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New developments on ChemCam laser transmitter and potential applications for other planetology programs

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New Developments on ChemCam Laser Transmitter and Potential Applications for other Planetology Programs

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Abstract— ChemCam is a LIBS Instrument mounted on the MSL 2011 NASA mission. The laser transmitter of this Instrument has been developed by the French society Thales Optronique (former Thales Laser) with a strong technical support from CNES. The paper will first rapidly present the performance of this laser and will then describe the post-ChemCam developments realized on and around this laser for new planetology programs.

Keywords : Laser; ChemCam; LIBS; MSL; Planetology; Lidar

I. INTRODUCTION

Development of the ChemCam laser transmitter was concluded by the delivery of a flight model in December 07 and a spare model in December 08. MSL Curiosity Rover, with ChemCam Instrument onboard, will now soon arrive on Mars (landing scheduled in August). We will first remind the main optical performances of this 1.06 μm solid-state pulsed laser, in particular its large operational temperature range without any active cooling. This characteristic had been made possible by the choice of Nd:KGW as gain material. Nd:KGW indeed exhibits a very wide absorption linewidth, making it mostly insensitive to the thermal shift of the pumping wavelength.

Due to the good adaptation of this laser to the severe environments encountered on planetology programs, it has been decided to pursue technical developments for new potential applications. The first post-ChemCam target application of the laser was the study of Venus rocks, in the frame of a JPL proposal called SAGE. For this kind of program, the laser would be used as a luminous source for LIBS and Raman experiments on Venus surface. LIBS experiment requires more laser energy on Venus than on Mars because of the higher density of the atmosphere. A technical study has then been done at Thales Optronique to increase the energy of the laser. An emission up to 60 mJ at 1.06 μm has been demonstrated. For Raman experiments, a visible

emission is more efficient than an IR emission. A frequency conversion stage is then necessary. A non-linear crystal (KTP) had then been added at the output of the laser and the efficiency of the conversion from 1067nm to 533nm had been tested on a large temperature range. A thermal study has also been done to evaluate a technical solution to adapt the laser for the hot environments of Venus (while the environments expected for ChemCam on Mars are mainly cold). The main results of these adaptations for Venus exploration will be presented.

The second target application is the development of a Doppler Lidar to study Martian wind velocities. Study of the winds would be indeed very useful to the understanding of the Martian climate. For this application, work has been done with the French lab LATMOS. Our laser is highly spectrally multimode, but thanks to an adapted and patented detection system, it would be nevertheless possible to use it as a transmitter for a Doppler Lidar system. The detection system is a 4 channels Mach-Zehnder interferometer whose optical path difference precisely matches the Free Spectral Range of the laser. The main advantage of such a system is to avoid the development of a complex monomode laser (frequency injection, stabilization,...). A laboratory model of the complete Lidar system has been designed, developed and tested by LATMOS. Architecture of the Lidar and results of atmospheric tests will be presented.

A new study, potentially useful both for spectroscopy and Lidar programs, aims to increase the duty cycle of the laser. Another study will test the possibility to replace the traditional active Q-Switch system by a passive Q-Switch system in the space solid-state lasers.

II. CHEMCAM LASER

A. ChemCam Instrument

ChemCam instrument is composed of two parts: "Mast Unit" (MU) and "Body Unit" (BU). MU corresponds to the

French part of the project, and BU to the American part. MU contains the laser source, a Cassegrain telescope, a camera, and the electronics driving the laser. The laser emits a short and energetic pulse. The laser beam is then focused by the telescope to increase the optical intensity of the pulse. The goal is to obtain, on the Martian rock, an irradiance superior to 1GW/cm². Thanks to this high optical intensity, a luminous plasma is created on the rock. The light coming from this plasma is then collected by the telescope and sent to BU via optical fibers. Then, the grating spectrometers situated inside BU analyze the light (on the range 240-800 nm). Thanks to the spectra recorded by BU, we obtain information on the chemical composition of the rock.

