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DEVELOPMENT OF A LASER IGNITER FOR THE SCRAMJET ENGINE OF THE 14-X HYPERSONIC AEROSPACECRAFT

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Abstract. *The Hypersonic Aerospacecraft 14-X, under development at the IEAv/DCTA, aims at the flight demonstration of a waverider with a hypersonic airbreathing propulsion system (scramjet). One of the scramjet challenges is to accomplish stable, efficient mixing and combustion in a supersonic air flow within a burner of reasonable size. To meet such a challenge, we are developing a suitable on-board laser igniter for the 14-X scramjet engine. This paper concerns the preliminary results obtained through interdisciplinary studies involving literature reviews on the 14-X project, laser-assisted supersonic combustion and laser technologies. We identified five laser parameters that can directly influence the mechanism of supersonic combustion, thereby the combustion efficiency: Wavelength, energy-per-pulse, repetition rate, pulse duration and propagation mode. We already selected the lasers Nd:YAG, Nd:YLF and Titanium-Sapphire as potential technologies for use as radiation sources. Furthermore, we are investigating, by dimensional analysis, a mathematical relationship for the efficiency of a laser-ignited supersonic combustion in scramjets. Finally, we are studying the viability of using fiber optics to drive the laser energy to the combustor. Although there is still much work to do, the prospects for developing a laser igniter for the scramjet of the 14-X looks good.*

Keywords: *laser, scramjet, supersonic combustion, hypersonics, 14-X project*

1. INTRODUCTION

There is considerable worldwide interest and effort in developing technologies for aerospace exploration through aerospace vehicles able to take off and land in aerospace-ports using scramjet technology *(*short for supersonic combustion ramjet*)* to provide a hypersonic air-breathing propulsion system based on supersonic combustion (Toro et al., 2010; Drummond et al., 2006; Smart et al., 2007). Under this scenario, Brazilian General Command for Aerospace Technology (DCTA) conceived the project of the 14-X Hypersonic Aerospacecraft (see Fig.1), under development at the Institute for Advanced Studies (IEAv), whose purpose is the development and manufacturing of a hypersonic propulsion research vehicle, which includes the in-flight demonstration of an installed scramjet engine (Toro et al., 2011).

Figure 1. 14-X Hypersonic Aerospacecraft (Toro et al., 2010).

Scramjets engines are the state-of-the-art of propulsion technology for aerospace vehicles traveling between five and twelve times the speed of sound in air (Heiser and Pratt, 1994) and, as shown in Fig 2, conceptually, are able to maintain the combustion reactions between its fuel and a supersonic flow of air. However, get the full supersonic combustion is a hard technical task, because the fuel must be injected, mixed, ignited and then burned in a few millionths of seconds. Although the concept of hypersonic engines with air intake has almost half a century of R&D, its technology is still difficult to be successfully accomplish in practice.

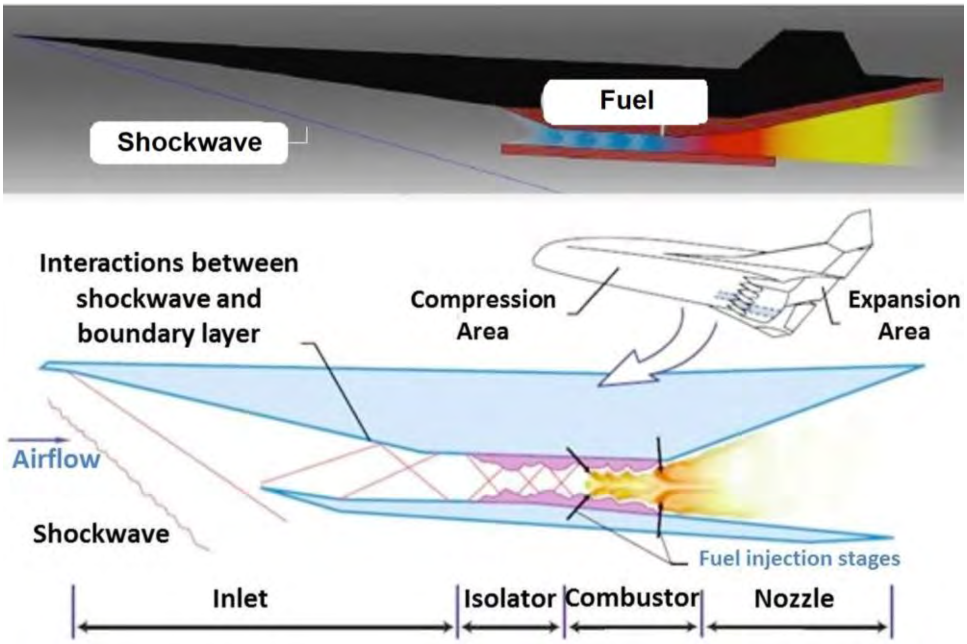

Figure 2. Conceptual project of a hypersonic vehicle using scramjet (Adapted from Toro et al. 2010 and 2011).

