Iodine frequency stabilized telecom laser sources

Développement d'une source laser IR & visible, compacte, fibrée, stabilisée en fréquence

Joannès Barbarat

Objective of the development

- Ultra-stable iodine frequency standard
- Transportable and compact setup

Possible Applications:

- Ultra-stable optical links (ground-space or inter-satellite)
- Ground tests of the LISA payload
- Laser ranging
- Future generation of gravitational wave (ground) detectors at 1.5 µm
- Atmospheric spectroscopy, femtosecond laser frequency stabilization

Outline

Outline

I. Background and improvements on free space setup

- Telecom and iodine frequency stabilization
- Improvements of the previous optical setup

II. Study of the Zeeman effect from an external magnetic field

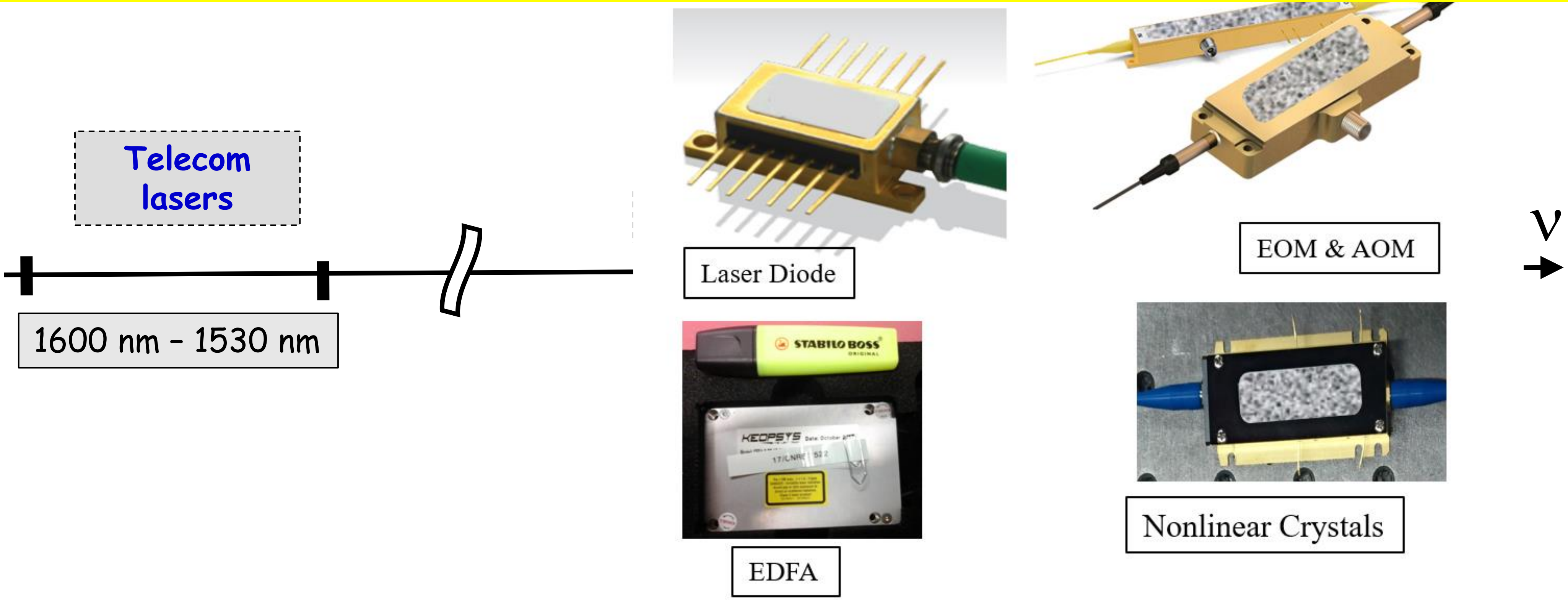
- Long term frequency stability limitation
- Influence of an external magnetic field

III. Development of a compact and fibered setup

- New optical architecture
- Development of a new compact transportable laser setup
- Preliminary frequency stability

