WP3 PERIODIC REPORT

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Project acronym: ISENSE

Project title: Integrated Quantum Sensors

Funding Scheme: STREP (ICT-FET-Open)

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Periodic report: 1st ☐ 2nd ☐ 3rd X 4th ☐

Period covered: from 1. July 2012 to 30. June 2013

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[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the grant agreement
[2] The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm ; logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

WP 3- *Integrated Sensor*

Work package leader: BHAM

Introduction

The overall objective is to demonstrate the iSense technology platform in a proof-of-principle instrument and to include all electronic modules needed to operate and control the lasers, magnetic field coils, and other components. The particular instrument chosen is an optical lattice based cold atom gravity sensor, which will bring together all aspects of the technology platform and all expertise generated.

The work package is organised in two tasks, which are listed in the table below.

Task-Nr.	Task	Task Leader
3.1	Electronics	LUH
3.2	Integrated gravity sensor	BHAM

Summary of progress towards objectives and details for each task;

All electronics modules have been designed and delivered except for the chip current driver and DDS boards.

The fibre-based integrated optical system has been integrated with the vacuum chamber and the atom chip and a magnetooptical trap has been realised.

Details for each task

Task 3.1

- ***Develop basic electronic modules which are computer controlled (months 1-18)***
- ***Develop FPGA based laser frequency control methods (months 1-24)***

This year, 14 Modules have been delivered to iSense:

- 5 Temperature controllers to keep the operating temperature of the lasers and integrated optics devices stable.
- 3 Current drivers in the high power variant to operate optical power amplifiers (tapered amplifiers)
- 2 Current drivers in the low power variant to operate DFB and ECDL master lasers.
- 2 Analog output devices for the integrated optics devices, each with 16 output channels.
- 1 Frequency controller which is capable of frequency stabilizing the entire iSense laser system. It contains everything needed to stabilize one laser on a spectroscopy (modulation, demodulation, filtering) and up to 3 lasers with frequency offset locking simultaneously.
- 1 Band pass filter (6.25MHz) for the frequency modulation spectroscopy to stabilize the reference laser onto a rubidium transition.

A major breakthrough is the development of an automatic stabilization method that can stabilize onto any transition without manual assistance to select a specific line, significantly enhancing the reliability of the laser locking system. This development is not yet finished, but the results are very promising.

The last two electronics components to be delivered to iSense (DDS and chip-current drivers) are still in development.

The delay in the production of the electronic components is mainly due to the development of the modules with a large software component that has taken more time than expected. These are also the components that show the largest advantage over their classical analog counterparts.

- ***Develop a compact frequency reference chain operating at 6.8 GHz (months 1-27)***

The reference frequency system delivers the various microwave signals used for the control of the laser system EOMs, which are used to create sidebands in the lasers spectrum, for the generation of the Raman lasers and for the control of the detuning of the Raman lasers.

The primary source of the microwave signal is based on an integrated PLDRO (Phase Locked Dielectric Resonator Oscillator). It is composed of a 7 GHz DRO, phase-locked on a 100 MHz radio-frequency source, which is itself phase-locked on a reference quartz oscillator at 5 MHz. This integrated PLDRO delivers three outputs: at 7 GHz, 100 MHz and 10 MHz. The 5 MHz quartz can be frequency tuned by the mean of a (gross) mechanical tuning or a (fine) electrical tuning.

In the system we have built, the 7 GHz signal is distributed into three channels, one for the control of the Raman frequency difference between the two Raman lasers, one for a microwave antenna, which can be used for diagnostic purposes to induce transitions between the two hyperfine states, and the last one used for the generation of a frequency comb. For the Raman frequency difference and the microwave channels, the 7 GHz is first split, then mixed with a DDS signal, eventually filtered (Raman channel) and finally amplified. As for the frequency comb channel, it is simply amplified with a 1W-amplifier.