Currently, the H_2-based fuel 14-X scramjet engine is under advanced phases of experimental tests at the Hypersonic Shock Tunnel T3 of the Brazilian Air Force (Marcos et al., 2011). However, although there are data that demonstrate the possibility of its operation with plasma torch igniters, there are still some difficulties concerning the achievement and maintenance of the complete supersonic combustion due to limitations involving electrical sparks.

Such igniters are installed on the inner walls of the combustor, which restricts the occurrence of combustion reactions to the boundary layer establish adjacent to the wall, which means that their influence on the flow is spatially limited. Furthermore, the positioning of these igniters within the burner is also limited due to their size, and, once installed it cannot be repositioned. Not only, the electrical power used to produce continuous electric-arc or uninterrupted plasma torches - conditions required for stable combustion – has similar orders of magnitude as the thrust power that a scramjet engine provides, which makes the use of these igniters impractical in terms of overall efficiency.

Recent simulations (Negishi et al., 2003; Negishi et al., 2006) and experiments (Garner, 2008; Brieschenck, 2011), have shown that high-energy lasers can in principle be used to ignite fuel in supersonic flows of air for operation of scramjet engines. In 2011, Universidade Federal do ABC (UFABC) established a collaborative research with IEAv to the development of a new igniter technology based on laser radiation for use in the 14-X scramjet engine (Nascimento et al., 2012a; Nascimento and Rêgo, 2012b).

The development of this technology is sensitive, because several factors make the technology of laser igniters more advantageous than the electrical ones. First, with the use of laser igniters, any internal region of the burner can receive laser energy almost instantaneously and without the need to use any electrodes such as it is usually done for scramjets engines ignition. Accordingly, the high-laser radiation energy can be focused directly on the jet fuel, creating a spark, i.e., a hot fuel plasma whose temperature can reach hundreds of thousands of Celsius degrees in a few billionths of seconds (Negishi et al., 2003; Negishi et al., 2006). This hot fuel plasma consists of ions and radicals, which reacts exothermically with the pure fuel and increases the combustion speed between the supersonic airflow and the fuel. Moreover, the power required for the generation and maintenance of the laser beam is much smaller than the necessary for the other igniters.

Next, as the scramjet has no moving parts and the focal point of the laser can be easily changed during operation of the engine, it is possible in principle to manipulate the shock waves by means of laser beams in order to "virtually" shape the geometry of the combustor. This new capability may not only maximize the engine combustion, but also change properly the aerothermodynamics flow design of the engine. Added to this, it may also maximize the mixing processes via multiple laser-induced recirculation zones and lower the internal drag generated by physical flame holders put into

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the airflow, thereby enhancing the engine performance. Hence, scramjets equipped with laser igniters may be more efficient, safer and more economical than those with electrical igniters.

This paper presents the preliminary results obtained during the development of the first on-board laser igniter for the scramjet engine of the 14-X Hypersonic Brazilian Aerospacecraft.

2. LASER-FLOW INTERACTION INTERPRETATION

We identified that the laser-induced supersonic combustion mechanism were influenced by the following laser parameters: pulse energy, wavelength, pulse duration and pulse repetition rate. In this section, we will present the main physics aspects involving quantum mechanics and fluid mechanics, which may govern the interaction between the laser and the supersonic combustion.

2.1 Influence of the wavelength at supersonic combustion mechanism

In accordance with quantum mechanics, by knowing the quantum states of the H_2 molecules (fuel for the 14-X scramjet), it is possible to calculate the minimum photon energy necessary to ionize them and in turn, select a laser beam with a suitable wavelength for efficient absorption and subsequent ionization of the air-fuel mixture, thereby maximizing energy transfer and generation of reactive radicals for the combustion process (Brieschenck, 2011).

