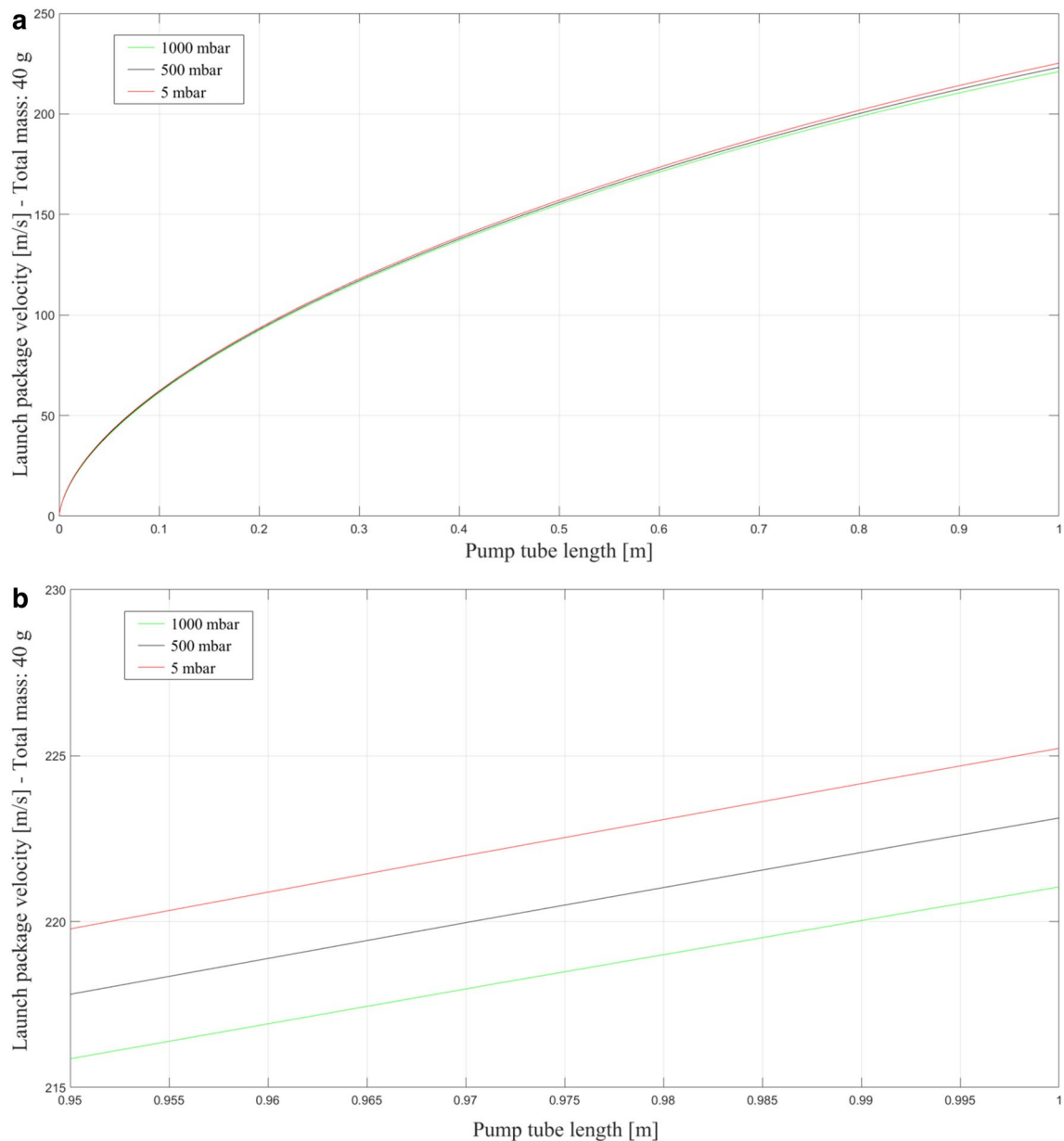


Fig. 8 Performances at different pressures in the impact chamber (top) and zoomed area (bottom)

rubber disc, for radial deformations, and a cylinder, for axial deformations, that surround the tube. This solution avoids to the holder, which is sustained by the supporting structure and constrained by the two flanges. One advantage of this configuration is the possibility to test different shapes of impact tubes, without increasing the complexity of the system.

The detailed study of this system will be divided in two parts, both with conservative approach, due to safety reasons. First, a mass-spring-damper Simulink model will be developed to assess the reaction force of the system to the impact; in a second time, Finite Element Analysis will be

performed to assess the behaviour of the structure. This phase will be fully implemented once the gas-dynamic parameters and structural design of the first stage of the LGG will be finalized.

