D2.4: 813 nm laser systems

Project acronym: AQuRA
Project full title: Advanced Quantum Clock for Real-World Applications
Grant agreement no.: 101080166

Due Date:	Month 24
Delivery:	Month 24
Lead Partner:	EXAIL
Editors:	EXAIL
Reviewer:	CNRS
Dissemination Level:	Public
Status:	Final
Approved:	Yes
Version:	V2.0

This project has received funding from the *European Union's Horizon Innovative Actions programme* under grant agreement No 101080166 (AQuRA project).
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DOCUMENT INFO

Date and version number	Author	Comments
V1.0, 17/06/2024	Ineke Brouwer (PM)	*Template document*
V1.1, 15/11/2024	Yves-Vincent BARDIN (EXAIL)	*First draft*
V1.2, 25/11/2024	Pierre Eberschweiler, Jérome Lodewyck (CNRS)	*Review*
V2.0, 26/11/2024	Yves-Vincent BARDIN (EXAIL)	*Revised document based on internal review by P. Eberschweiler & J. Lodewyck (CNRS)* *Final draft for submission*

GLOSSARY

CW	Continuous wave
SHG	Second Harmonic Generation
DFG	Difference Frequency Generation
iMOB	Micro-Optics Assemblies
ECDL	External-Cavity Diode Laser
ASE	Amplified Spontaneous Emission
OSNR	Optical Signal to Noise Ratio
DFB	Distributed feedback laser

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Executive summary

1 List of contributors

Name	Organisation	Role(s)
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2 Introduction

2.1 Exail role within consortium

Exail role within consortium is to develop a compact and robust optical lattice laser for a strontium optical lattice clock (lattice laser at 813 nm). Particularly, Exail will generate a 813nm laser system with an output power in the 1 W range and a linewidth of less than 50 kHz.

2.2 813 nm laser systems presentation

Because of the difficult access to the radiation necessary for quantum technology, a system based on a combination of fibered amplifiers and frequency conversion techniques is studied to achieve the 813 nm specific wavelength. We took part in developing an optical architecture similar to the scientific publication from William J. Eckner and all[1]. which present 1W at 810nm for Magic-Wavelength Trapping in Neutral-Atom Optical Clocks.

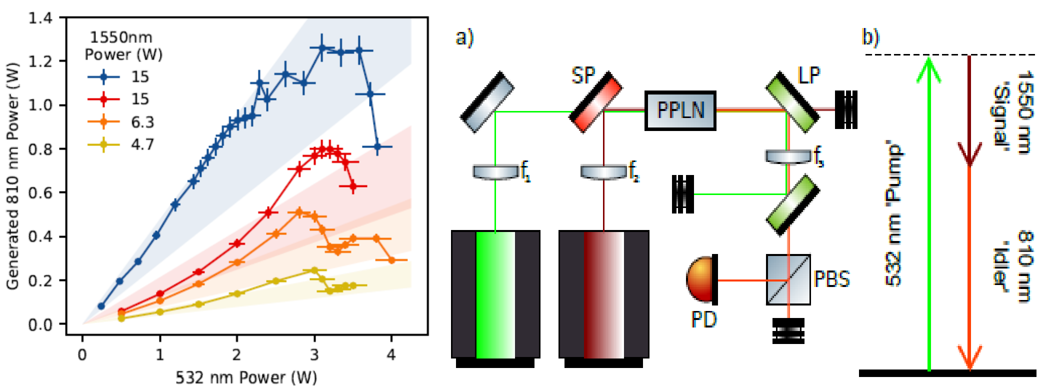

Figure 1: High-Power, Fiber-Laser-Based Source for Magic-Wavelength Trapping in Neutral-Atom Optical Clocks, William J. Eckner[1]

Our fiber optical architecture will include an ECDL for the Erbium seeder at 1542 nm in order to ensure that the laser can be locked easily and a DFB for Ytterbium seeder at 1065 nm. Besides, two optical amplifiers will increase the power of each seeder up to around 10-15W depending on efficiency frequency conversion. Our conversion module will be split into two parts. The first part will be allocated for the 532nm generation by Second Harmonic Generation (SHG) from the Ytterbium laser system. The second will generate the 813nm required by Difference Frequency Generation (DFG) from the Erbium laser system and the 532nm produced before.