In this sense, by analyzing tables of dissociation energies for H_2 and O_2 – it is possible to determine the range of wavelengths more suited for a laser igniter applied to the scramjet. However, for an efficient analysis for energy transfer purposes, it is important to consider the various mechanisms of photons-molecules interactions, such as theories of multi-photon absorption (Brieschenck, 2011).

Currently, we are undergoing studies related to such methods and mechanisms in order to narrow the ideal range of wavelengths for the 14-X laser igniter, which we considers for sure to be near infrared.

2.2 Influence of the repetition rate at the supersonic combustion mechanism

The flow must absorb at least a minimum energy during its residence time in the combustor for the engine achieve and maintain stable combustion. In that matter, the influence of the laser repetition rate acts on the scope of the number of pulses that the air-fuel mixture can receive during this residence time within the combustion chamber. The repetition rate of the laser must be sufficiently high so that the required amount of radicals formed after laser ignition constantly remains in the combustor.

Not only, by controlling the pulses repetition rate and the position where the laser is focalized , it is possible to control how the laser energy is distributed over the combustor, which in turn enable the control of the location where the shockwaves are generated and the moment when it will happen. Thus, by manipulating the conditions of generation of the laser-induced shockwaves within the flow it becomes possible to manipulate the flow path within the combustor, by using such shockwaves as “virtual walls” of the engine. Thence, the flow will behave as if the geometry of the scramjet combustor had been temporarily shaped. This would generate a positive impact on the utilization of the ingested air, generation of recirculation zones and, consequently, would generate positive effects on the mixture process, on the flameholding action and more important on the escape velocity. Moreover, if it were possible to vary the repetition rate of the igniter during the engine operation, it would enable us to control the laser energy distribution through time, which would help the continuous manipulation of the “virtual” shape of the combustor and increase the radical production therein during faster flights.

2.3 Influence of the relationship between pulse duration and energy per pulse at the supersonic combustion mechanism

The shorter the pulse duration, the higher the pulse power, and hence, the higher the chance of the mixture temperature reach above the ignition temperature required for start the combustion process and the greater the probability of forming free radicals, which works as "catalyzers" for the combustion. If we interpret this according to quantum mechanics, we obtain that when the duration of a pulse focusing in a flow is reduced without modifying its energy, by considering the pulse energy as the sum of all of its photons energies, the number of photons will also remain constant and, therefore, the photon density of that pulse will increase. Thus, during the pulse lifetime, there will be a greater number of photons in the focal point at any given moment and, therefore, there would be a greater probability to electrons in the chemical bonds of the molecules in the mixture interact properly with those photons absorbing sufficient energy to break their bonds, generating free radicals, or to transfer kinetic energy to the molecule, increasing the mixture temperature.

It is important to note that although the flow velocity is orders of magnitude smaller than the speed of light, when we analyze this laser-flow interaction from a quantum electrodynamic standpoint, we must consider that the electrons on the chemical bonds are relativistic particles. Hence, the absorption mechanism suffer a large influence of the pulse photons density, since the electrons have average speeds comparable to the photons. Furthermore, although counterintuitive,

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address the laser-flow interaction as a quantum electrodynamic process govern by photons-electrons interactions is a suitable explanation for the absorption process, because a laser can transfer high energy to the flow with pulses durations shorter than the necessary theoretical time, from classical electromagnetics, for that energy absorption.

Finally, since the initial conditions of the laser-induced plasma nucleus, and of its surroundings in the flow, determines the subsequent behavior of the supersonic combustion process (Negishi et al., 2003; Negishi et al., 2006; Brieschenck, 2011), it is possible to optimize those initial conditions, increasing the supersonic combustion efficiency, if we deal with the process by which the initial plasma nuclei arises in the flow, by considering that a higher density of photons in the focal point at a given time determines a higher probability of formation of free radicals in the flow and that, the energetic states of these radicals are determined in a greater extent by the photon energy and not by the total energy of the pulse, in accordance with the quantum mechanisms proposed.

3. THEORICAL EFFICIENCY OF A LASER-IGNITED SUPERSONIC COMBUSTION IN SCRAMJETS

In order to find a mathematical relationship that helps us to understand quantitatively the efficiency of supersonic combustion as a function of those laser parameters discussed in Section 2, we must consider that the laser-flow interaction is also influenced by the fluid nature. Thus, we identified a number of potential flow parameters that may influence this interaction and thereby influence the laser-induced supersonic combustion efficiency (Negishi et al., 2003; Negishi et al., 2006; Brieschenck, 2011). A list of laser and flow parameters is shown in Tabs. 1 and 2, respectivley.