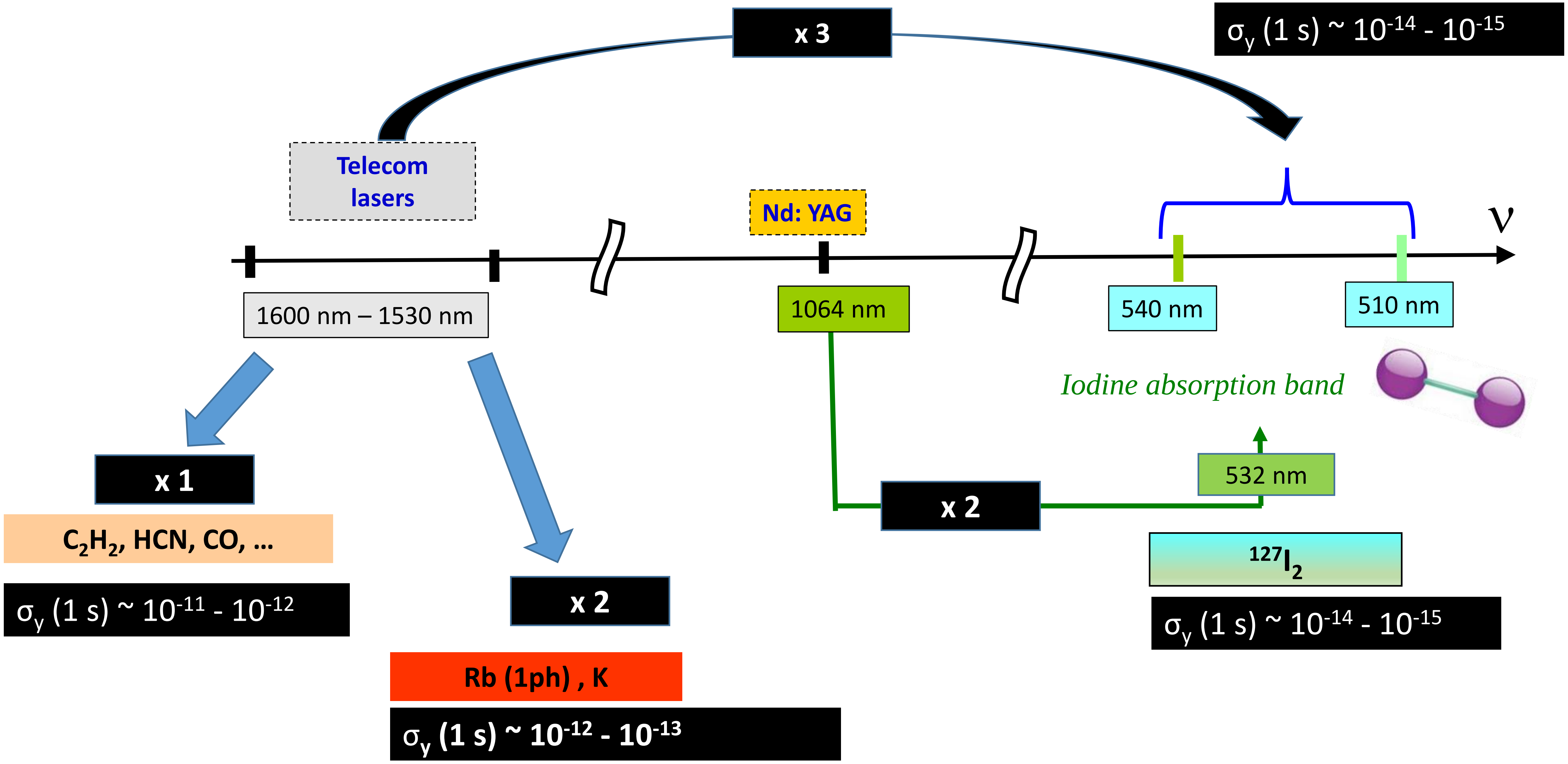
IV. Next steps and conclusion

Background

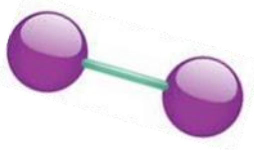


- Telecom lasers have very low intrinsic phase noise (linewidth ~kHz), are compact (cm^3), …
- Optical amplifiers (EDFA) are powerful, compact and fibered, low power consumption
- Many optical devices exhibit high TRL (AOM, EOM, non linear crystals, …)
- Low coast commercial solutions and exhibit high TRL

Background

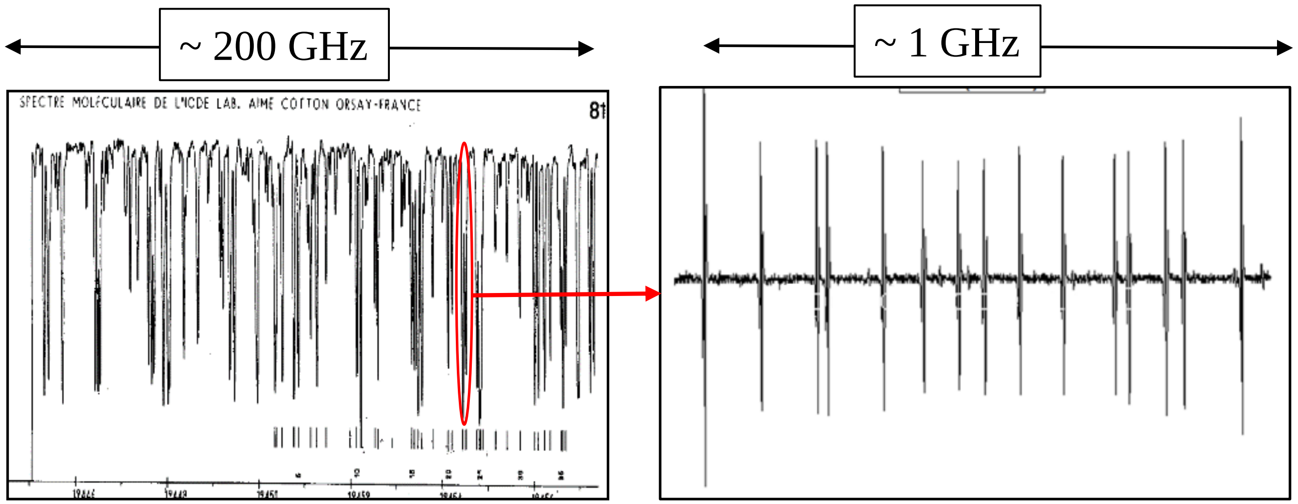

x 3
σy (1 s) ~ 10-14 - 10-15
Telecom lasers
Nd: YAG
ν
1600 nm – 1530 nm
1064 nm
540 nm
510 nm
Iodine absorption band
x 1
C2H2, HCN, CO, …
σy (1 s) ~ 10-11 - 10-12
x 2
Rb (1ph) , K
σy (1 s) ~ 10-12 - 10-13
x 2
532 nm
127I2
σy (1 s) ~ 10-14 - 10-15

Iodine absorption band



Iodine hyperfine lines in the green:

- ❖ Thousands of lines existing in the 510 nm – 540 nm range (~ 30 THz)



GERSTENKORN, S. and al, Atlas du spectre d'absorption de la molécule de l'iode C.N.R.S. 1978.

Odd-J are split into 21 hyperfine components.
Even-J are split into 15.

J rotational quantum number

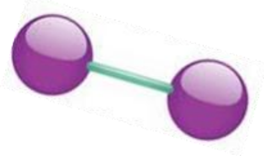
R34 (44-0)

R: ΔJ = + 1
P: ΔJ = -1

Upper vibrational state

Ground vibrational state

Iodine absorption band



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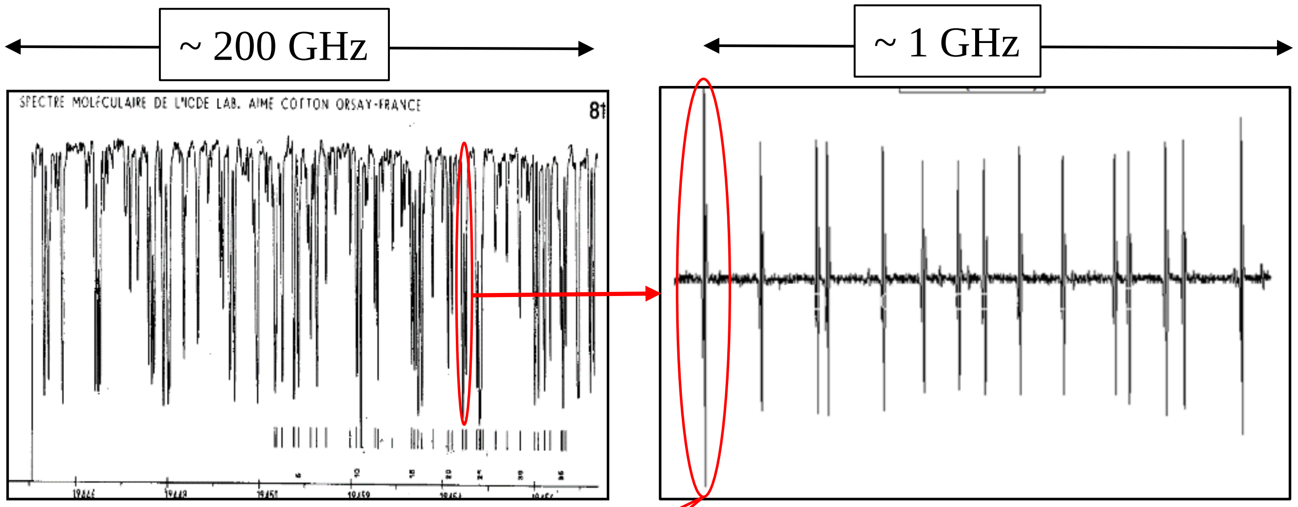


GERSTENKORN, S. and al, Atlas du spectre d'absorption de la molécule de l'iode C.N.R.S. 1978.