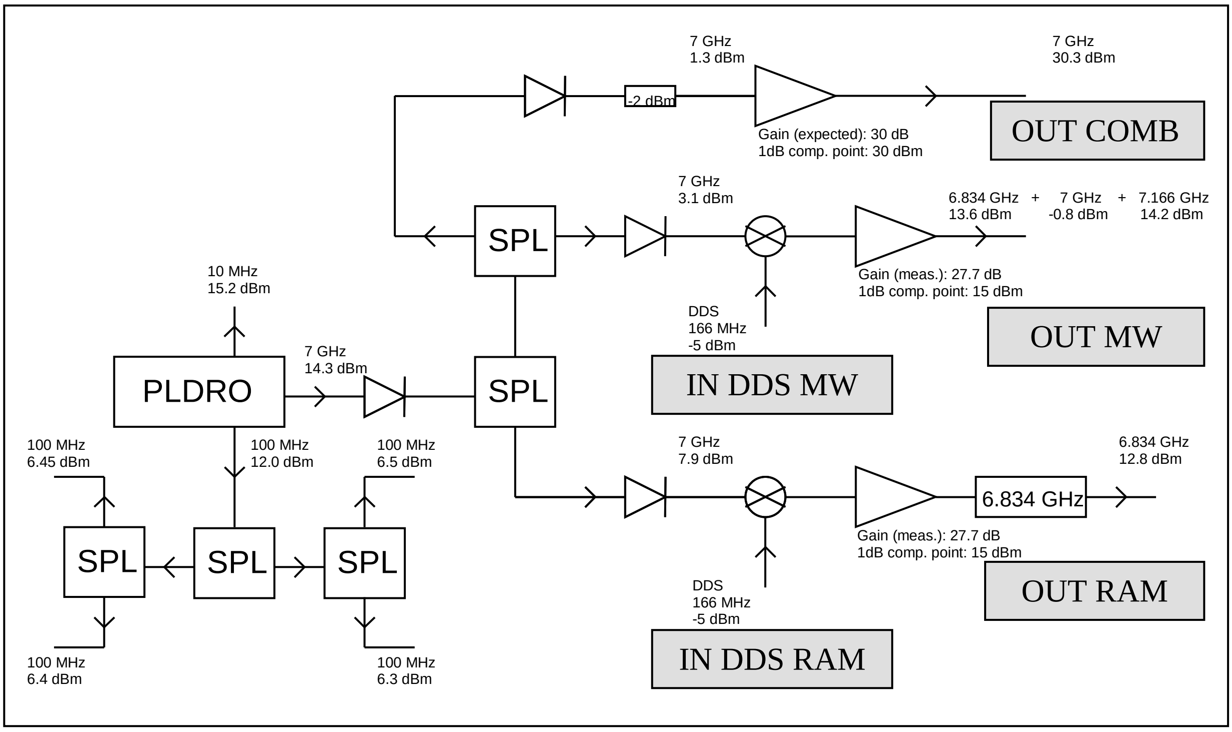

Fig.1 - Schematics of the PLDRO microwave chain

The supply being filtered by three low dropout voltage 12V-regulators, the system can be supplied with a 13.2V battery. The total consumption is 2.2A in the startup phase and decreases to 1.8A in steady state.

Outputs levels as a function of DDS input power:

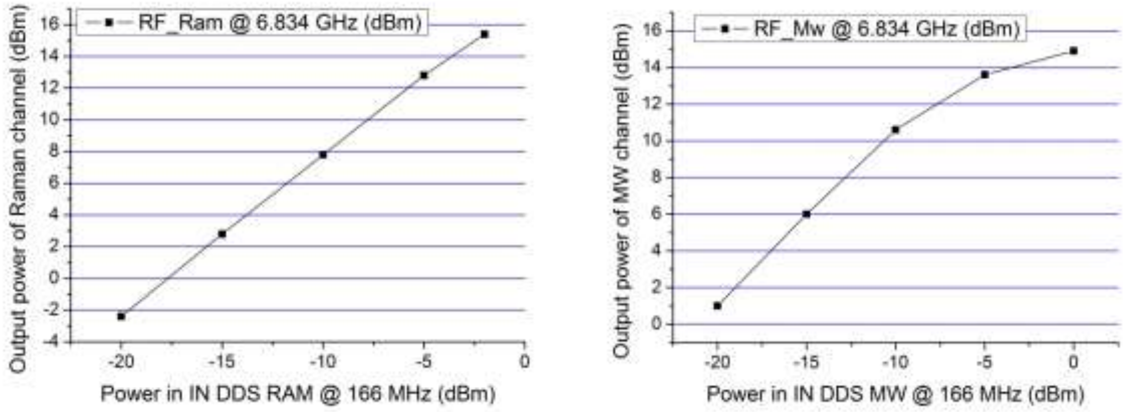

Fig. 3.2 - Output levels on the Raman and MW channels as a function of the DDS input power

The output power of the comb output is 1 W, which will allow the generation of high order sidebands (up to the 7th sideband).

The output power of the Raman channel exceeds the power required for having about equal power between the carrier and the first sideband (about 20 mW).

Phase noise of the PLDRO:

The phase noise spectral density of the system, as measured by the manufacturer of the PLLDRO, is displayed in figure 3. The specifications are close to the target specifications at low and high frequencies, displayed by red dots and lines.

We have also performed independent measurements of the phase noise of the system, which confirmed these specifications.

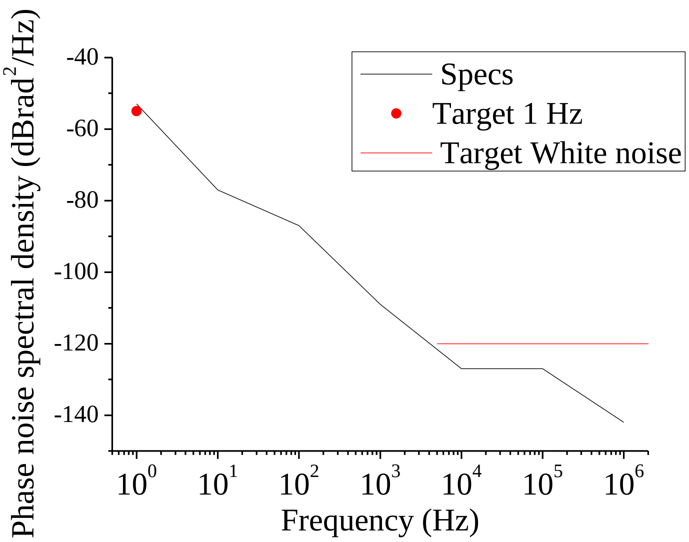

Fig. 3.3 - Phase noise power spectral density at 7 GHz (from the manufacturer specifications), and target specifications at 1 Hz and above 5 kHz.

The system was delivered to BHAM in March 2013.

- ***Design the central computer system and develop the programming to control the electronic modules and to coordinate the experimental sequence. (month 20-30)***

A fully functional experiment control program has been developed using synergies with the QUANTUS project. The program has been used to control the ion pump, to set temperature and current for the laser systems, to realise the spectroscopy and offset locks and to create a MOT. The control program has been further improved to add functionality for triggering the fibre switches and fibre AOMs. This will allow us to implement the sequence of light pulses for measurements. The integration of DDS and chip current drivers will require some additional small modifications, which will allow the necessary frequency chirps and complete implementation of the measurement sequence.