Table 1 - Laser parameters that can influence the supersonic combustion efficiency.

Parameters	Unit	Dimension [MLTθ]
Energy per pulse	E_p [Joule]	$M^1L^2T^{-2}$
Wavelength	λ [m]	L^1
Pulse duration	Δt_p [s]	T^1
Repetition rate	f_p [Hz]	T^{-1}

Table 2 - Fluid parameters that can influence the supersonic combustion efficiency.

Parameters	Unit	Dimension [MLTIθ]
Flow Enthalpy	h_f [Joule]	$M^1 L^2 T^{-2}$
Flow density	ρ_f [kg / m ³]	$M^1 L^{-3}$
Flow temperature	T_f [Kelvin]	θ^1
Flow thermal conductivity	k_f [kg.m.Kelvin / s ³]	$M^1 L^1 T^{-3} \theta^1$

Both tables show only the parameters that are subject to a feasible experimental measurement. Therefore, Eq. (1) is the preliminary functional relationship obtained from our initial investigations, through the application of the Vaschy-Buckingham π Theorem of dimensional analysis (Carneiro, 1993; Fox et al., 2006). This mathematical relationship represents somehow the scramjet laser-induced supersonic combustion efficiency (η_{cs}).

$$\eta_{cs} = \varphi\left(f_p\Delta t_p, \frac{h_f}{E_p}, \frac{k_f\Delta t_p\lambda}{T_f E_p}, \frac{\rho_f\lambda^5}{E_p\Delta t_p^2}\right) \quad (1)$$

In order to enable a further investigation of the laser-flow interaction mechanisms suggested at Section 2, Eq. (1) was obtained in terms of the laser parameters presented in Table 1. That was accomplish by choosing E_p, λ and Δt_p as repeating variables during the dimensional analysis.

The refinement of Eq. (1) still need to be done through experimental analyses in order to identify those Π groups that may be more convenient for the understanding and the control of the laser-induced supersonic combustion efficiency.

4. LASER ENERGY TRANSMISSION MECHANISMS

We conducted a preliminary study on the advantages, disadvantages and feasibility of the concepts of direct and indirect modes of transmission of the laser beam from the radiation source to the scramjet engine combustor. As illustrated in Fig. 3 and the direct mode of transmission concept is based on the radiation source close to the burner and use of lens systems for conducting the laser beam. This concept is advantageous because it enables a greater preservation of the characteristics of the beam during transmission. Additionally, its layout is simple, with a relatively low number of

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components, which provides a lower risk of failure than the indirect mode and facilitates the design, construction and maintenance of a transmission mechanism. Nevertheless, as illustrated in Fig. 4, the indirect mode of transmission concept is based on the source distant from the combustor and the use of optical fibers for the beam transmission. This mode of transmission is advantageous because the laser source could theoretically be installed in any location of the aerospace vehicle. Therefore, the radiation source could be installed in a position distant from the scramjet combustor chamber, which would leave it less susceptible to extreme conditions present next to the chamber, such as high temperatures, high pressures and high vibrational charges.

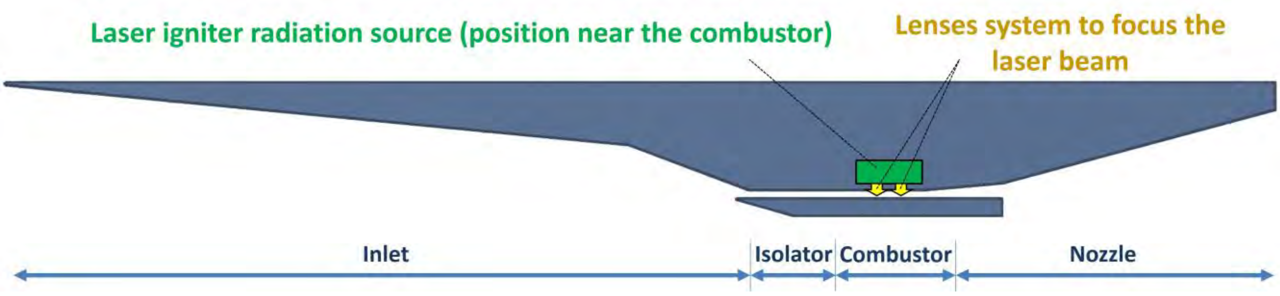

Figure 3. Concept of the 14-X scramjet equipped with a direct transmission laser igniter (Adapted from 14-X layout provided by IEAv courtesy).