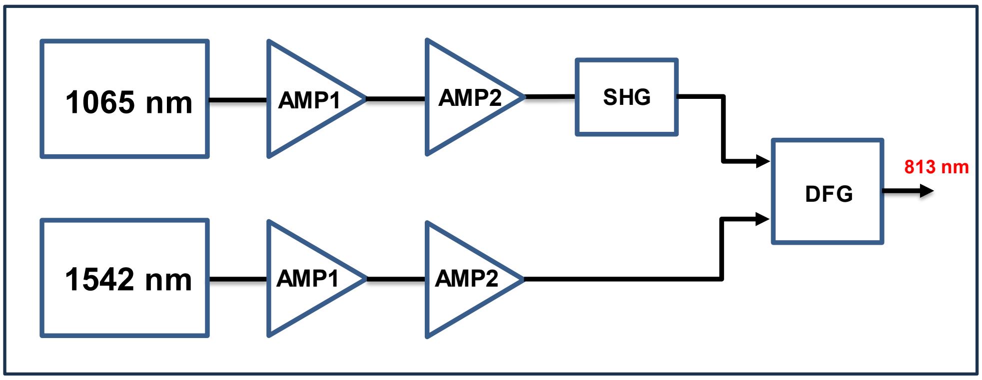

Figure 2: Optical laser architecture

The system is composed of five modules. One of them is dedicated for the power supply of the system.
The first module enables to drive each seeder with a dedicated low noise electronics and allows to control optical frequencies stability using current modulation. Two platforms for different optical amplifiers have been developed taking care of thermal effect. Besides, a high-power low noise driver electronic board and an embedded software has been realised in order to control all the system ensuring safety between the different amplification stages. The last module includes all Micro-Optics Assemblies (iMOB) able to reach non-linear optical frequency converters performances and customized laser output beam and ultra stable power splitting with adjustable ratio.

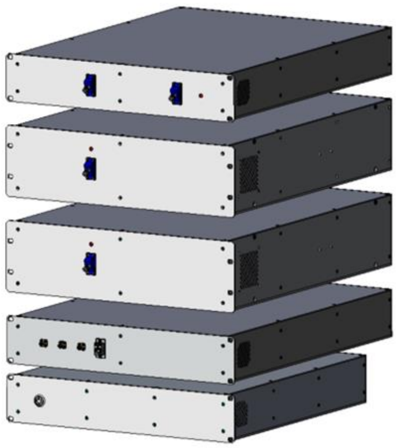

Figure 3: System laser architecture

The specifications and system performances required for 813 nm laser systems work package WP2 are summarized in the following table:

Parameters	Specifications	Comments
Wavelength	813.428 nm	
Frequency	368 554 725 MHz	
Seed wavelengths	1542.11 nm & 1065.06 nm	
813 nm Output Power	1W	
813 nm Output Tap Power	0.5 mW	Request Best effort >3mW
1542 nm Output Tap Power	0.1 mW	Request Best effort >3mW
1065 nm Output Tap Power	0.5 mW	Request Best effort >3mW
Output connector	FC/APC	
Fiber length	5m	
1542 nm Slow modulation Input	>500 MHz	
1542 nm Fast modulation Input	/ ±1.2 GHz	
1065 nm Fast modulation Input	±100 GHz	
Analog Input signal	2.5 V	(SMA connector)
Digital interface	USB 2.0/Ethernet	
Interlock input	Closed contact	
Power supply requirements	600 W/230 V	
Height units	16 HU	

Table 1: 813 nm laser systems specifications

3 Optical System Performances

3.1 1065nm Fiber Amplifier

Based on the scientific publication from William J. Eckner, an output power around 2W at 532 nm is required in order to achieve 813 nm performances.