Fig.1 gives a view of the MSL Rover (named “Curiosity” by NASA) and shows the position of ChemCam instrument :

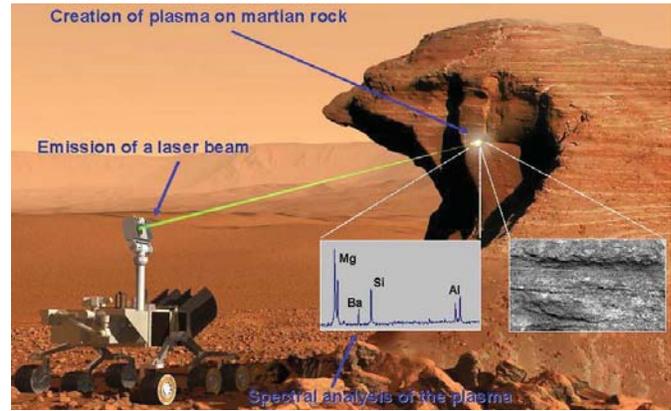


Fig.2. General principle of ChemCam

ChemCam Mast Unit (IRAP)

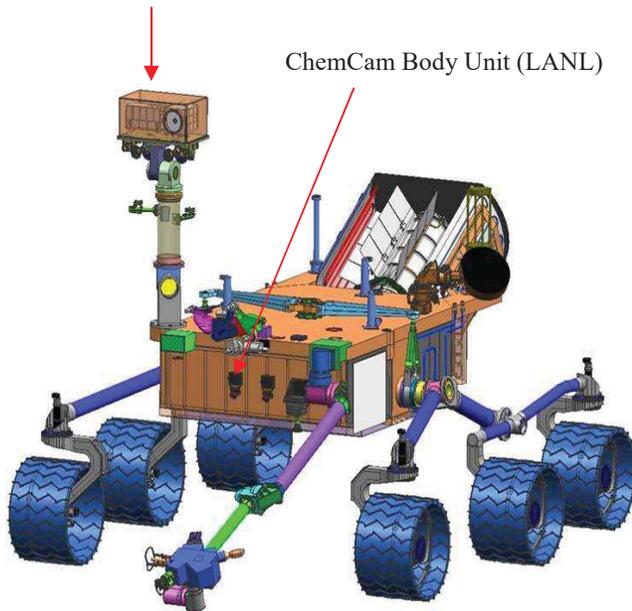


Fig.1. View of MSL Rover and situation of ChemCam (copyright NASA)

MU has been developed by IRAP and CNES. BU has been developed by the US lab Los Alamos National Laboratory.

Fig.2 shows the general principle of ChemCam:

We can see on Fig.3 a view of MU :

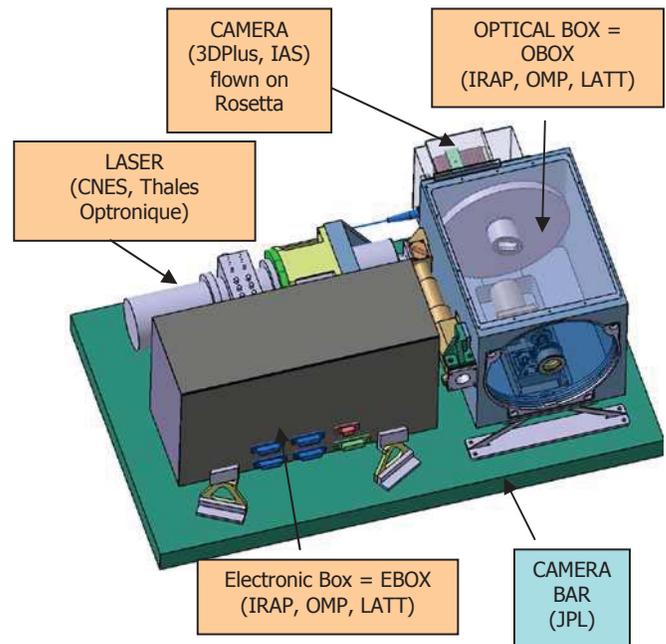


Fig.3. ChemCam Mast Unit

The same telescope is used for the emission of the laser beam and for the reception of the plasma light. Fig.3 gives information on the suppliers of the different components of MU. IRAP has the responsibility of the whole MU.

B. Laser Requirements

All the following text will now be dedicated to the laser transmitter.

During the mission, the laser will have to run in very harsh environmental conditions. In particular, thermal environments are very severe: the laser will be exposed to daily thermal cycles on the range -40/+35°C. It must work within the

-30/+30°C range, with nominal performance on the -20/+20°C range (performance can be slightly degraded outside).

The mechanical environments of the mission are also constraining. The laser has been then mechanically qualified: shocks up to 800 g and random vibrations up to 22 grms have been passed.