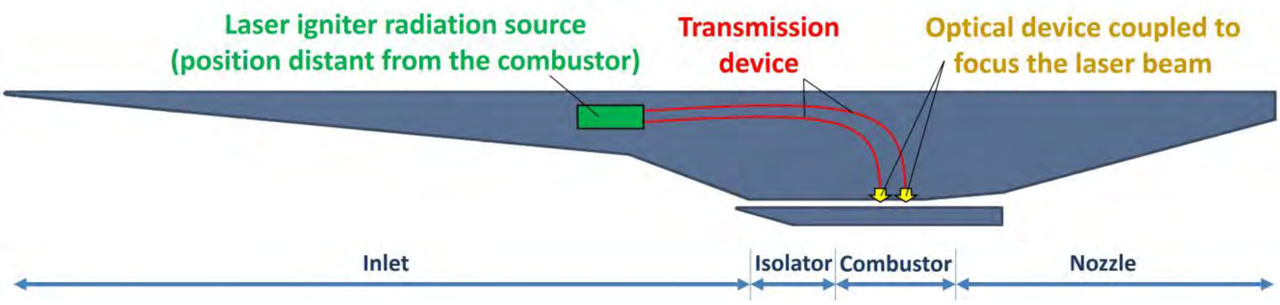

Figure 4. Concept of the 14-X scramjet equipped with an indirect transmission laser igniter (Adapted from 14-X layout provided by IEAv courtesy).

In these studies, we conducted a literature review in order to confirm the existence of fiber optic technologies capable of supporting the high-energy laser radiation transmission needed for a laser igniter with indirect transmission mode. A few examples are: Swiderski et al. (2004), Washburn et al. (2004), Chang et al. (2008), Dupriez (2007), Farrow et al. (2006), Röser et al. (2007), Schmidt et al. (2007), Wright (2009), Ortaç et al. (2007), Wan et al. (2013), Buckley et al.(2005) and Buckley et al.(2007).

5. PRELIMINARY SURVEY OF COMMERCIAL LASERS FOR EXPERIMENTAL TESTS

In order to select a source of laser radiation appropriate to better assist the supersonic combustion, after literature review of Silfvast (2004) we compared different laser sources in Figs. 4 to 6 where we grouped a large number of wavelengths, repetition rates, pulse energies and pulse durations, which can be obtained for each one of the existing laser technologies surveyed.

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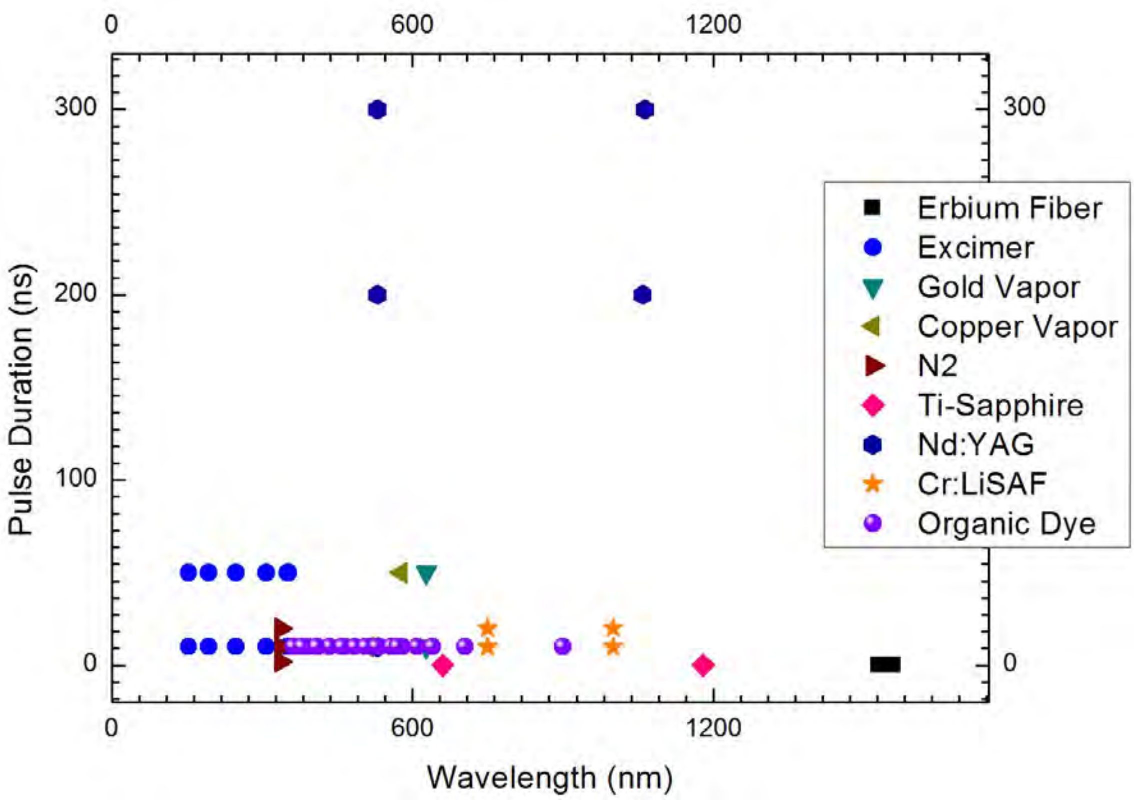