Task 3.2

- ***Tests of prototypes and individual subsystems (months 12-27).***

1. The compatibility of the laser temperature and current control electronics with the laser modules has been tested in the context of the QUANTUS projects and by now has also been confirmed in the iSense apparatus.
2. UHV compatibility of the atom chip was tested before delivery, revealing some issues: Although UHV was reached, a bakeout left some residue on the inner side of the test vessel. Further investigation about the chemical content (high silicone) revealed that this was due to the adhesive capton tape used for insulation – contrary to the specifications by the manufacturer, which clearly stated full UHV compatibility to the 10^{-10} mbar range. It was decided to subject the chip to a prolonged vacuum bake in the test chamber to remove any residue before delivery and to keep bakeout temperatures of the Sense chamber with integrated chip to below 100 ºC.
3. The compatibility of the ion pump controller with the selected ion pump has been confirmed in the iSense apparatus.
4. A preliminary test of the iSense probe chamber, atom chip, atom source and integrated fibre optics system for compliance with laser cooling needs was performed by realising a first MOT on April 18th 2013. This test used free running commercial lasers but ensured that the respective subsystems were compliant with the requirements of Annex-I.
5. The compatibility of the laser – optics system interfaces has been ensured by very closely coordinated development and has been confirmed in the iSense setup for all delivered modules so far.
6. A prolonged test of the first iSense laser modules in the iSense apparatus revealed an issue with the stability of the used miniature thermal sensor (NTC), which degraded and caused a malfunction of the temperature control. The respective laser modules have been returned to FBH for repair and the NTC has been replaced by a different model, which was also implemented in all other laser modules.
7. Running the MOT with the integrated fibre system revealed fluctuations of the polarisation output of the pm fibres, likely due to small individual misalignments during splicing and input coupling accumulating to a significant effect. The fluctuations were removed by adapting the output telescopes to include a polariser.
8. We have installed a dedicated optical test setup at the University of Nottingham in order to be able to assess the parameters and compatibility of the integrated optical waveguide system components as soon as possible.

- ***The laser, optics modules and chip trap will be integrated with the probe chamber included in the vacuum system.(months 24-30)***

During the first three months of the reporting period the vacuum system of iSense has been mounted at IOGS. The design, realized at Birmingham, has been finalised, then all the components of the vacuum system have been ordered. The titanium vacuum chamber has been realised by Riaal Vacuum (Italy), then cleaned and mounted during August 2012 at IOGS. The windows have been mounted on the vacuum chamber using the indium sealing technique to preserve the viewport planarity and optical quality. The system has been closed and the UHV condition tested ($<10^{-9}$ mbar), using a blank flange where the atom chip will be installed once ready, and without rubidium source.

After shipment to Birmingham the vacuum integrity was tested and after retightening one flange UHV conditions ($<10^{-9}$ mbar) were achieved again. The chip was delivered and installed at the beginning of 2013, a smaller valve integrated into the chamber and after bakeout UHV at <10-10mbar was reinstated. Finally the compression flanges securing the windows were removed, finalising the preparation of the vacuum system, i.e. the probe chamber in April 2013.

The laser cooling part of the integrated fibre optics system (see Task 1.4) has been integrated with the probe chamber in Spring 2013 as shown in the figure 3.4. The fibre optic system is linked to the probe chamber with specifically designed telescopes, which act as mechanical adapters between the fibre system FC connector output and the vacuum chamber body to which they screw directly. In addition the telescopes adapt the polarisation of the light and collimate the light to create circularly polarised beams of 0.75 cm waist, as needed to operate the MOT.