For this reason, we have realized an optical system able to reach an output power greater than 10W at 1065 nm using a multistage amplifier and a single-frequency input signal (< 10 kHz linewidth). The single frequency signal at 1065 nm is preamplified to around 1W before being launched into the second power stage to reach 10W output power. The amplifier module has two optical outputs, the main output is injected into the conversion module, the other one is necessary to allow frequency-stabilization of the seeder.

The Figure 4 presents the power stability analysis over a few hours with power control. The output power is measured by a Thorlabs S350C and S146C power sensor and a sample rate of 2 kHz is used for this record. Each shot (point) is the average power over one second. The mean power over the full set of data is given. Besides, we calculate the standard deviation over each hour. The standard deviation given is the maximum std over an hour on our full set of data.

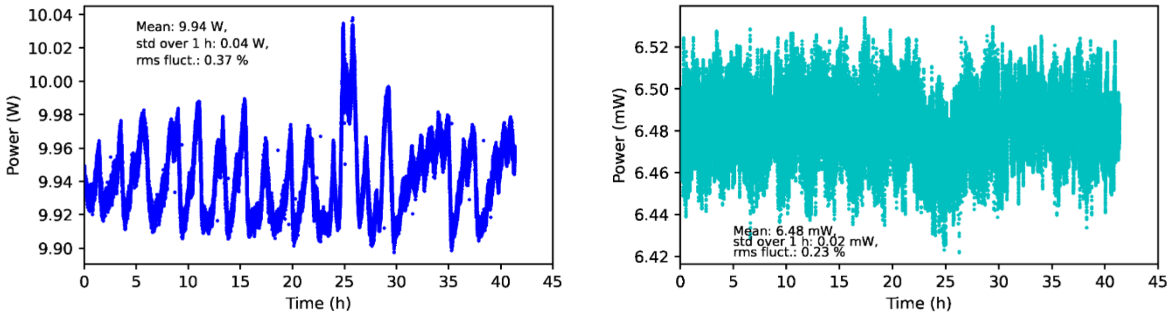

Figure 4: Long term stability analysis for 1065 nm amplifier and Tap output port

The laser output spectrum (Fig. 5) is measured by an AQ6375E optical spectrum analyser with a 0.1 nm spectral resolution. At a wavelength of 1065.08 nm, the measured OSNR at the signal wavelength is > 55 dB. The total ASE present in the laser output was estimated to be 0,01 % of output power based on the integrated spectra taken from 1000 – 1100 nm.

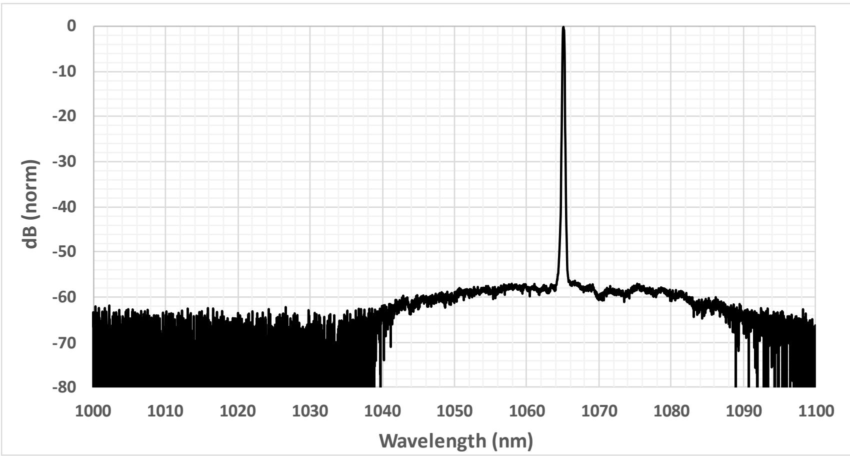

Figure 5: 1065 nm laser output spectrum

The conformity of the 1065 nm fiber laser system measurements is presented in the following table:

Parameters	Specifications	Performances	OK/KO	Comments
Seed wavelengths	1065.06 nm	1065.08 nm	OK	Adjustable wavelength by design
1065 nm Output Power	~10 W	10 W	OK	
1065 nm Output Tap Power	0.5 mW	> 5 mW	OK	Best effort >3mW
Tap Output connector	FC/APC	FC/APC	OK	
1065 nm Fast modulation Input	±100 GHz	-	OK BY DESIGN	
Analog Input signal	2.5 V	2.5 V	OK	(SMA connector)
Interlock input	Closed contact	Closed contact	OK	

Table 2: 1065 nm laser systems specifications and performances

3.2 1542nm Fiber Amplifier

Based on the scientific publication from William J. Eckner, an output power around 15W at 1550 nm is required in order to achieve 813 nm performances.

For this reason, we have realized an optical system able to reach an output power greater than 15W using a multistage amplifier and a single-frequency input signal (< 10 kHz linewidth) at 1542 nm. The single frequency signal at 1542 nm is preamplified to level around 1W before being launched in the second power stage to reach an output power between 10 and 15W. The amplifier module has two optical outputs, the main output is injected into the conversion module, the other one is necessary to allow frequency-stabilization of ECDL seeder using current modulation.

The Figure 6 presents the power stability analysis over a few hours. The output power is measured by a Thorlabs S350C and S146C power sensor and a sample rate of 2 kHz is used for this record. Each shot (point) is the average power over one second. The mean power over the full set of data is given. Besides, we calculate the standard deviation over each hour. The standard deviation given is the maximum std over an hour on our full set of data.

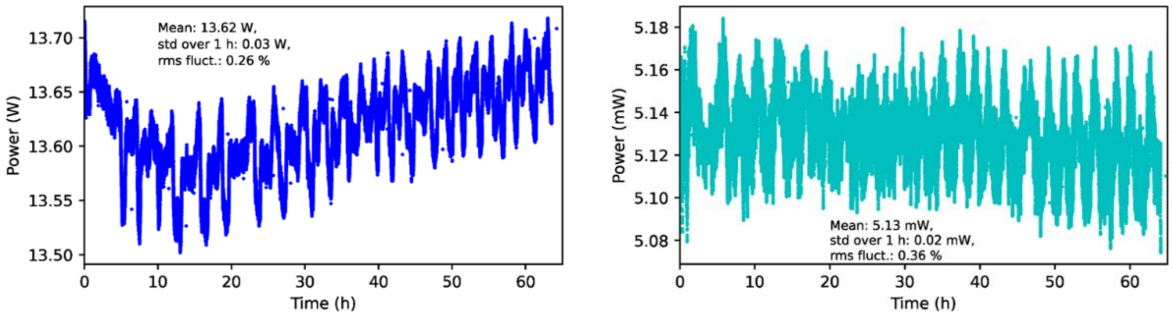

Figure 6: Long term stability analysis for 1542 nm amplifier and Tap output port

The laser output spectrum (Fig. 7) is measured by an AQ6375E optical spectrum analyser with a 0.1 nm spectral resolution. At a wavelength of 1542.14 nm, the measured OSNR at the signal wavelength is > 50 dB. The total ASE present in the laser output was estimated to be 0,28% of output power based on the integrated spectra taken from 1500 – 1600 nm (Fig. 3.2). The peak of the ASE output was seen at 1544 nm.