Figure 4. Pulse duration against wavelength of various technologies.

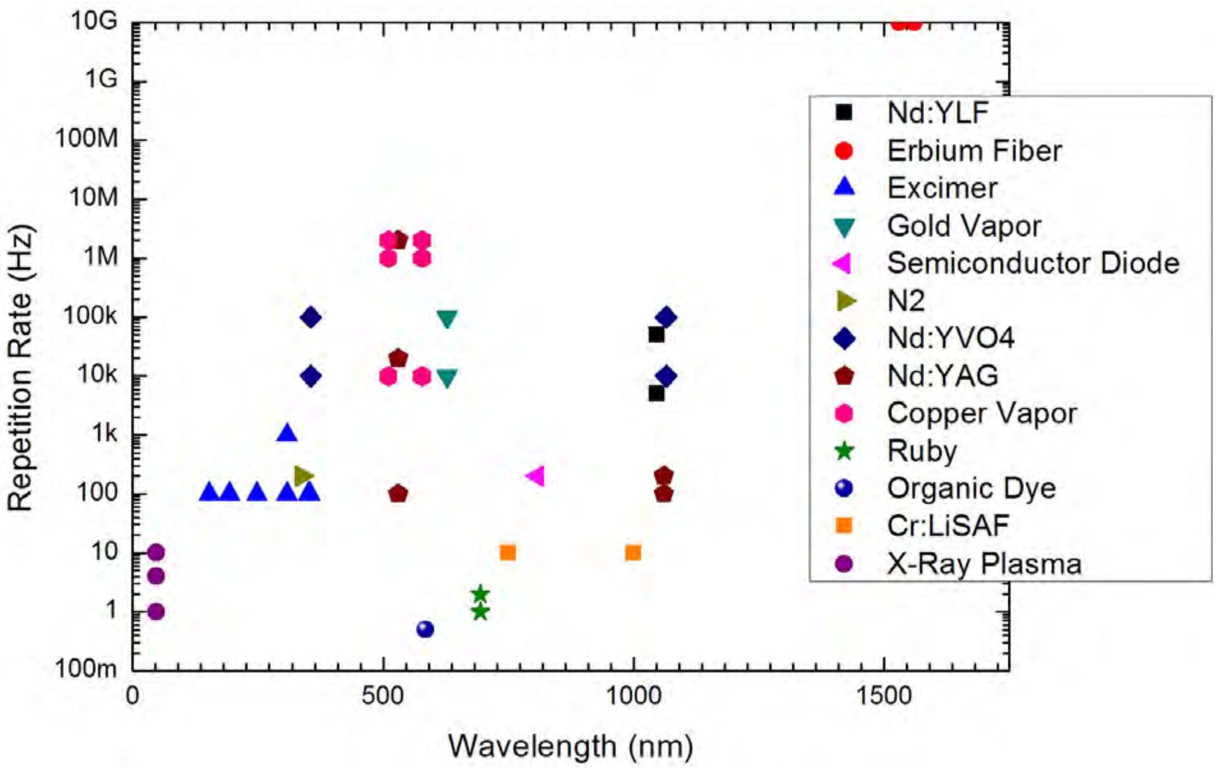

Figure 5. Repetition rate against wavelength of various technologies

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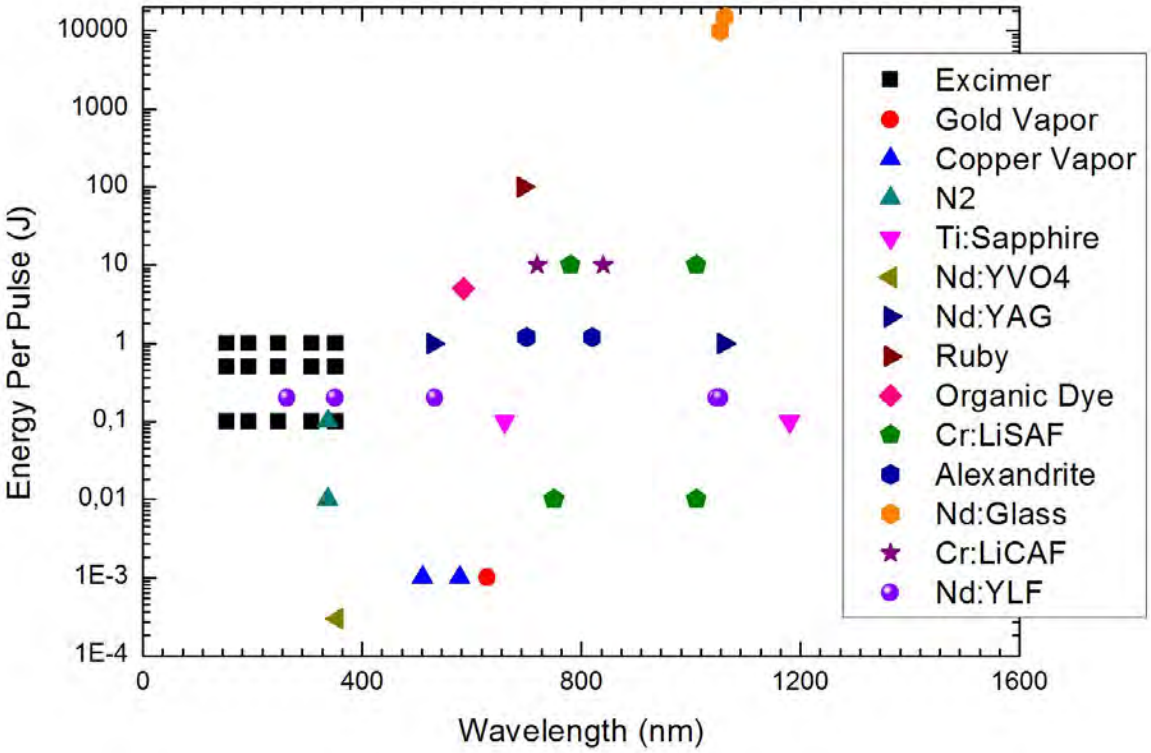

Figure 6. Energy per pulse against wavelength of various technologies

In addition to this, through our access to the 14-X aerothermodynamic and propulsion system characteristics, enabled by the UFABC collaboration with IEAv, we determined preliminary conditions, shown in Tabs. 3 and 4, required for a suitable on-board laser igniter for the scramjet in question.

Table 3: Table of preliminary conditions for suitable on-board laser igniter of the14-X

Wavelength [nm]	$700 < \lambda < 1200$
Energy per pulse [J]	$0{,}01 < E_p < 1$
Average Power [W]	$5 < P_m < 2500$
Pulse Duration [ns]	$\Delta t_p < 50$
Repetition Rate [kHz]	$f_p > 0{,}5$
Laser Beam Quality	$M^2 < 2.0$

Table 4: Table of aerospace requirements for an on-board laser igniter of the 14-X.

Long operation lifetime
Low energy consumption
Lightweight
Compact Size
Low cost

Thus, we have identified three laser technologies with specifications near to ideal for use as radiation sources of a laser igniter for the 14-X Aerospacecraft scramjet engine (see Tab. 5). A refinement of these results is being done through the detailed study of their aerospace requirements mentioned in Tab. 4.

Table 5 – Comparative between the characteristics of Nd:YAG, Nd:YLF and Titanium-Sapphire laser and ideal conditions for a 14-X laser igniter radiation source.

