International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas

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International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 10563, 105633T · © 2014 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2304072

SODERN DEVELOPMENT OF A HIGH LIDT LASER BEAM EXPANDER FOR ATLID

Abstract

Sodern has been contracted for the development of the laser beam expander used on the lidar of the ATLID instrument developed by Airbus Defence & Space France and Germany (Formerly ASTRIUM) embarked on the EathCARE satellite, element of the ESA (European Space Agency) Living Planet Programme.

The ATLID emission beam expander (E-BEX) has two functions: one is to reduce the divergence of the laser in order to achieve a high spatial resolution and the other is to enlarge the laser beam to reduce the power density and thus reduce Laser Induced Contamination (LIC) and Laser Induced Damage Threshold (LIDT) effects on the outer surface exposed to vacuum.

This paper exposes the design drivers of the beam expander which are: having optical components withstanding very high laser fluence at a wavelength of 355nm and exhibiting a very low depolarization ratio., hermetically sealing the cavity with metallic gaskets in order to keep the pressure constant so that beam collimation is not affected, choosing housing material compatible with both hermiticity requirements and thermal control.

To obtain a high spatial resolution on Earth, ATLID requires a means for controlling beam collimation. This is ensured by an active thermal control on the beam expander in order to change its Wavefront Error (WFE) by a few tens of nanometers.

Keywords: organic-free, LIDT, LIC, laser, lidar, optical mounting, lens, window, thermal control, beam expander

I. INTRODUCTION

The design drivers for developing a beam expander for a 355nm lidar are the high laser fluence which the optical elements must withstand, the spatial resolution needed to have a good signal to noise ratio and maintaining the beam spot on Earth within the detector's field of view. ATLID adds as an additional requirement a very depolarization of the input beam in order to separate Rayleigh and Mie diffusion signals.

ATLID operating at 355nm imposes several very strong constraints on optical elements and their assembly. First, they must have a very high Laser Damage Threshold (LIDT) in order to withstand the laser fluence without damage (described in section B). Second, no organic contamination is allowed within the beam expander, which implies that the assemblies are organic-free (described in section D). And third, in order to alleviate the effects of any Laser Induced Contamination (LIC), the optics must be in a gas-filled hermetic cavity.

Spatial resolution of the lidar beam is assured by using a nominal spot much smaller than the detector field of view and using a thermal control in order to change the E-BEX collimation by change of optics index of refraction and structural material.

Maintaining the beam spot within the detector field of view is assured by the Beam Steering Assembly (BSA), also contracted to Sodern. The BSA is a mirror driven by piezo-electric actuator and is used to compensate Line-Of-Sight drifts resulting from inhomogeneous temperature variations within the satellite.

A low depolarization means that there is no birefringence in the optical components. This is assured by selection of a low-birefringence material and by taking care that mechanical stress in the materials add up to a lower depolarization than required.

Figure 1 shows the different elements of the E-BEX which are described in the article.

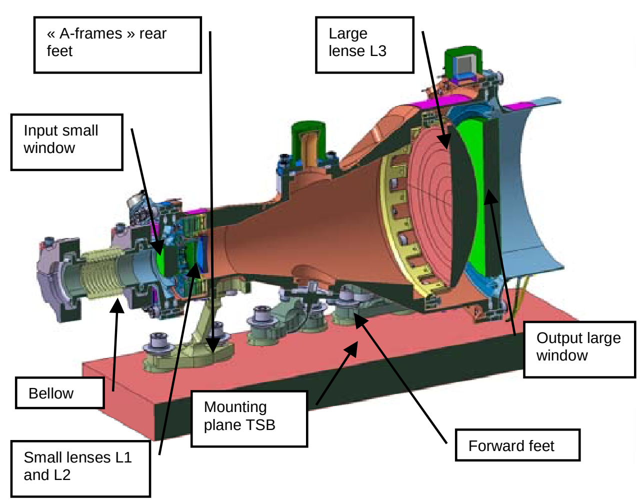

Fig. 1: A cut-away view of the E-BEX

II. BEAM EXPANDER DEVELOPMENT

A Coating and laser damage

To face laser induced damage, E-BEX optical coating design has been optimized at each manufacturing step and validated with regard to this issue.