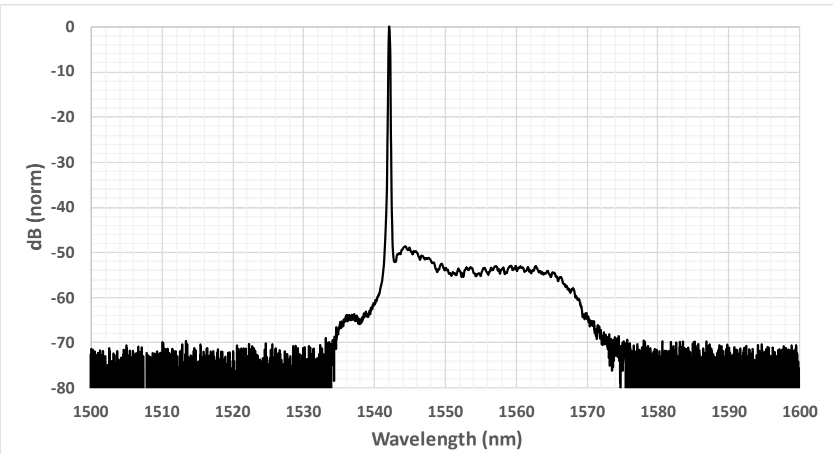

Figure 7: 1542 nm laser output spectrum

The conformity of the 1542 nm fiber laser system measurements is presented in the following table:

Parameters	Specifications	Performances	OK/KO	Comments
Seed wavelengths	1542.11 nm	1542.14 nm	OK	Adjustable wavelength by design
1542 nm Output Power	~15 W	14,3 W	OK	Power level sufficient
1542 nm Output Tap Power	0.1 mW	> 5 mW	OK	Best effort >3mW
Tap Output connector	FC/APC	FC/APC	OK	
1542 nm Slow modulation Input	>500 MHz	-	OK BY DESIGN	500 MHz
1542 nm Fast modulation Input	±1.2 GHz	-	OK BY DESIGN	±1GHz
Analog Input signal	2.5 V	2.5 V	OK	(SMA connector)
Interlock input	Closed contact	Closed contact	OK	

Table 3: 1542 nm laser systems specifications and performances

3.3 Frequency conversion module

As described in previous part, two frequency conversion modules are required for 813nm generation. On the one hand, we have generated 2.2 W of CW single-frequency radiation at 532 nm using a SHG from the CW single-frequency Ytterbium laser system at 1065 nm (Fig. 8). A linear efficiency without any saturation is maintained for the full fundamental power with a maximum of 25% at high power.

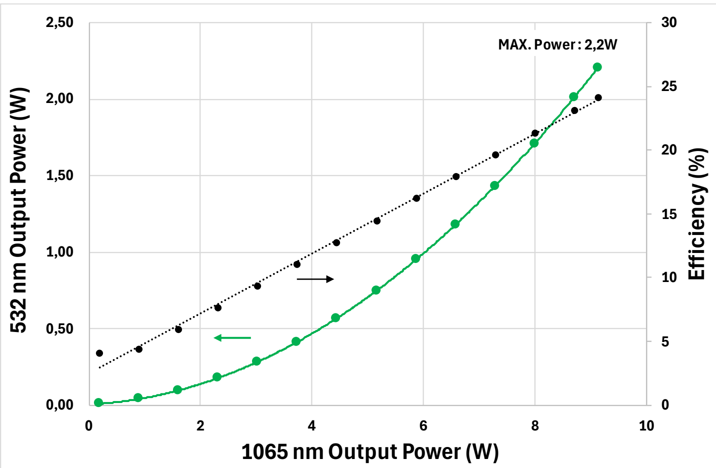

Figure 8: Non-linear frequency conversion performances for 532 nm generation

On the other hand, we have generated more than 650 mW in free space operation of CW single-frequency radiation at 813 nm using a DFG from the CW single-frequency radiation laser system at 532 nm and the CW single-frequency Erbium Ytterbium laser system at 1542 nm. The conversion efficiency increases up to 38% before observing saturation due to thermal effects in the crystal which comes from direct absorption of 532 nm pump light. After recombination in the output fibers and adjust the optimum setpoint temperature optimized at high power, we chose to work at constant green power at 532 nm injected into the second crystal and increase 1542 nm pump light. An output power of 560 mW was obtained at the main fiber output which corresponds to a coupling rate of 80%. Besides, 1.5 mW power at the tap fiber output is available to enable laser lock.