Laser Technology	Wavelength [nm]	Energy per pulse [J]	Pulse Duration [ns]	Repetition Rate [kHz]
Necessary conditions for a 14-X laser igniter radiation source	$700 < \lambda < 1200$	$0.01 < E_p < 1$	$\Delta t_p < 50$	$f_p > 0,5$
Nd:YAG	1060	1	200-300	10
Nd:YLF	1047	0.2	--	5 - 50
Titanium-Saphire	1180	0.1	0.1	--

We understand that these solid-state laser technologies identified have good application in ground experiments of laser-induced supersonic combustion due to their abundance as commercial technologies. However, we believe that if it is possible to use fiber laser technology, as REDFLs (short for rare earth-doped fiber lasers) (Agrawal, 2008; Agrawal, 2013; Goure, 2002), we strongly recommend this technology, rather than those identified, for the design of an on-board igniter due to their advantages relating to the aerospace requirements considered in Table 4.

Currently we have initiated contact with companies specialized in lasers, for further study of the feasibility of the acquisition, by the Brazilian Air Force and/or by the UFABC, of an appropriate technology available.

6. CONCLUSIONS

The 14-X Hypersonic Aerospacecraft brazilian project was conceived and it is currently in development at Institute for Advanced Studies (IEAv). However, the combustion in a scramjet engine is supersonic and this leads to the technical challenge of injecting, mixing, igniting and finally burning the fuel efficiently during the very short resident time of both air and fuel into the engine. Since electrical igniters have some limitations as regards to energy transfer to the air-fuel mixture into scramjets engines and consequently to the maintenance of the complete supersonic combustion in its burner, Universidade Federal do ABC (UFABC) has initiated the development of an on-board laser igniter for the 14-X scramjet engine which may overcome the current technological difficulties.

This first stage of our research was marked predominantly by studies and research to develop a mathematical relationship that would help us to understand quantitatively the overall efficiency of the laser-induced supersonic combustion as a function of the following laser parameters: wavelength, repetition rate, pulse duration and pulse energy.

As preliminary results of these studies and investigations, we obtained possible physical interpretations of the influence of the laser parameters on supersonic combustion mechanism. The shorter the pulse duration, the higher the pulse power, due to the increase of the photons temporal density on the pulse. That results in a possible higher temperature reached by the mixture (above the ignition temperature required to start the combustion process) and in a greater probability of forming free radicals, which works as "catalyzers" for the combustion. In addition, the laser repetition rate influence the constant maintenance of the required amount of radicals formed after laser ignition in the combustor in order to enable stable and complete supersonic combustion. Furthermore, the repetition rate is a key parameter to enable the manipulation of the virtual geometry of a scramjet combustor. Lastly, the laser wavelength influence the energy transfer process and the consequent generation of reactive radicals on the flow.

In addition to this, we obtained, by dimensional analysis, a preliminary functional relationship for supersonic combustion efficiency. The flow parameters considered on that relationship will be reviewed and refined by selecting those more convenient for the understanding and control of the laser-induced supersonic combustion efficiency.

Finally, studies have been initiated on the feasibility of using fiber technology to conduct the high-energy laser beam into the engine combustor and on the use of fiber lasers technology as possible radiation sources of the laser igniter. Not only, we identify Nd:YAG, Nd:YLF and Titanium-Saphire lasers as potential technologies for ground tests as radiation sources and a survey of commercial technologies for use in future experiments have been started.

Although there is still much work to do, the prospects of developing an on-board laser igniter device for the 14-X Hypersonic Aerospacecraft scramjet engine looks good.

7. FUTURE WORKS

In future works of this research we aims to investigate the mathematical relationship developed, and seek, via CFD simulations and experiments in Hypersonic Shock Tunnel, confirmation or not of the influence of the parameters considered on the efficiency of the laser-induced supersonic combustion mechanism. In addition, we intend to advance the research of the feasibility of using optical fiber technology as laser radiation conductor and fiber laser as the igniter radiation source.

Concomitantly, we intend to refine the selection of the best technologies to be applied as sources of radiation in an on-board laser igniter to be used in 14-X. It is also intended to determine the best mechanisms of transmission and focusing of the laser radiation in the flow of this aerospacecraft scramjet engine.

The following procedure will be adapt the technologies and mechanisms chosen to design and validate the on-board laser igniter. For this purpose, we intend to perform a work of mechanical, optical and electric design of the igniter. Besides, we also intend to perform additional simulations of laser ignition with the 14-X scramjet engine geometry, via CFD. This research will support the construction of the on-board laser igniter device for future tests in Hypersonic Shock Tunnel of laser-induced supersonic combustion to be conducted at IEAv and possible installation on the 14-X Hypersonic Aerospacecraft.

8. ACKNOWLEDGEMENTS

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