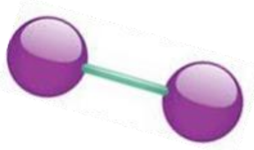
Metrologic hyperfine line must be:

$$\sigma \propto \frac{1}{Q * {}^{S}/_{N}} = \frac{\Delta\nu}{\nu * {}^{S}/_{N}}$$

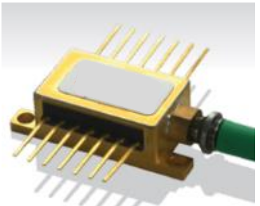
- ❖ Narrow ($Q = \frac{\nu}{\Delta\nu} > 10^9$), $\Delta\nu \sim 300$ kHz
- ❖ Exhibit high S/N ratio (~10^5 in 1 Hz bandwidth)
- ❖ Frequency stability ~10^{-14} @ 1s

Odd-J are split into 21 hyperfine components. Even-J are split into 15.

Iodine absorption band



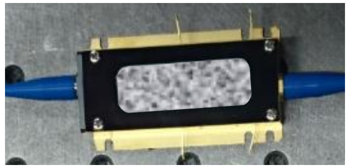
Frequency tripling process is required



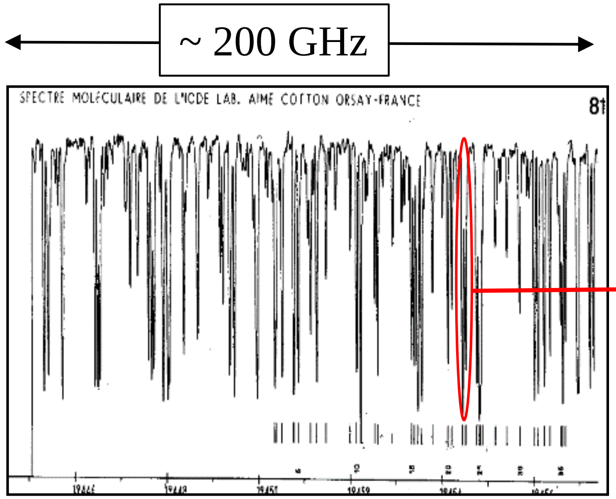
Laser Diode

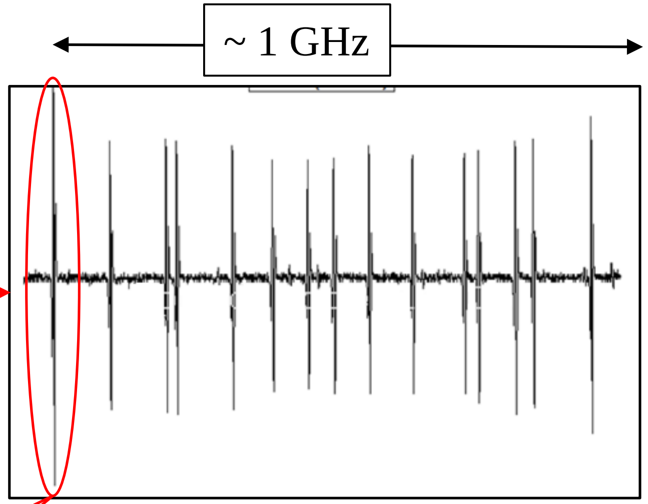
EOM & AOM

EDFA



Nonlinear Crystals





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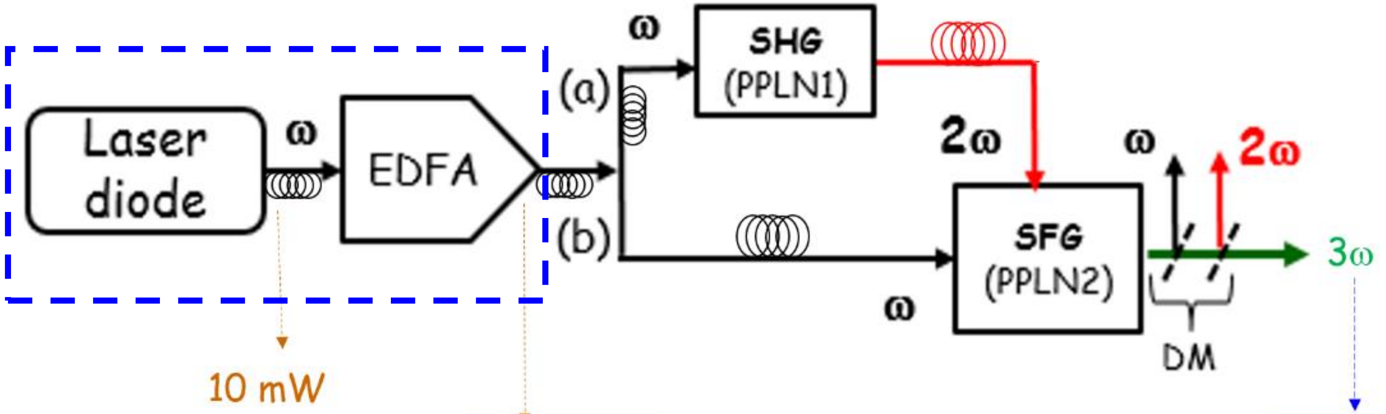
Odd-J are split into 21 hyperfine components. Even-J are split into 15.