The optical beam emitted by the laser source must be sufficiently short and energetic to obtain a high optical density on the rock, in order to create a luminous plasma. The main optical specifications of the laser are then, on the range -20/+20°C:

- energy of the pulses > 24mJ,
- an optimum superior to 30mJ,
- Pulse duration < 8ns,
- $M^2 < 3$.

C. Laser Design

Due to the mission constraints, compactness and weight were also two driving factors of the mechanical design, having the necessary stiffness at the same time. The dimensions of the laser are about: diameter of 55 mm, length of 220 mm; the weight is about 550 g.

The laser runs in the nanosecond regime, at a nominal repetition rate of 10Hz. The number of shots expected on Mars during the mission is 3 millions minimum, during two years (1 Martian year). The laser will run in burst mode (100 shots @ 10 Hz, break of at least 5 minutes between two bursts).

The architecture of the laser is based on an oscillator followed by two slab amplifiers. The oscillator is designed to provide a high beam quality. The output energy is enhanced in the amplifiers while keeping good spatial beam characteristics.

The design is made to insure a good mechanical and thermal stability under the severe conditions to which the laser will be exposed during launching, cruise, descent, landing and operation on Mars.

Indeed the laser has to survive and operate in a wide range of temperature, and during a large number of thermal cycles on Mars (around 670 minimum). It also has to survive high vibration levels during rover tests and launch, and high pyroshock levels during descent and landing.

Oscillator is based on a Nd : KGW rod longitudinally pumped by a 700 W diode stack. The very wide spectral acceptance of the Nd : KGW rod provides very small absorption variations over wide temperature ranges. This allows both the pumping diode and the rod to be only conductively cooled and to run on the large temperature

ranges expected on Mars. There is no active cooling of the laser. Oscillator is Q-switched with a RTP pockels cell to produce the nanosecond pulses needed for LIBS. The laser cavity is linear, closed on one side by the rod and on the other side by the output coupler. Reflectivity of the output coupler is 60%. A polarizer, a wave-plate and a pockels cell constitute the Q-switch system of the cavity. The oscillator provides an output energy of about 10mJ with a pulse duration < 8 ns and a beam quality factor (M^2) < 3.

Amplifiers are based on transversally diode pumped Nd : KGW slabs. Two identical amplifiers increase the energy at the oscillator output. Each amplifier is pumped by a 700W stack (identical to the 700 W stack of the oscillator). An energy higher than 30 mJ is obtained at the laser output, with a M^2 factor < 3.

Fig.4 presents the optical design of the laser.

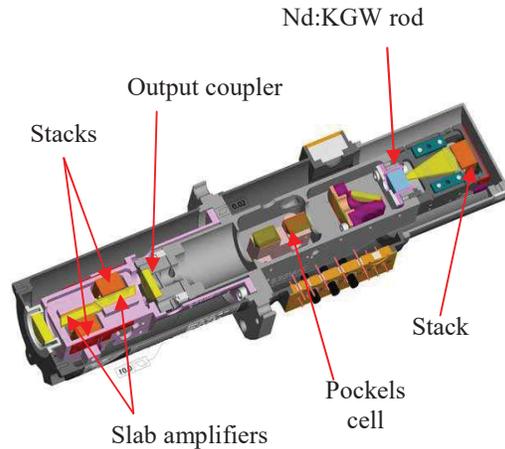


Fig.4. Optical design of the laser

To protect the optical components from the harsh environments of Mars, the laser is hermetically sealed by Titanium covers. This hermetic package is filled with dry air to mitigate the risk of Laser Induced Contamination on the optics and on the stacks. In complement, a getter is placed inside the cavity to adsorb pollutants which could be emitted by the organic elements (in particular by the glues).

Fig 5. shows an external view of the laser, with its hermetic covers. These covers are laser soldered on the mechanical structure of the laser.