E-BEX lens material was chosen for its resistance to high power laser beam at a wavelength of 355nm. Best quantitate, not only because of its high laser resistance (refer to §C depolarization) was corning 7980 Fused silica with the lowest inclusion/impurity class 0 and homogeneity grade A (for polarization purpose).
A specific polishing process has been developed at Sodern to improve high power laser resistance by optimizing micro-roughness and minimizing surface defect density. EBEX optical parts show micro-roughness bellow 0.5nm. A specific automatic control has also been implemented to validate large optics cosmetic qualiy.

A specific cleaning process with multi-bath and specific ultrasonic cleaning was developed with Swissoptic and tested successfully with regard to LIDT and windows tightness.

E-BEX coating process based on HfO_2 / SiO_2 stacks, was challenging for two main reasons, first because of high LIDT requirement in UV range, second because of coating temperature limitation to prevent damaging E-BEX windows soldered at low temperature.
Coating development has been subcontracted to Swissoptic.
In the frame of this contract, three LIDT test campaigns, in accordance with ISO 21254-2 standard, have been run.

First measurement campaign subcontracted both to DLR and LZH, for reliability purpose, have shown good results with a mean LIDT better than 5J/cm² for 10 000 shots delivered buy a 355nm laser with 20ns pulse duration and 100Hz repetition rate. These results were good enough to guaranty E-BEX optics to withstand ATLID Laser Pulse.

After last process improvement, final tests realized at LZH with a 355nm, 7ns pulse laser at 100Hz (refer to Table 1), highlights for 10 000shots, LIDT of 7J/cm².
Using Equation 1, this result can be converted to determine damage threshold in ATLID working conditions, that is to say laser pulse duration of 20ns.

$$LIDT_{20ns} = LIDT_{7ns} \cdot \left(20/7\right)^{0.35} \qquad (1)$$

In this representative condition LIDT is estimated at 10/cm² which fully cover ATLID LIDT requirement.

Company / Institute	LZH
Test facilities	
Environment	Laboratory
Test medium	Air
Laser source	INNOLAS Spitlight
	DPSS 250 with injection seeding
Standard	ISO 21254-2
Laser beam	
Wavelength	355nm
Pulse duration FWHM	7ns
Repetition rate	100 Hz
Spot diameter at 1/e²	0,351 mm (+/-0.010)

Tab. 1. LZH LIDT test configuration

Typical damage morphologies of two samples from the same batch are shown on Figure 2.

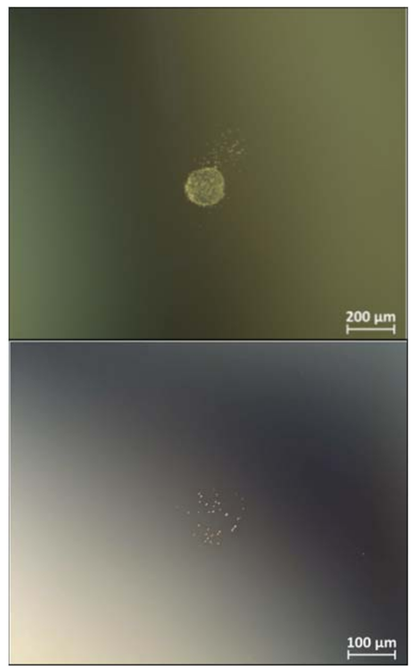

Fig. 2: Typical damage morphologies on E-BEX coating samples: Image (a) correspond to defects appeared after 2 shots at 26.3J/cm² on sample 1C28 and Image (b) correspond to defects appeared after 2 shots at 26.3J/cm² at 14.3J/cm² on sample 1C30.

B. Contamination and organic-free assembly

E-BEX mechanical design has been highly driven by laser power resistance issues in order to alleviate optical surface damage through laser beam absorption due to accumulation of contaminants. As a consequence the following solutions have been implemented:

- Organic free technologies (soldered windows, lens barrels, no glue, metallic gasket),
- Leak-tight pressurized cavity filled with high purity gas mixture,
- Optimized lens design and manufacturing process (polishing, cleaning, coating, control).