Frequency tripling process

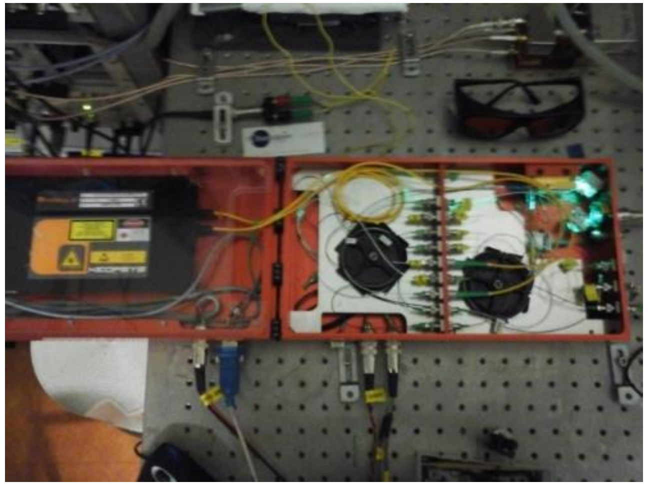


800mW @ ω → 300mW @ 3ω

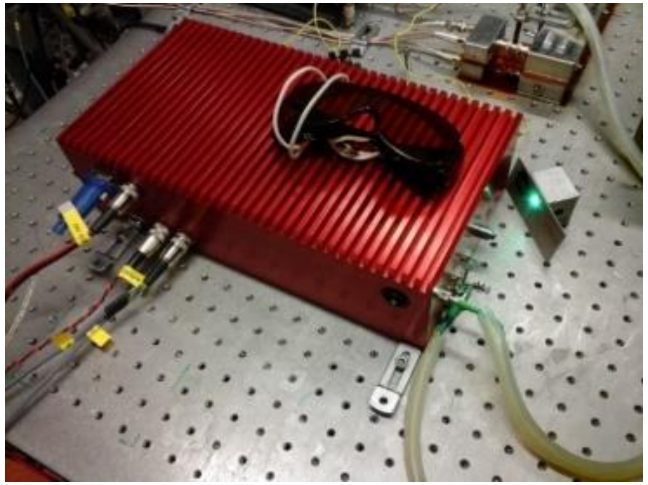
$$\eta = \frac{P_{3\omega}}{P_{\omega}} > 36\%$$