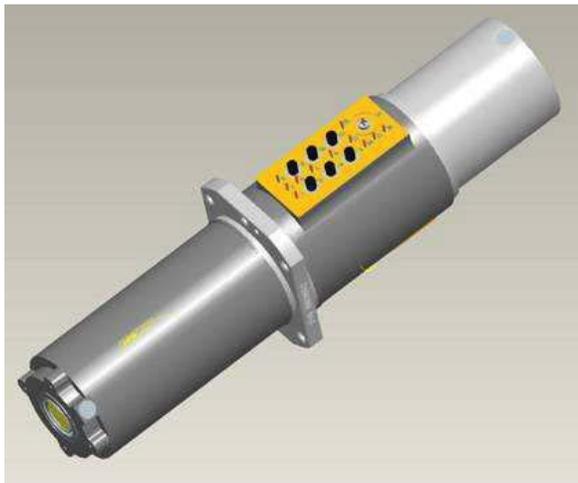


Fig.5. External view of ChemCam laser

D. Validation Strategy

Before the delivery of the Flight Model, four models of the laser have been developed in order to carefully define and validate its design. All the models of the laser have been deeply tested, in particular to measure their performance under thermal constraints. These tests showed that the laser pulses reach the optical specifications on the range -20/+20°C. The laser has also been qualified in space environments: thermal and mechanical tests.

After the Flight Model, a Spare Model has been developed. In total, six models of the laser have been then developed by Thales Optronique.

Qualification tests have also been done at components level, on stacks, optics, glues, getters. For each critical component, radiation, thermal and mechanical tests have been done (including long term thermal cycling representing the daily Martian thermal cycles: up to 1000 cycles have been done for most of the validation tests).

The expected lifetime for the critical components has also been evaluated by test, taking the specific operational conditions of CHEMCAM on MSL into account (including the long term thermal cycling). For example, the pumping diode stacks have been tested on a long time : lifetime tests (up to 28 millions of shots) combined with operational and non-operational thermal cycles.

E. Laser Performance

Fig. 6 describes the main results obtained on the Flight Model (energy and pulse duration versus temperature).

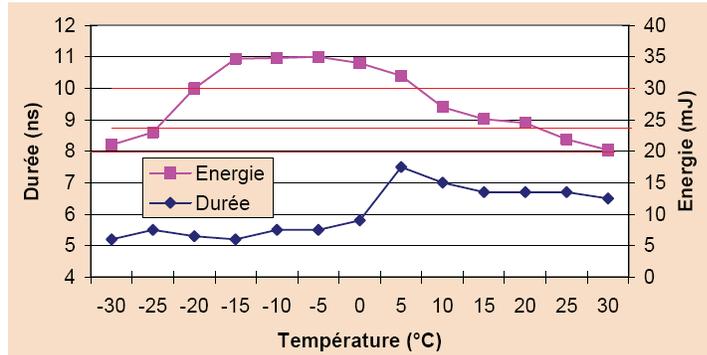


Fig. 6. Energy and pulse duration versus temperature

We can see on this figure that the optical characteristics of the Flight Model are within the specifications on the whole range -20/+20°C. Performance of the laser is still interesting outside of this range, up to +30°C and down to -30°C. The Spare Model presents similar performance.

III. NEW DEVELOPMENTS AND POTENTIAL APPLICATIONS

A. Martian Wind Measurement

After the development of the laser for ChemCam program, CNES has funded a new study to characterize the spectral properties of the laser beam. This study has been done by the French laboratory LATMOS. The goal was to determine if ChemCam laser could also be used for Doppler Lidar applications. As the laser is well adapted to the harsh environments of Mars, the target application would be an in-situ wind measurement on Mars, in the frame of an eventual future mission. This characterization showed that the use of the laser for this kind of applications is possible. The laser emits approximately 70 longitudinal modes on a spectral range of 70 GHz. The Free Spectral Range (FSR) is around 1 GHz. Fig.7 shows a part of the spectrum of the laser emission :

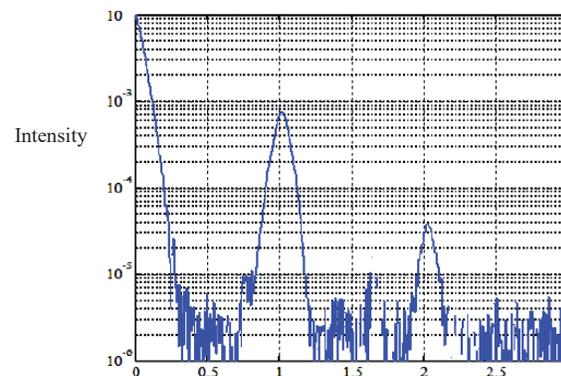


Fig. 7. Part of the spectrum of the laser emission

Using an appropriate direct detection system, LATMOS showed that it could be possible to use this laser as a luminous source for a Doppler Lidar despite its high spectral multimodality. Most of the existing Doppler Lidars require a

longitudinally monomode laser source. The lidar we aim to build would work with the ChemCam multimode laser, much simpler to develop than a monomode laser requiring the injection of a stable frequency and a servo-loop for stabilization of the laser on this frequency.