4 Future Development

Starting from the design parameters analyzed in this work, it is planned to carry on the development of the single-stage LGG facility. It is possible to foresee in the future the two impact facilities, the planned single-stage LGG in

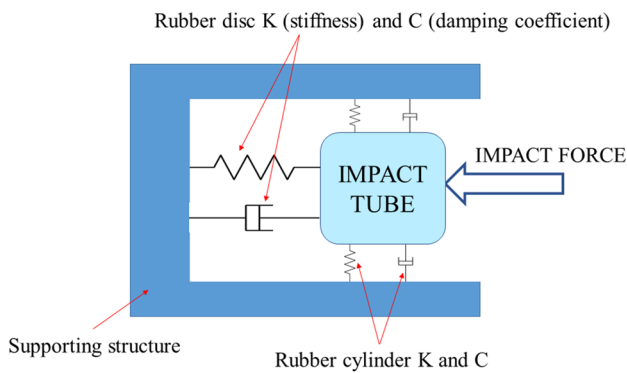


Fig. 9 Schematic of the sabot stopping system concept

Malta and the existing two-stages LGG at the University of Padova, supporting each other, cooperating to cover a complementary range of projectile test speeds and diameters, and impacting several different types of target materials. This will result in a unique collaboration at the European level, with the potential of further networking, as other universities and aerospace private enterprises look to this consortium to conduct activities for their research centers.

The next steps in the LGG development will be related to the detailed design of the facility, including the mechanical, fluidic, and electronic control systems, as well as the associated support and safety systems. It shall be noted that this is the first time such an activity has been proposed in Malta; further steps will depend on financial support and collected funding opportunities.

It is expected that this activity will promote the Maltese aerospace sector, in particular regarding the development of new technologies and materials for aviation and the

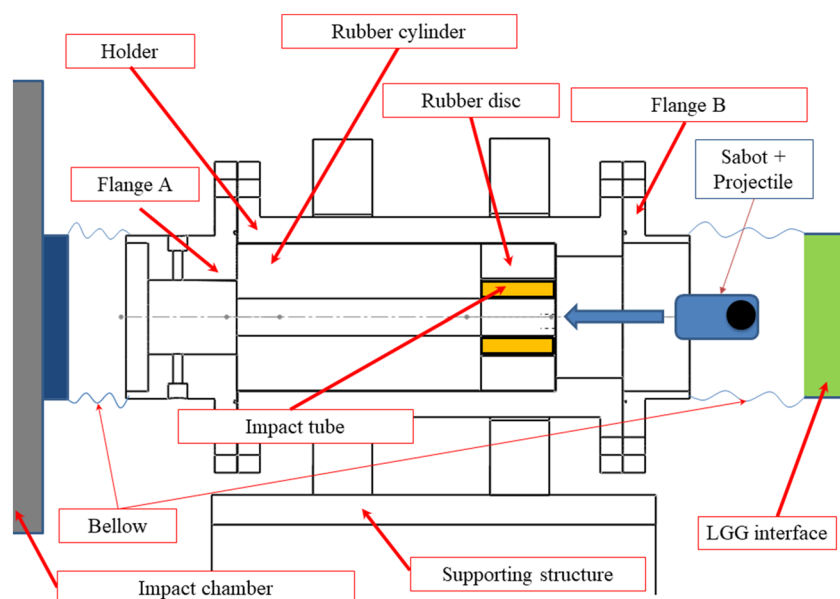
improvement of existing manufacturing and maintenance processes. In parallel, the existence of a high-level research facility will foster the academic field, boosting the studies related to impact dynamics, allowing the experimental verification of numerical collision simulations, and in general involving researchers with a different scientific background in interdisciplinary activities.

5 Conclusions

This paper presented the conceptual evaluation for the development of a single-stage light-gas gun for hypervelocity research. Following a preliminary business analysis that indicated a favourable situation in Malta for establishing a single-LGG at MCAST, a general layout was defined, and a zero-dimensional gas dynamic model was used for preliminary simulations, presenting the results of various configurations with different main parameters. In addition, a concept evaluation of the sabot stopping system has been carried out.

Results confirm the feasibility of the proposed facility and identify the main parameters determining the performance of a single-stage LGG. With these data, it will be possible to examine further the market opportunities and, in a subsequent phase, develop a set of target and operational requirements for the impact facility's detailed design.

Fig. 10 Schematic of the sabot stopping system



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Declarations

Conflict of Interests On behalf of all authors, the corresponding author states that there is no conflict of interest.

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