This paragraph gives an overview of EBEX definition, tests and performances with regards to LIC and LIDT.

Optical components of E-BEX are subjected to a very high laser fluence beam at a wavelength of 355 nm. At this high energy level and this wavelength, Laser Induced Contamination (LIC) effect can occur in the presence of molecular contamination and lead to severe optical damages.

Reducing the risk of LIC occurrence implies not only a very high Laser Induced Damage Threshold (LIDT) level on optical surfaces (above 3J/cm²), but E-BEX must also be pressurized with a gas mixture, which will oxidize contaminants on the optical surfaces.

The need to pressurize E-BEX requires keeping pressure constant as variation of pressure directly affects beam collimation. Variation of pressure will be below 1 mbar over 10 years, which means that E-BEX must be a hermetic cavity.

Besides, as organic compounds present the highest risk of LIC, organic-free design solutions have been implemented and applied to lenses assembly and Contamination and organic-free assembly windows assembly.

Therefore, Sodern has developed and space-qualified new optical mounting technologies in order to meet the requirements of handling a high-power ultra-violet pulsed laser beam.

The first organic-free mounting technology i to a high-stability lens assembly. It consists in holding lenses made of fused silica, with diameters up to Ø 130 mm, with titanium barrels without using standard methods such as gluing or elastomeric gaskets. The stability required is a decentring between the barrel and the lens below 7µm.

The technology developed is based on a double-clamping system with flexible metallic parts. One part insures the radial pre-load and the second one the axial pre-load. The double-clamping provides sufficient pre-load forces to withstand accelerations and flexures to withstand a large temperature range.

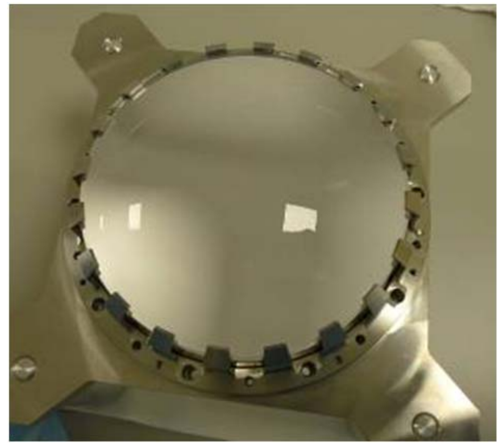

Fig. 3: L3 Lens assembly

The clamping parts have been designed by analytical analysis and optimized by a finite element model analysis with regards to many aspects:

- Materials CTE (mismatch of 8.5 10^{-6}m/m°C between Fused Silica and Titanium)
- Mass (structure parts<280g for a lens mass of 440g)
- Stresses in Fused Silica lens (<16MPa according to a Weibull failure probability of 0.5%)
- Rigidity (1st resonance frequency>2000Hz)
- Space environments such as temperature range [-40°C; + 50°C], random vibrations (70g peak 3σ)
- Manufacturing and integration (tolerances for pre-load implementation)

Otherwise, stress-induced polarization effects are modelled with an in-house software.

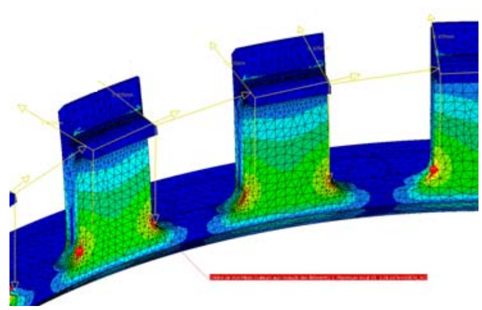

Fig. 4: FEM analysis - Thermo-elastic case

The manufacturing and integration processes have also been optimised to minimise stress concentration in lenses. Birefringence measured after integration close to the clamping has confirmed the level of stress predicted by our mechanical analysis.