The detection system developed by the LATMOS is a Mach-Zehnder interferometer. A sketch of its optical design is shown on Fig.8:

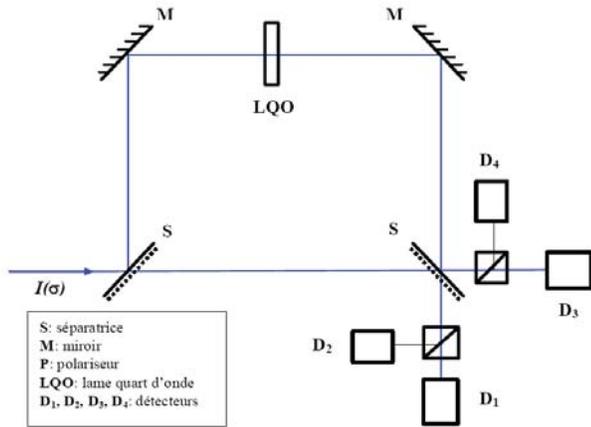


Fig.8 : detection system of the Doppler Lidar (Mach-Zehnder interferometer)

We measure the optical fluxes S_1 , S_2 , S_3 and S_4 respectively on the photodiodes D_1 , D_2 , D_3 and D_4 . The signals detected by the four photodiodes are given by the system of equations (1):

$$\begin{aligned} S_1 &= I_0 A_1 \left(1 + M_1 M_a \sin \frac{2\pi\delta\nu}{c} \right) \\ S_2 &= I_0 A_2 \left(1 + M_2 M_a \cos \frac{2\pi\delta\nu}{c} \right) \\ S_3 &= I_0 A_3 \left(1 - M_3 M_a \sin \frac{2\pi\delta\nu}{c} \right) \\ S_4 &= I_0 A_4 \left(1 - M_4 M_a \cos \frac{2\pi\delta\nu}{c} \right) \end{aligned} \quad (1)$$

where M_i is the contrast of the interferences of channel i , M_a is a contrast coefficient common to the 4 channels (coming from the atmospheric scattering), I_0 is the luminous intensity at the input of the interferometer, δ is the Optical Path Difference (OPD) of the interferometer and ν is the optical frequency of the input signal. The unknown of this system is ν , containing the information on the atmospheric radial velocity.

From this system (1), we can create q_1 and q_2 :

$$\begin{aligned} q_1 &= \left(\frac{S_1}{A_1} - \frac{S_3}{A_3} \right) \frac{1}{M_1 + M_3} \\ q_2 &= \left(\frac{S_2}{A_2} - \frac{S_4}{A_4} \right) \frac{1}{M_2 + M_4} \end{aligned} \quad (2)$$

We then define the Q complex as :

$$Q = q_2 + iq_1 \quad (3)$$

We can then obtain ν by equation (4) :

$$\nu = \frac{c}{2\pi\delta} \arg(Q) \quad (4)$$

Radial atmospheric wind velocity (V_R) is then obtained by Doppler equation (5) :

$$V_R = \lambda_0 c (\nu - \nu_0) / 2 \quad (5)$$

where λ_0 and ν_0 are respectively the wavelength and the optical frequency emitted by the laser and c is the light velocity.

Fig.9 shows the S_1 , S_2 , S_3 and S_4 signals detected by the four photodiodes with respect to the optical frequency ν of the input signal (coming from the backscattering of the laser signal by the atmosphere) :

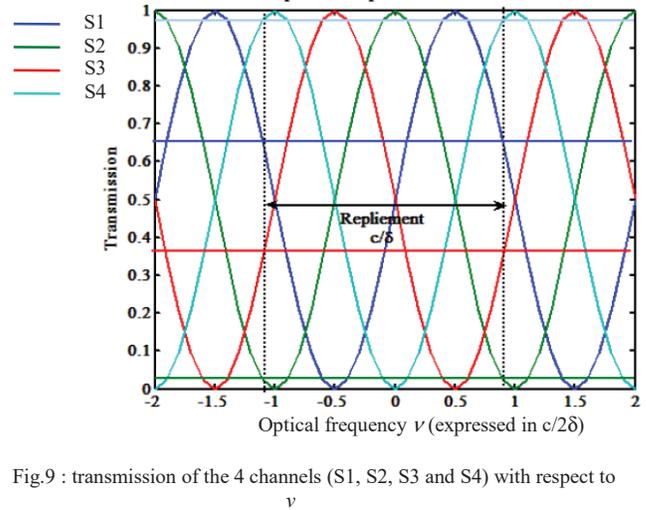


Fig.9 : transmission of the 4 channels (S_1 , S_2 , S_3 and S_4) with respect to ν