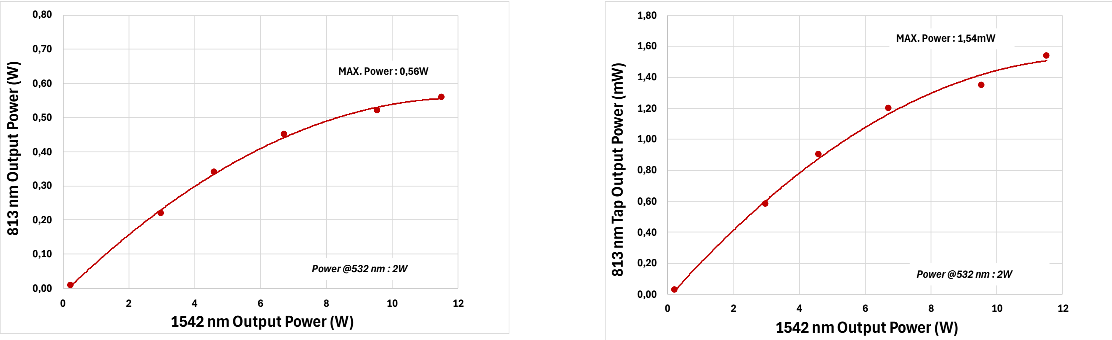

Figure 9: 813 nm system performances after fiber recombination

Output port (left) – Tap port (right)

The laser output spectrum (Fig. 10) is measured by an MS9740A optical spectrum analyser with a 0.2 nm spectral resolution. At a wavelength of 813.6 nm, the measured OSNR at the signal wavelength is > 50 dB. The total ASE present in the laser output was estimated to be 0,09% of output power based on the integrated spectra taken from 788 – 838 nm. In so far as this level of ASE could be too high to reach the clock accuracy, a filter will be implemented in the light distribution module.

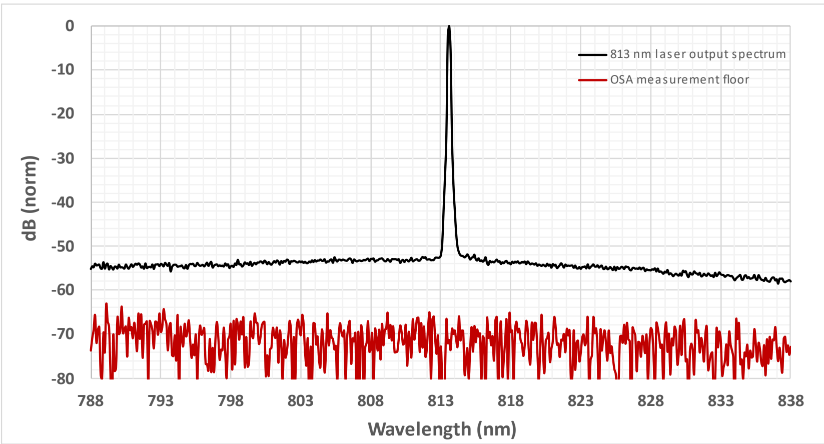

Figure 10: 813 nm laser output spectrum

Note: At the time of writing this technical document, the final system conversion modules have just been completed. A power stability analysis over a few hours of the system will be realized to validate the behaviour in the time.

The conformity of the 813 nm laser system measurements is presented in the following table:

Parameters	Specifications	Performances	OK/KO	Comments
Wavelength	813.428 nm	813.6 nm	OK	Adjustable wavelength by design
Frequency	368 554 725 MHz	368 476 472 MHz	OK	Adjustable frequency by design
813 nm Output Power	1 W	560 mW	NOK	Power level validated by consortium
813 nm Output Tap Power	0.5 mW	1,2 mW	OK	Power level validated by consortium
Tap Output connector	FC/APC	FC/APC	OK	

Table 3: 813 nm laser systems specifications

4 User interface

The 813 nm laser system can be monitored and controlled using the EXAIL CONTROL user interface (GUI). A dedicated version has been developed to allow control of the prototype system.
The EXAIL CONTROL INTERFACE is illustrated in Figure 11.