This new mounting has been qualified with a fully representative model (QM). All space environments have been applied to this model:

- bake-out, +65° during 100h

- thermal cycling, 8 cycles [-40°C; + 50°C]
- random vibration, 37gRMS [20Hz; 2000Hz]
- quasi-static load, 35g at 100Hz

A very accurate metrology procedure was applied throughout the environment testing.
Final optical performance is a 5µm positioning stability, verified by a 3D machine measurement, and a polarisation contrast above 100:1 has been also verified by an in-house optical GSE (refer to paragraph C).

This mounting technology developed for the larger lens (L3) has been also adapted for the two others smaller lenses (L1 and L2).

C. Hermiticity and organic-free window assembly

The second organic-free mounting technology relates to leak-tight windows used to keep the inner volume of the beam expander under pressure during all the life time.

Sodern has thus adapted its soldered windows developed for the PHARAO (Projet d'Horloge Atomique à Refroidissement d'Atomes en Orbite – Cold Atoms Atomic Clock in Orbit) that will fly on-board the ISS (International Space Station) in 2016.
PHARAO leak tightness is lower than $4 \cdot 10^{-10}$ mbar.l/s in order to maintain pressure below 1.5×10^{-10} mbar while in orbit (the pressure around the ISS being 10^4 times higher).

E-BEX will be equipped with silica windows soldered on titanium flanges. The soldering material is an indium-based alloy that presents many advantages: low stress level put inside the window (i.e. low polarisation), very high leak tightness, low soldering temperature.
The adaptation for E-BEX consists in soldering larger windows up to Ø 120 mm while reducing the polarisation effect due to stress inputs and ensuring hermeticity in flight (launch and thermal environment) between materials having different CTE. Much attention has been paid to the design of the titanium flange, especially the elastic shape closed to the soldering interface.

Fig. 5: E-BEX large window

Currently E-BEX windows qualification is successful. Windows remain hermetic (< 5.10^{-10} mbar.l/s) after vibrations (random levels up to 40 gRMS) and thermal cycles (48 cycles [-40; + 50] °C). Polarisation remains also at a very low level (depolarisation ratio < 0.2 % on the whole surface as shown in Fig.8, which means that stress put inside the windows remain very low.

E-BEX hermeticity requirement combined with absence of organics implies the use of metallic gaskets. These gaskets must also withstand in-flight environment while keeping their hermetic performance. Pharao's heritage is again used as a fully qualified solution to meet this requirement.

At the end of assembly operations, E-BEX is hermetically sealed using a cold welding process. E-BEX is equipped with a copper tube brazed on a titanium flange. The copper tube is cold welded by pinching at high pressure. This kind of assembling is organic-free, extremely reliable and clean, and avoids the use of a heavy valve.

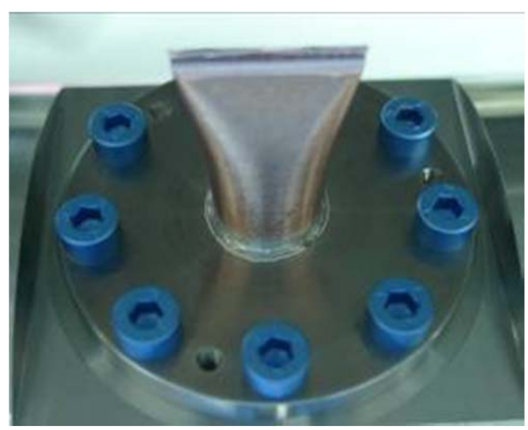

Fig. 6 : Copper pinch-off tube

In addition, to keep the optical path between the laser head and the beam expander free of contaminants, a metallic bellows permitting misalignment of both sub-systems was developed, space qualified and implemented on the beam expander.