We can see on Fig.9 that two optical frequencies spaced by the quantity c/δ experiment exactly the same optical transmissions (same S_1 , S_2 , S_3 and S_4 signals). Thanks to this folding of the signals, the equations (1) to (5) will then be exactly the same for these two frequencies. Then, if the Free Spectral Range of the emission laser equals c/δ , all its longitudinal modes will give the same system of equations and

there will not be any degradation of the wind velocity measurement despite the multimodality of the laser. Equation (6) gives then the interferometer Optical Path Difference δ to choose to have a good Doppler measurement with the highly multimode ChemCam laser:

$$\delta = 2L \quad (6)$$

where L is the length of the laser cavity.

The design of a detection system adapted to a longitudinally multimode laser has been the subject of a CNES/LATMOS patent.

LATMOS has then developed a complete Doppler Lidar laboratory model, integrating a prototype of ChemCam laser and the detection system described above. Fig. 10 shows a sketch of this model :

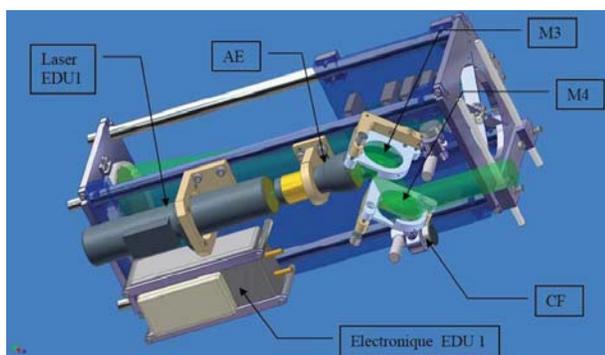


Fig. 10 : View of the Doppler Lidar laboratory model developed at LATMOS

Once the Lidar developed and calibrated, atmospheric tests had been done at the Observatoire de Haute-Provence (OHP, French astronomy observatory).

Fig. 11 shows one of the measures realized at OHP. The vertical wind, expected to be null, has been measured.

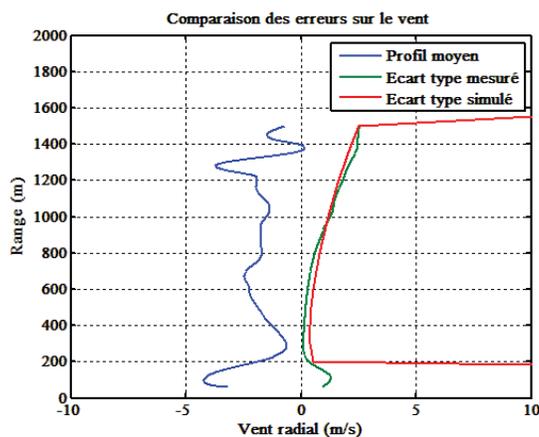


Fig. 11 : measurement of vertical wind

The root mean square of the measurement is compliant to the simulations. But the wind velocity measurement shows a bias (the measurement is not centred on 0m/s). It has been identified that this bias comes from temporal instabilities of the calibration parameters. A new study is now in progress to reduce these instabilities. The measurements at OHP have nevertheless demonstrated the validity of the concept of this Lidar integrating the ChemCam laser and its capacity to make backscattering and Doppler measurements.

B. LIBS/Raman spectroscopy on Venus

Another new potential application for the laser would be a planetology program on Venus. This has been studied in the frame of a JPL proposal called SAGE (finally not selected by NASA). SAGE stands for Surface and Atmosphere Geochemical Explorer. The goal of the proposed mission was to study the composition of the rocks and of the atmosphere of Venus. This study would have in particular been done by a LIBS/Raman instrument. This instrument would have integrated a laser based on ChemCam heritage. Some adaptations are nevertheless required for a mission on Venus.