Total electrical power consumption ~ 20 W

The iodine spectroscopy needs only ~ **10 mW à 3ω**

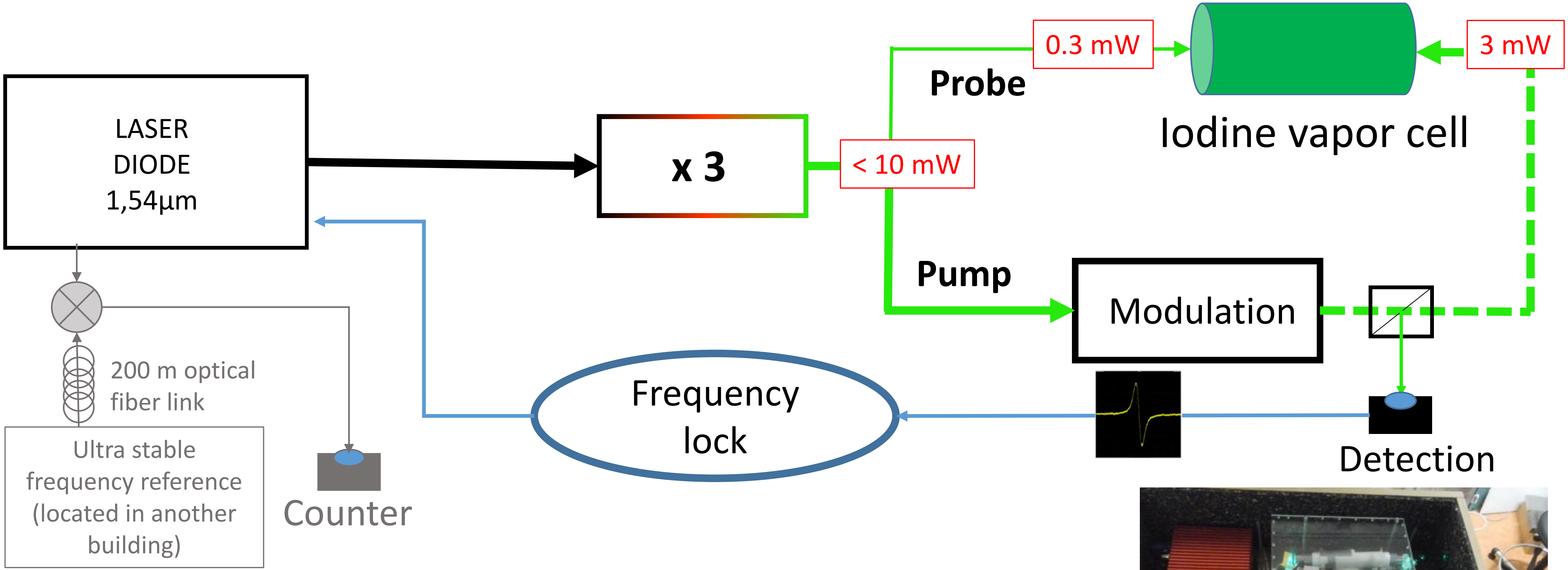


Volume ~ 5 l

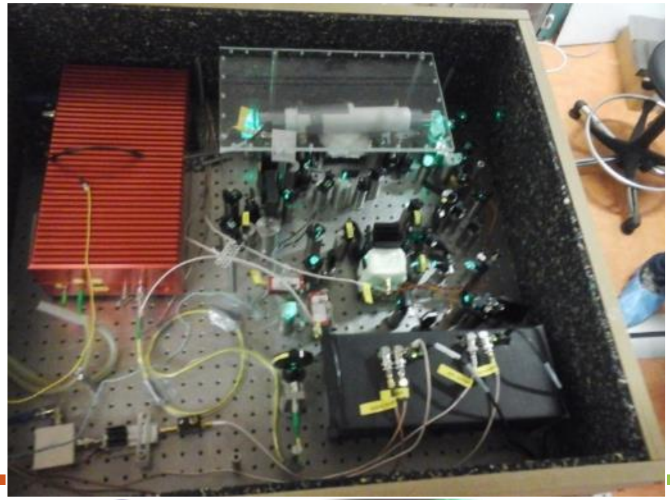


TRL ~ 4

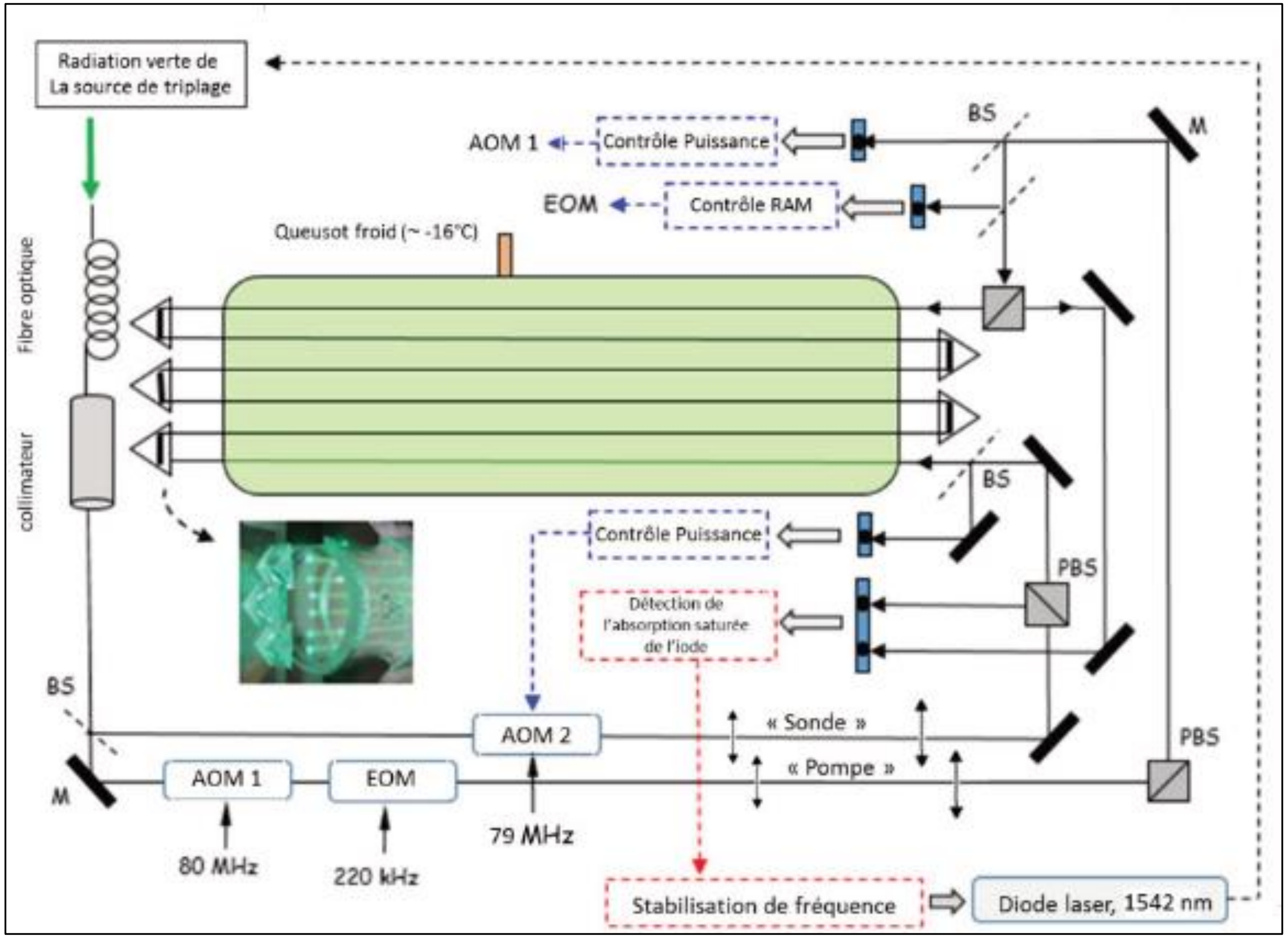
Ch. Philippe et al., « Efficient third harmonic generation of a CW-fibered 1.5 µm laser diode", Appl. Phys. B 122 (10) 265 (2016)



- ❑ Modulation transfer spectroscopy is used
- ❑ Saturated absorption signal intense and narrow
- ❑ Linewidth ~ 300kHz ; SNR ~ 10^5 in 1 Hz bandwidth
- ❑ Balanced optical detection is used

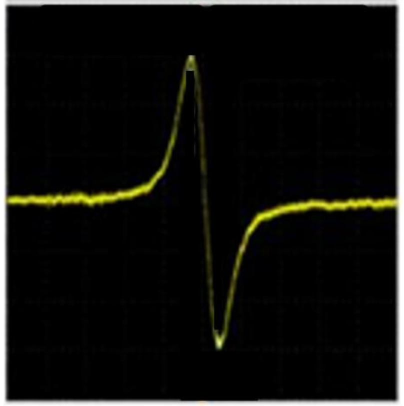


Previous optical setup



Iodine cell used on the legacy setup:
Ø= 3 cm, L = 20 cm

$$\sigma \propto \frac{1}{Q * S/N} = \frac{\Delta\nu}{\nu * S/N}$$



S: Depends on the laser and iodine interaction length.

With a 30 mm diameter iodine cell and a 1mm laser beam we are able to do 6 pass that correspond of 6 x 20 cm = 120 cm (typical for 10^{-14} stability).

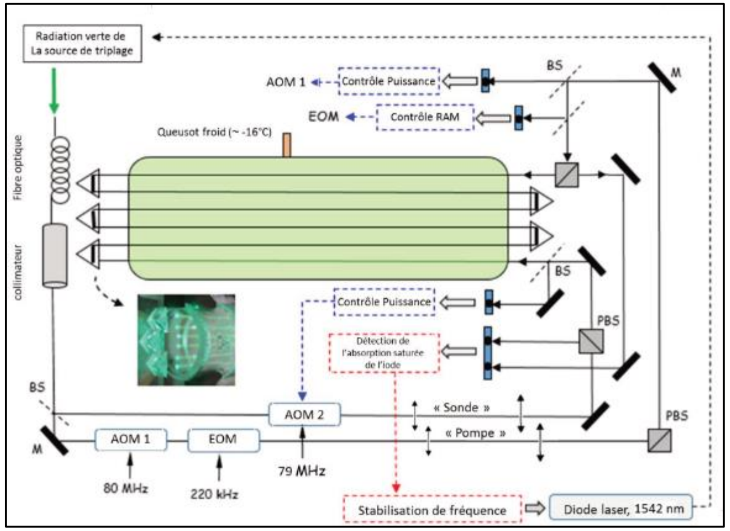
However we have a power lost about 2 % each time that the laser beam cross the non perfect AR coating of the windows (N = 12)

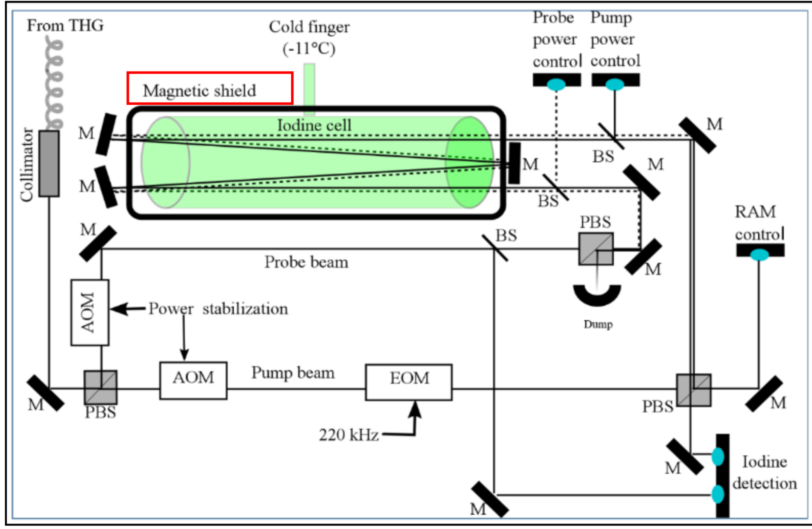
To optimize short & long term frequency stability:

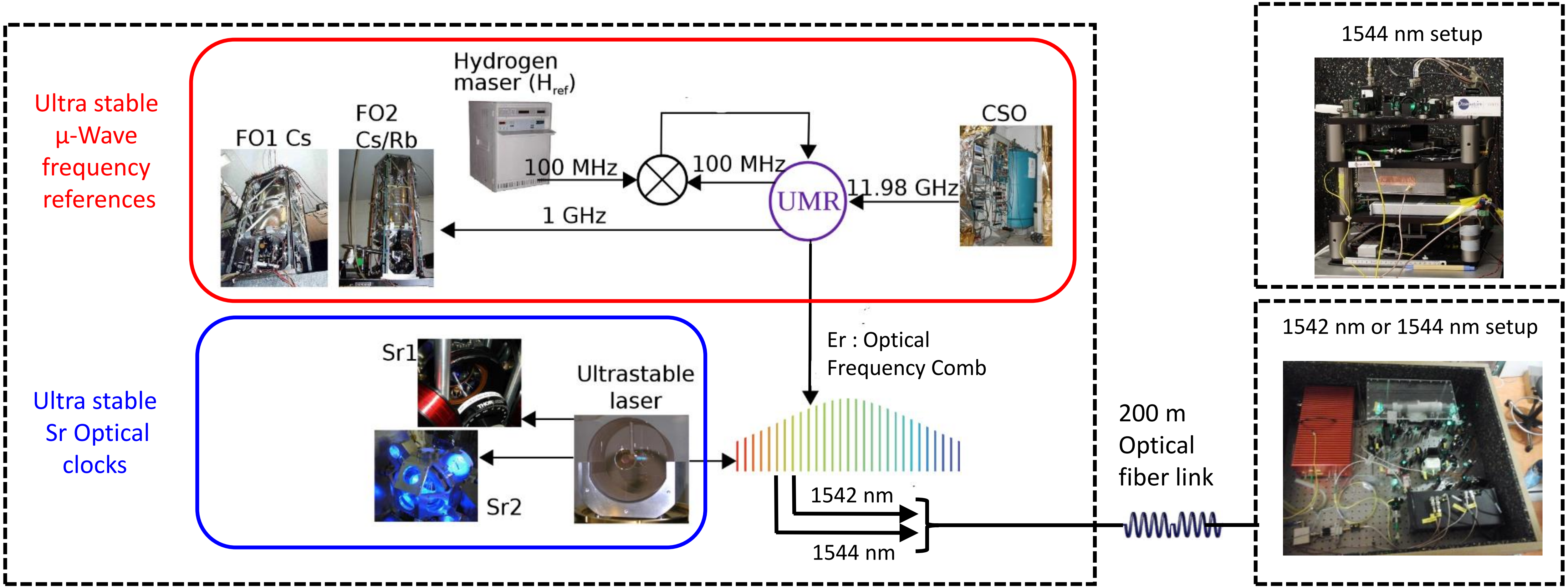
$$\sigma \propto \frac{1}{Q * {}^{S}/_{N}} = \frac{\Delta\nu}{\nu * {}^{S}/_{N}}$$

- ✓ New iodine cell
  (Diameter similar, length increased : 30 cm) in order to reduce the number of passes, but the total interaction length is the same (120 cm).
- ✓ Increase the laser beam diameter into the cell
- ✓ Investigation of the best ratio probe-to-pump optical powers in the cell by comparing the short term stability with an independent optical reference for different power inputs.
- ✓ Reduce optical feedbacks
  Replace dihedral by mirrors
  Make an angular tilt with the iodine cell
- ✓ Magnetic shield are introduced (describe later)

Previous setup	New setup
➢ 6 pass in 20cm iodine cell	➢ 4 pass in 30cm iodine cell
➢ EOM pump modulation at 220 kHz	➢ EOM pump modulation at 220 kHz
➢ AOM power stabilization	➢ AOM power stabilization
➢ Balanced photodetector	➢ Balanced photodetector
➢ Pump ~ 3 mW, Probe ~ 0.3 mW	➢ Pump ~ 2 mW, Probe ~ 0.12 mW







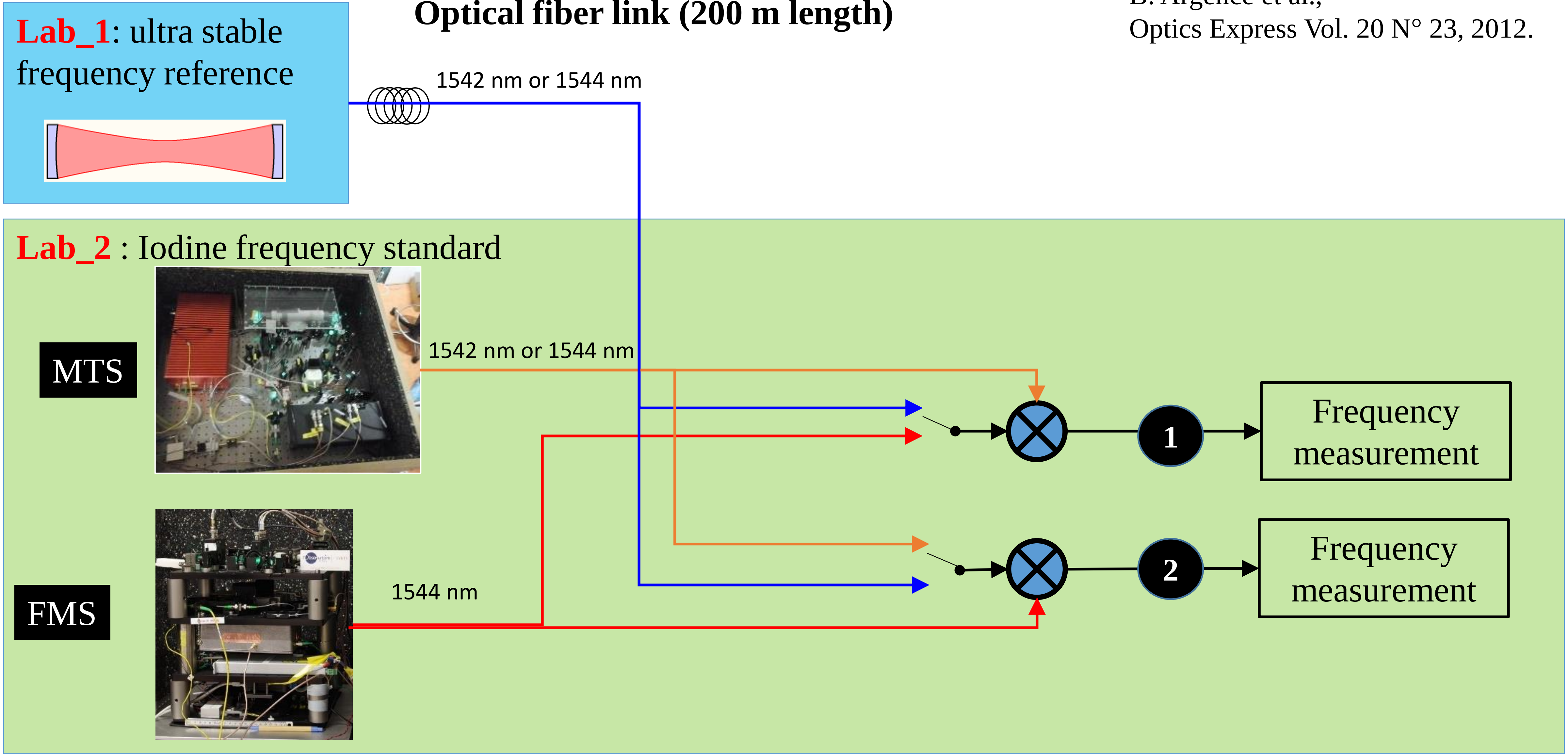
SYRTE ultrastable frequency references ensemble