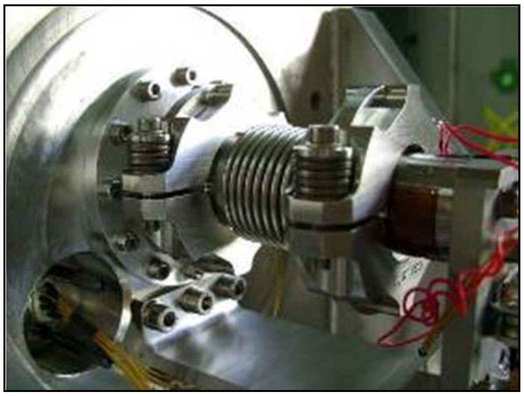

Fig. 7: Metallic bellows with its clamp on the vibration tool

D. Polarization

ATLID detection unit being polarization-sensitive, there is a strong constraint upon the optical system of the E-BEX which must not change the polarisation of the input beam. This means that the fused silica must be of a low-birefringence type and that the stresses in the optical elements must be low enough so that the level of birefringence keeps very low. This is antagonist with the need to maintain the lenses aligned without any organic material while withstanding launch accelerations. For the windows, an hermetic indium-lead soldering on a radial flexure was chosen. This induces some stress birefringence at the edge of the window (see figure 8) which is of very low effect on the laser Gaussian beam. For the lenses, soldering could not be used and the double-clamping technique described in part B is used. Some birefringence is generated close to the clamping pads but drops off very rapidly towards the centre of the lens and is also of very low effect on the Gaussian beam..

Individual measurements on components show that E-BEX will meet its requirement of having a depolarisation ratio under 0,5%.

Fig 8 shows depolarization mapping of a window in two orientations. It can be noticed that the EBEX depolarization requirement will be met whatever the orientation of this window.

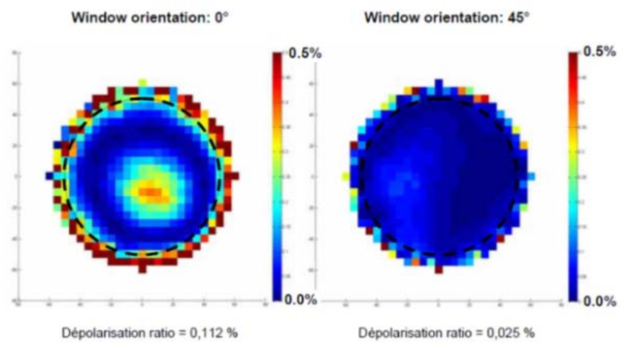

Fig. 8: Window depolarization mapping

E. Spatial resolution

Spatial resolution of the emission beam is important to obtain a high signal-to-noise ratio in the detection unit. As indicated in [ref 1], the detection field of view is 75µrad so that sun-emitted UV light diffused by Earth's atmosphere and clouds does not reach the detector. Also indicated in [ref 1] the emission beam must have a full divergence under 45µrad.

Considering a Gaussian beam with 99% of energy in 45µrad, it means that the laser beam full divergence at $1/e^2$ is 30µrad. Aberrations will introduce a wavefront error (WFE) which will enlarge the beam divergence. They mainly come from optical components fabrication tolerances and small misalignments during assembly and vibration qualification tests.

Defocusing mainly comes from temperature variations of the close environment inside the satellite. As it orbits the Earth, its inner temperature will change, introducing changes of the input beam collimation and of the beam expander optics and mechanical structure. As this change of thermal environment during satellite life-time may induce thermal gradients in optical components of the lidar, the output wavefront may change and beam divergence will increase.

To counter this effect, the -EBEX is equipped with a thermal control which can correct the output wavefront at a rate of 25nm/°C. To achieve this level of control, thermo-optical modelling of the optical elements and of the structural material must be done in order to place heaters at appropriate locations and to obtain the most stable configuration possible with regards to changing environment conditions.

As described in section II.A, in order to withstand a high fluence, the optics are made of fused silica. To alleviate LIC effects, the E-BEX features a gas-filled hermitic cavity closed by windows with a titanium flange. The materials choice is thus driven by wavelength, laser pulse energy and hermiticity requirements.