Due to its higher density (compared to Mars), Venus atmosphere is indeed less favorable to the creation and expansion of a LIBS plasma. The requirements on the laser are therefore more stringent : the energy per pulse should attain 60 mJ. Moreover, as we want to add Raman spectroscopy and as Raman spectroscopy is more efficient in the visible range than in the Infra-Red range, we must add a second channel integrating a frequency doubling stage for an optical conversion from 1067 nm to 533 nm. Finally, as Venus environments are hotter than Mars environments, thermal adaptations are needed.

Technical developments to increase the energy level at 1067nm and to double the frequency of the laser had then been done by Thales Optronique in the frame of a CNES R&T study. The creation of 60mJ pulses at 1067nm has been obtained thanks to the addition of a complementary amplifier at the output of ChemCam laser. This supplementary amplifier consists in a 30mm slab pumped by a 3000W dual stack, as shown in Fig. 12 :

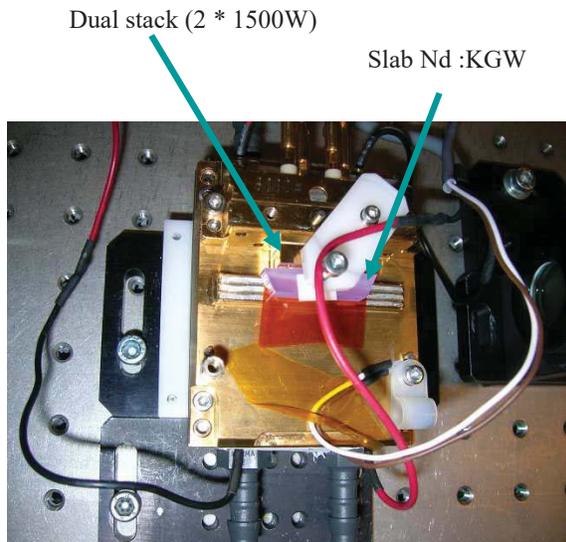


Fig. 12: design of the additional amplifier for SAGE

Fig. 13 shows the optical performance obtained at the output of this amplifier with an incident laser pulse of 26 mJ :

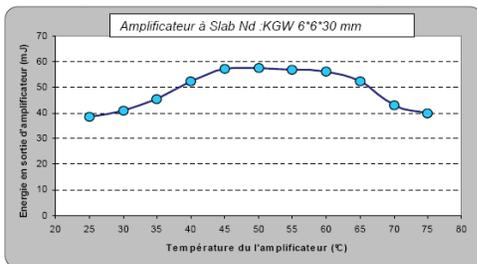


Fig. 13 : energy level at the output of the additional amplifier for an incident pulse of 26mJ

Considering an incident pulse directly coming from ChemCam laser output with performance described on Fig. 6, the energy at the output of the amplifier could easily reach the 60mJ required for a LIBS mission on Venus, at least in the central region of the operating temperature range.

The frequency doubling study for the shift of the laser emission towards the visible region has led to the integration of a KTP crystal at the output of the amplified laser. Tests had been done in several configurations : with 1 or 2 KTP crystals and with different crystal lengths. The energy obtained at 533 nm for a 58 mJ injection at 1067nm is shown on Fig. 14:

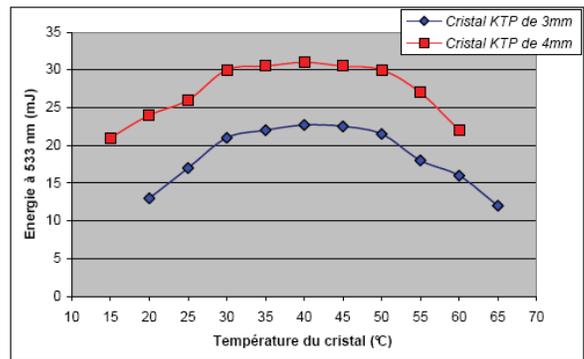


Fig. 14 a : energy at 533nm with one KTP crystal (length of 3mm and 4mm) for an input energy of 58mJ at 1067nm