Located in two distant buildings

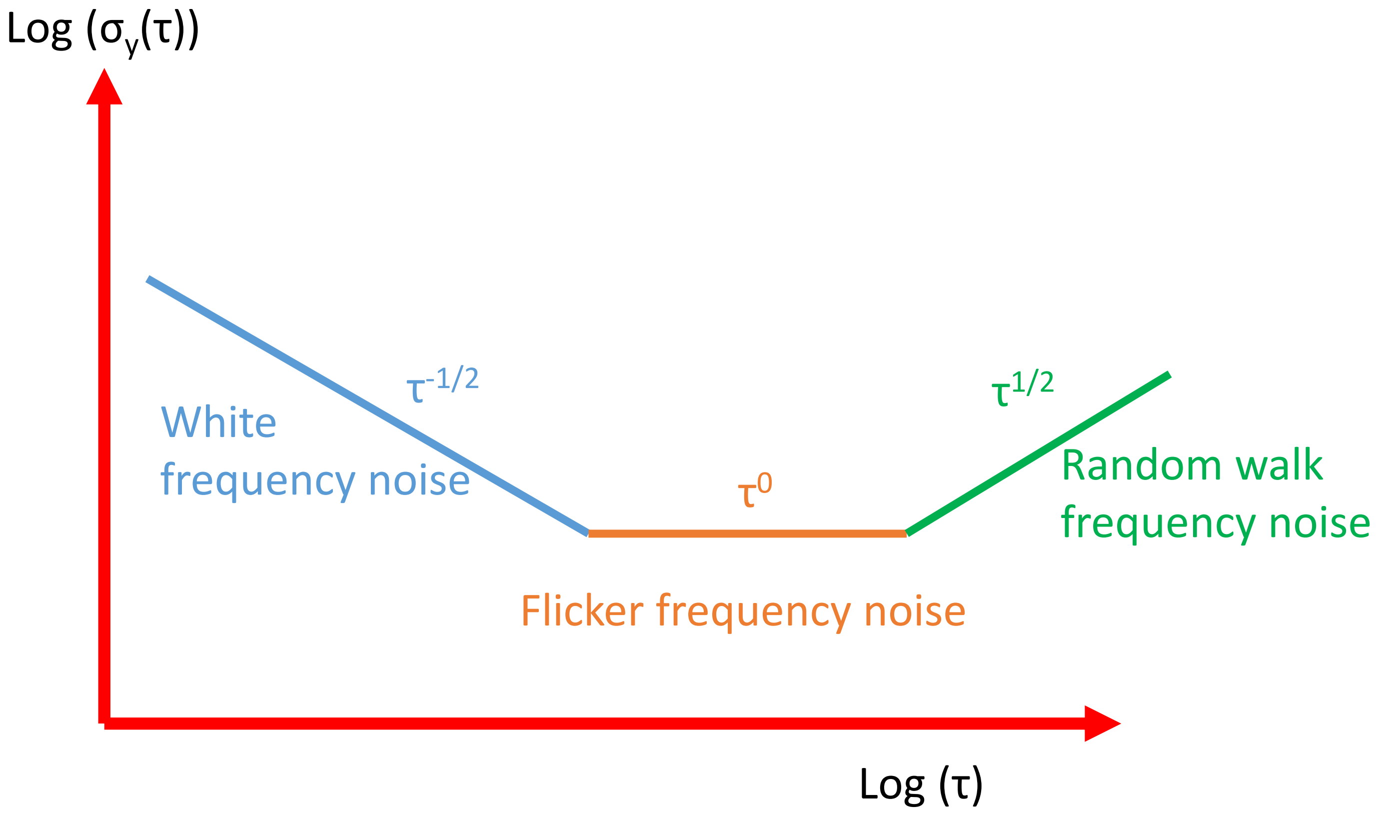
Iodine stabilized lasers laboratory

Optical fiber link (200 m length)