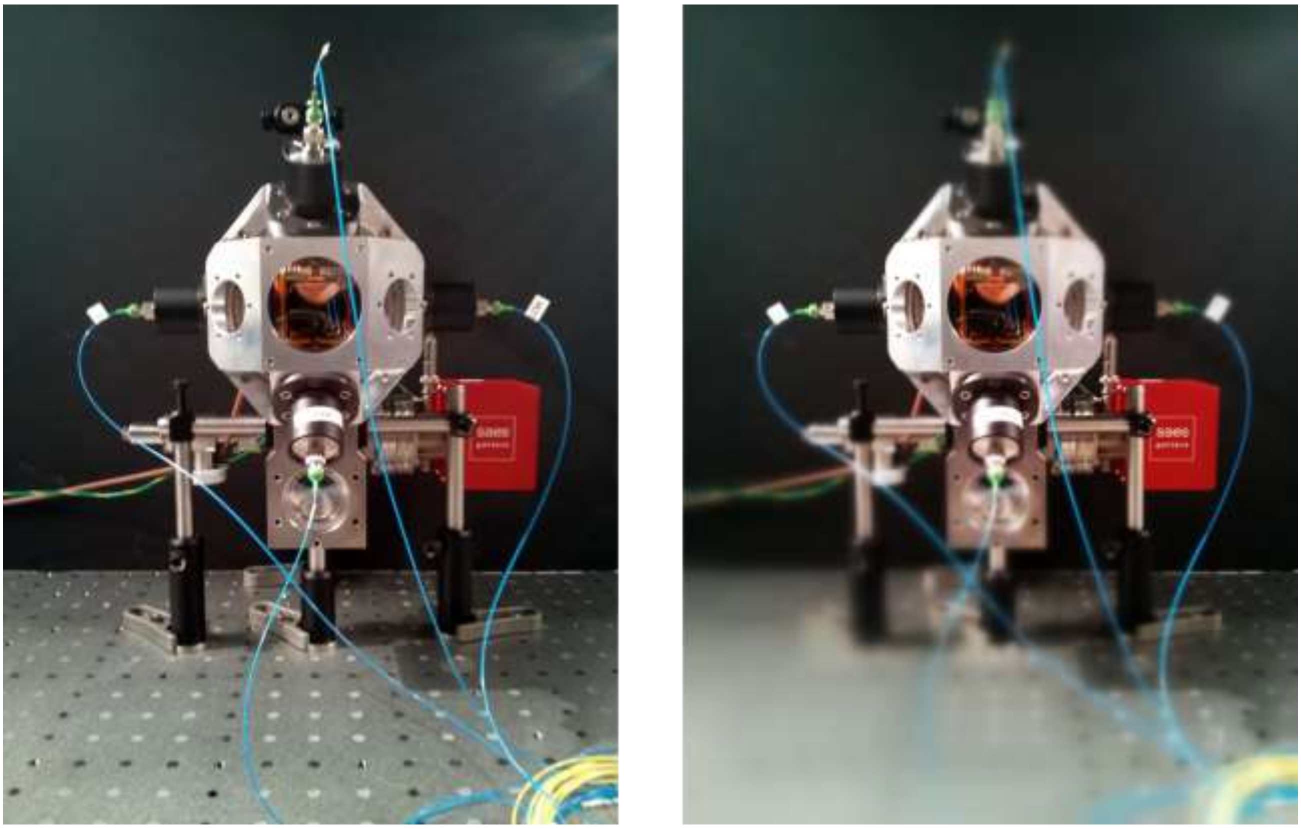

Fig 2: Science chamber setup with MOT fibres and telescopes

Recently we have been able to achieve a stable MOT of ^{87}Rb, figure 3.5 in the iSense probe chamber using the iSense electronics and computer control system to stabilize a set of commercial laser systems. The iSense laser modules will act as drop-in replacements for these commercial laser systems, as both are fibre coupled. However we anticipate some software adjustments of control parameters to be necessary.