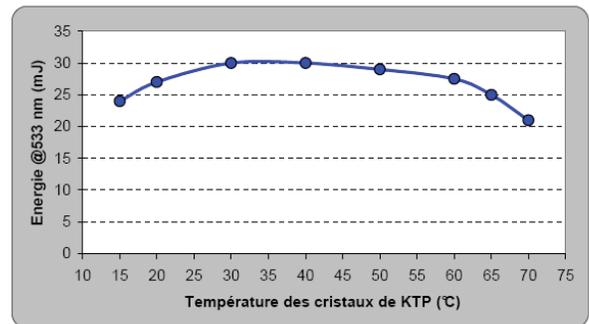


Fig. 14 b : energy at 533nm with two KTP crystals (length of 4 mm) for an input energy of 58mJ at 1067nm

Results show an energy at 533 nm superior to 25 mJ on a large temperature range (amplitude of 50°C). We can note a good conversion efficiency : for example, with the two crystals configuration, the conversion yielding exceeds 50% on a 30°C amplitude temperature range. These are promising results for the non-thermally regulated laser envisaged for this kind of mission.

As the thermal environments are strongly hotter on Venus than on Mars, a thermal study has been done with BTS Industrie to limit the increase of temperature of the laser after its arrival on Venus ground. The goal is to keep the laser temperature in the operating range during a few hours (which is the maximum lifetime of an in-situ Venus mission due to the harsh environments). The studied dispositive consists in the integration of a Phase Change Material (PCM) around the laser. This PCM material is paraffin packaged in a flexible aluminized bag around the laser. Thermal analysis by computing shows that the temperature increase after five hours on Venus ground is reduced of 25°C by the integration of this PCM material around the laser structure.

C. *Increase of the duty cycle of ChemCam laser*

The main limitation of ChemCam laser is its relatively low duty cycle. The laser is indeed designed to work in a burst mode. The number of shots per burst and the frequency repetition are limited by thermal issues inside the Nd:KGW crystal under pumping. This limitation mainly comes from the thermal characteristics of Nd:KGW, associated with the absence of any thermal regulation. This crystal has indeed a quite low thermal conduction.

The nominal operation mode of ChemCam laser is then the next: 100 shots at a repetition frequency of 10 Hz. After this 10 seconds burst, a five minutes break is needed to make the temperature inside the laser crystal decrease and then to limit the impact of thermal effects (thermal lens, astigmatism,...) on the laser beam.

The study aims to reduce these thermal issues in the crystal and to achieve a "continuous" mode (without any break) at a frequency repetition of 10 or 20 Hz. To achieve this new working mode, the Nd:KGW crystal is replaced by a more thermally conductive Nd:YAG crystal.

The drawback of this replacement would be a reduced operating temperature range of the laser, as Nd:YAG has a narrower absorption bandwidth than Nd:KGW. When the temperature of the pumping stacks will shift (because of the change of environmental conditions and/or because of the thermal duty caused by the operation of the stack itself), the pumping wavelength will shift and come off the absorption band of the crystal, driving to a catastrophic loss of performance of the laser.

To prevent this effect and keep a large operational temperature range despite this change of crystal, a multiwavelength pumping stack will be used. The principle of this multiwavelength stack is the next : the stack is composed by several bars, each emitting at a different wavelength so that in any moment the wavelength of at least one bar matches with the absorption band of Nd:YAG.

This multiwavelength pumping stack enables then to compensate the narrower absorption bandwidth of Nd:YAG. We can then take benefit from the good properties of the Nd:YAG crystal without losing the main advantage of ChemCam laser : its large operating temperature range without any thermal regulation. This design change also presents the convenience of the use of a reliable crystal developed by many commercial suppliers in Europe.

First tests on this new design will be done in the next few months by Thales Optronique.

D. *Passive Q-Switch system*

Space pulsed lasers generally integrates an active Q-Switch system for the generation of the pulses. These systems are more often electro-optics modules presenting the advantages of good performance and high reliability. Nevertheless, they require to be driven by a specific high voltage supply.

To suppress this high voltage signal, the possibility to use a passive Q-Switch system will be studied. These passive systems are based on the use of saturable absorbers. Cr⁴⁺ doped materials (for example Cr⁴⁺:YAG) are often used for this application.

Functional tests on this technology will be done in the next few months. The goal is to demonstrate an efficient passive Q-switch of the laser and evaluate the performance of the pulsed laser developed : temporal accuracy of the switching, temporal shape of the pulses, frequency repetition of the laser,... Tests at elementary level are also scheduled on the saturable absorber: laser damage threshold, saturable absorption threshold, optical transmission,... This study will give first indications on the advantages and drawbacks of a passive Q-Switch system for a space solid-state laser for LIBS or lidar applications.