Some insight into the thermal behaviour of the E-BEX can be drawn in a first order analysis. This enables to establish the following formula :

$$Defocus_{RMS}(nm) = -4{,}66\Delta T_{L1} + 31{,}2\,\Delta T_{L2} + 10{,}1\Delta T_{Body}$$

Where :

Defocus is the RMS variation of wavefront error due to defocus

ΔT_{L1} is the temperature variation of the first group of lenses
ΔT_{L2} is the temperature variation of the large lens
ΔT_{Body} is the temperature variation of EBEX body

Even if this formula needs be correction for thermal gradients, it shows that the effects of a temperature change are :

- 6,7 times stronger on the large lens L2 than on L1. This is also the ratio of the focal lengths.
- 3 times less important on the body than on the large lens L2.

The conclusion is that the thermal control must be optimized near L2 and that it is where the temperature reference point must be placed. After thermo-optical modelling of the EBEX and the environment, it was shown that thermal leaks to the environment and through the interfaces on both extremities of E-BEX required that two thermal controls must be implemented near L1 and near L2. Figure 9 shows the E-BEX with its heaters and an additional heater for the decontamination mode to heat the output windows and keep contaminants from condensing on the outer surface of the output window.

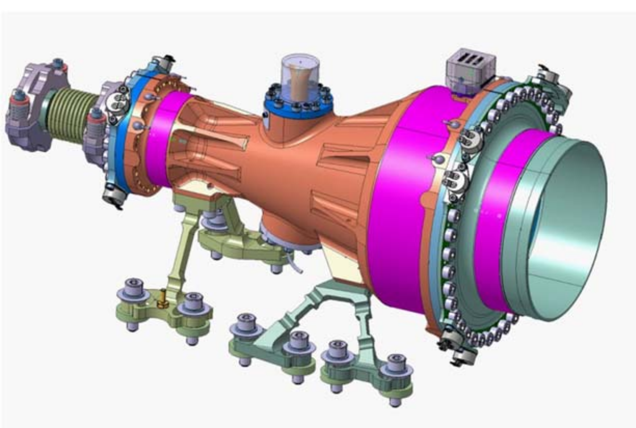

Fig. 9: Location of E-BEX heaters

G. OGSE

Testing the E-BEX in its thermal environment has required the development of a specific Optical Ground Support Equipment (OGSE). It features transmission and depolarization and wavefront measurements. The OGSE is equipped which a cryostat and two water circuits in order to simulate the thermal environments EBEX will encounter during its mission. It can thus be used to measure defocus, wavefront error and line-of–sight variations with changing environment conditions.

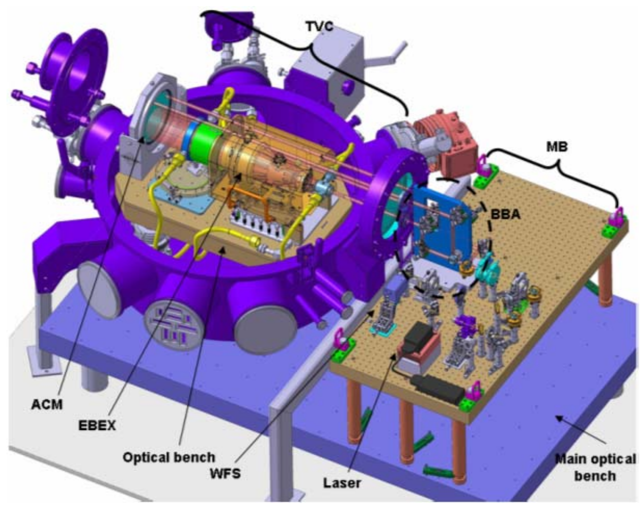

Fig. 10: E-BEX in its testing environment

III. CONCLUSION

The development issues of a thermally-control beam expander for a space-borne lidar have been described. Two points have required all our attention : the development and testing of the processes with have led to obtaining high resistance to laser damage and the development of organic-free technologies which are able to withstand the launch vibration environment and the thermal variations in the satellite;

Critical sub-assemblies have been successfully tested and next steps are the integration of the E-BEX and its test campaign. Following this, it will be delivered to Airbus Defence and Space for integration in the ATLID instrument.

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