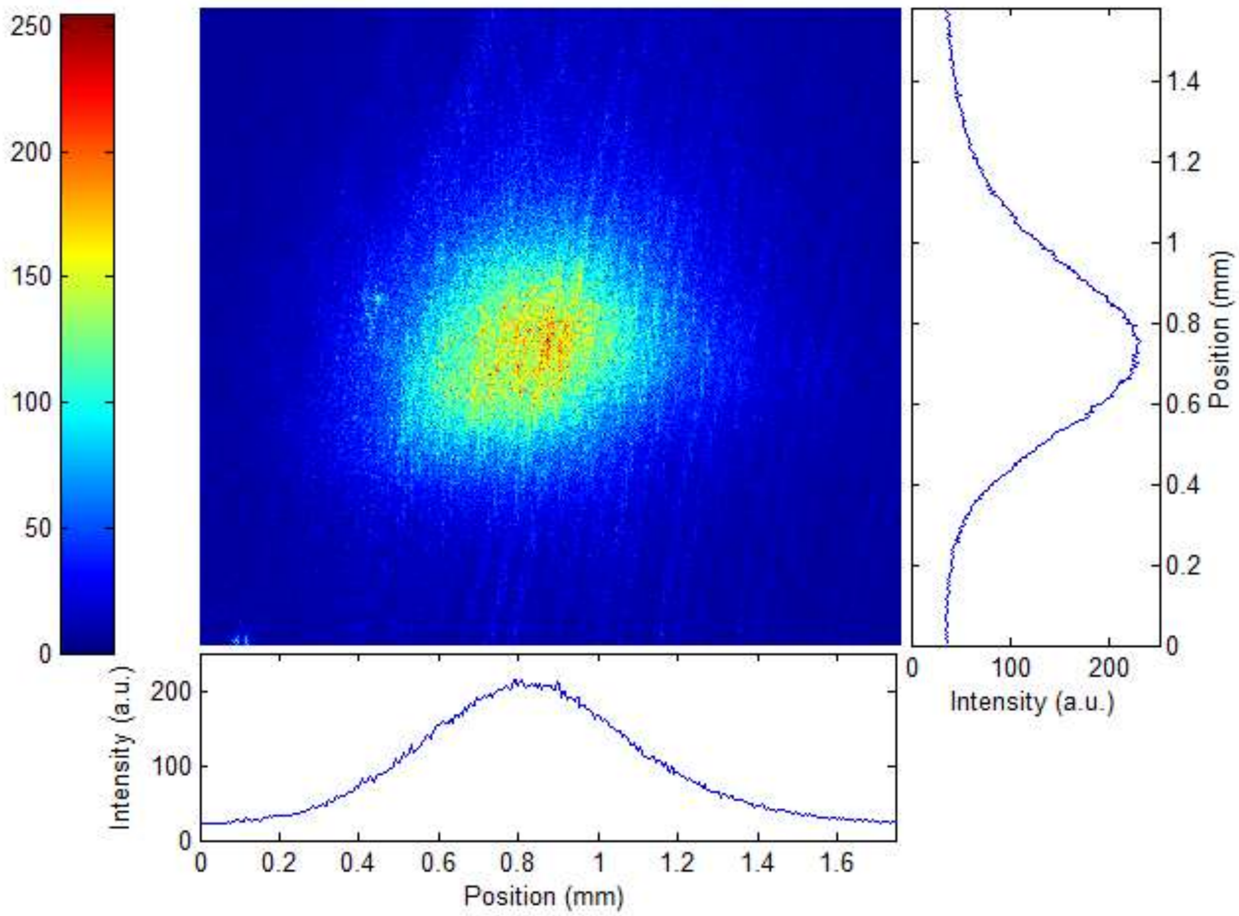

Fig. 3: Fluorescence image of a ^{87}Rb cloud of atoms in the MOT.Color coded is the light intensity collected by the CCD camera

- ***We will integrate a control system optimized with respect to the finally selected sensor scheme and implement gravity sensing operation*. (28-40)**

The electronics stack control system has been implemented by LUH. It consists of a PC104 computer with LabView realtime programming an FPGA for precise timing of all boards in the stack. For programming purposes this is interfaced with a PC. After integration with the probe chamber and laser systems in BHAM we have been able to lock the frequencies of the lasers to the necessary transitions to realise laser cooling and a magnetooptical trap has been operated with the control system. The control system layout has been optimized to achieve all tasks necessary for laser cooling and we anticipate that it will allow implementing both, the atom interferometry sequence for the finally selected sensor scheme as well as free fall atom interferometry.

The preliminary control sequence for atom interferometry operation of the iSense sensor is as follows:

Description	ONERA scheme Duration (ms)	Free Fall Scheme Duration (ms)
MOT Loading	500	500
Molasses cooling	10	10
Lattice Launch	9	-
Lattice off	0.3	-
$\pi/2$ Raman Pulse	0.03	0.03
Free Fall	6	0-50
$\pi/2$ Raman Pulse	0.03	0.03
Stationary Lattice On	0.2	-
Bloch Period	0-xxxx	-
Stationary Lattice Off	0.2	-
$\pi/2$ Raman Pulse	0.03	0.03
Free Fall	6	0-50
$\pi/2$ Raman Pulse	0.03	0.03
Atoms Fall into detection region	150	50
Detection Pulse	0.5	0.5
Repumper Pulse	0.5	0.5
Detection Pulse	0.5	0.5