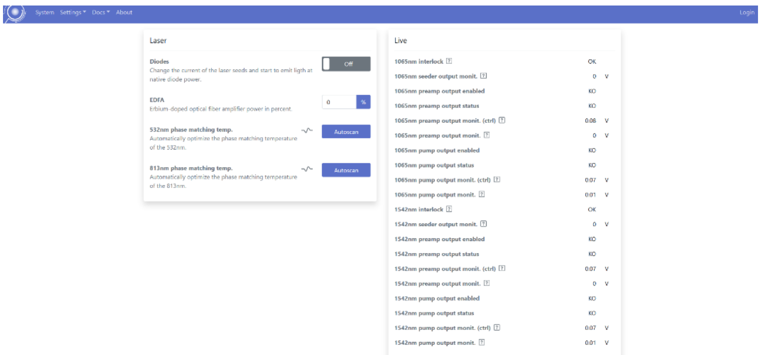

Figure 11: 813 nm EXAIL control interface system

5 Deviations from the description of action

On the technical description of the proposal part, Exail have mentioned a risk that the conversion module is not capable of generating the required 1W output power at 813 nm.

More than 650 mW output power has been generated at the output of the conversion module in free space operation and 560 mW output power is available at the end of the system after recombination in the output fiber. This optical output power is lower than the specification required (established with generous margin). The main reasons come from losses of optics used for conversion module assembly, thermal issues and physical properties of the crystals used.

After consortium meeting, the minimum required output power 813 nm from Exail laser system must be 200mW to have the clock running considering light distribution module losses at 813 nm and the input power needed into the physics package. However, 400 mW is needed for other measurements at SYRTE. In conclusion, the available output power of 560 mW should be sufficient for all measurements, integration and clock operation.

6 Conclusions

EXAIL - Quantum Sensors Division has demonstrated a high-power, low-noise 813 nm laser, based on frequency conversion of rack-mountable fiber lasers. This system should synthesize light at 813 nm for strontium's clock transition.

While the power demonstrated here is sufficient for optical-lattice-based systems and especially AQuRA clock running, higher powers would be interesting to increase performances. In that way, other solutions based on similar schemes are under study to increase output power at 813 nm.

The conformity of the EXAIL laser system measurements is presented in the following table:

Parameters	Specifications	Performances	OK/KO	Comments
Wavelength	813.428 nm	813.6 nm	OK	Adjustable wavelength by design
Frequency	368 554 725 MHz	368 476 472 MHz	OK	Adjustable frequency by design
Seed wavelengths	1542.11 nm & 1065.06 nm	560 mW	NOK	Power level validated by consortium
813 nm Output Power	1 W	560 mW	NOK	Power level validated by consortium
813 nm Output Tap Power	0.5 mW	1,2 mW	OK	Power level validated by consortium
1542 nm Output Tap Power	0.1 mW	> 5 mW	OK	Best effort >3mW
1065 nm Output Tap Power	0.5 mW	> 5 mW	OK	Best effort >3mW
Output connector	FC/APC	FC/APC	OK	
Fiber length	5m	5m	OK	
1542 nm Slow modulation Input	>500 MHz	-	OK BY DESIGN	500 MHz
1542 nm Fast modulation Input	±1.2 GHz	-	OK BY DESIGN	±1GHz
1065 nm Fast modulation Input	±100 GHz	-	OK BY DESIGN	
Analog Input signal	2.5 V	2.5 V	OK	
Digital interface	USB 2.0/Ethernet	USB 2.0/Ethernet	OK	
Interlock input	Closed contact	Closed contact	OK	
Power supply requirements	600 W/230 V	-	OK BY DESIGN	
Height units	16 HU	16 HU	OK	

Table 4: EXAIL laser systems specifications

7 References

[1]William J. Eckner, Aaron W. Young, Nathan Schine, and Adam M. Kaufman, "High-Power, Fiber-Laser-Based Source for Magic-Wavelength Trapping in Neutral-Atom Optical Clocks," (2021).