Technical requirements for implementation of the ONERA scheme.
In addition to the standard laser cooling and detection requirements, which are all met by the control system the following more additional features will have to be met:

1. An optical lattice to launch and hold the atoms. As in the ONERA paper the optical lattice will be created by the Raman laser (see schematic in figure 3.6), making dual use of one system.
2. For the launch with the lattice, the Raman AOM needs to contain the usual 80MHz signal and an additional 80MHz $+\Delta\nu$ to perform the launch. This creates three standing waves for the Bloch laser, a stationary one and two moving in opposite directions with velocity $\pm\lambda\,\Delta\,\nu/2$. In the paper, the team at ONERA used a 9ms ramp of $\Delta\,\nu$ from 35kHz to 312kHz which is then adiabatically switched off in 0.3ms.
3. A jump has to be applied to the Raman laser after the Bloch oscillation section in order to keep it in resonance since the atoms change velocity when inside the lattice. The uncertainty in this frequency jump of 0.3Hz led to the main source of error in the gravity measurement from ONERA. The DDS chip used by the LUH board (AD9959) has a resolution of 0.1Hz and in addition allows phase corrections, which should allow to improve on this limitation.
4. For the gravity measurement, the Raman frequency has to have a chirp α applied to it, which is around 25MHz/s. α needs to be varied to find the point where it exactly cancels the gravitational acceleration, from this we can calculate a value of g. The DDS chip is capable of this sweep rate.
5. We will need six controllable DDS frequency outputs for iSense; two for the fibre AOMs for the cooling and the repumper light, two for the AOM in the Raman path and two to connect to the frequency chain for Raman and microwave transition generation. The Raman path AOM needs two frequencies on it so we can successfully operate the launching of the atoms in the lattice. Since the DDS from LUH has two channels, this means we will need three boards.

While the DDS firmware is developed at LUH we will use, a commercial Novatech DDS system will be used, which has the same base DDS chip.

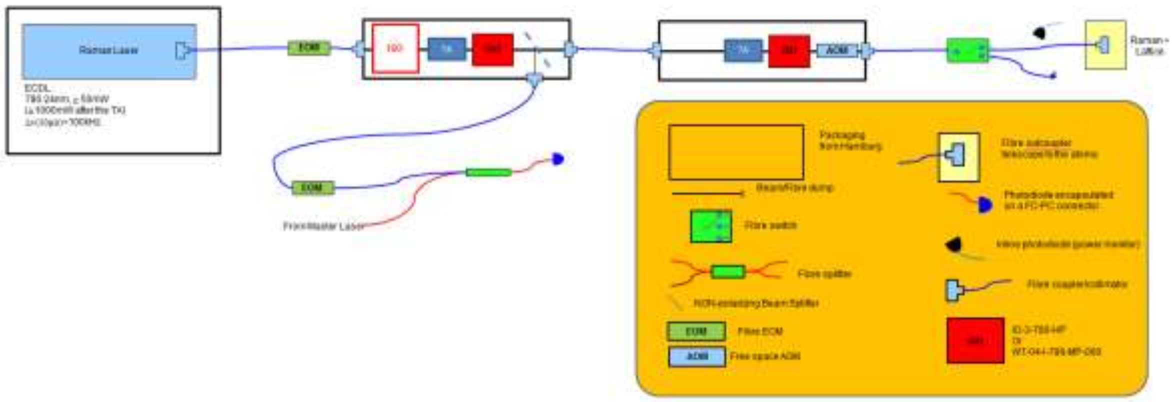

Fig. 4: Schematic of the Raman/Lattice laser

Clearly significant results
A small form factor frequency chain was developed and delivered, which matches the iSense specifications.

The probe chamber has been integrated with the fibre-based optical system and laser cooling demonstrated.

Deviations from Annex I and their impact on other tasks, available resources and planning

Reasons for failing to achieve critical objectives and/or not being on schedule and explain the impact on other tasks as well as on available resources

Statement on the use of resources, highlighting and explaining deviations between actual and planned person-months per work package and per beneficiary in Annex 1
The resources are in general agreement with Annex-I.