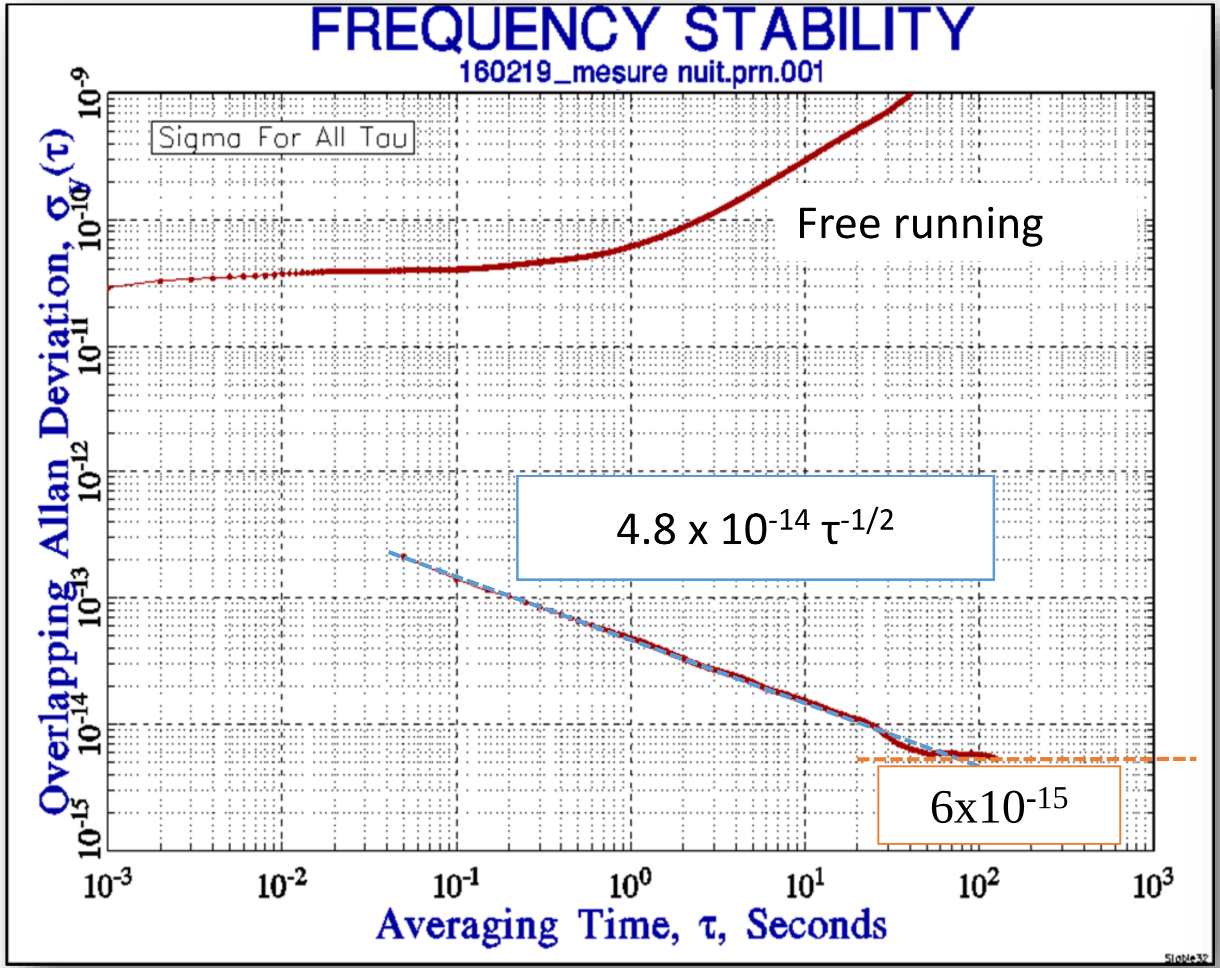
B. Argence et al.,
Optics Express Vol. 20 N° 23, 2012.

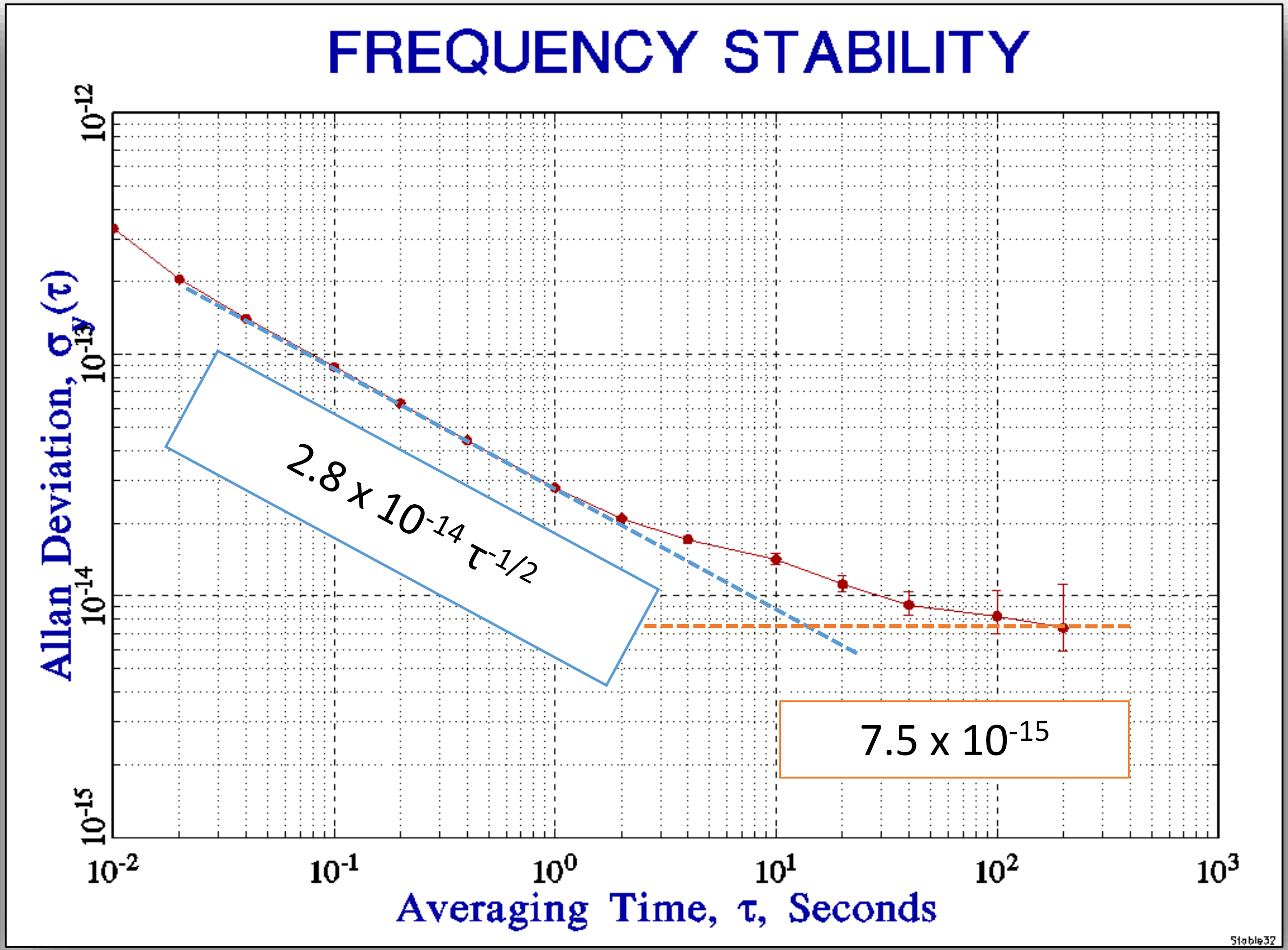


Allan deviation



Intermediate result (before magnetic shielding)





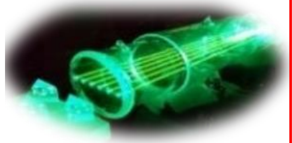
This long term frequency stability was obtained only during short period in the night when the metro lines are stopped
This effect has not been studied during Charles Thesis

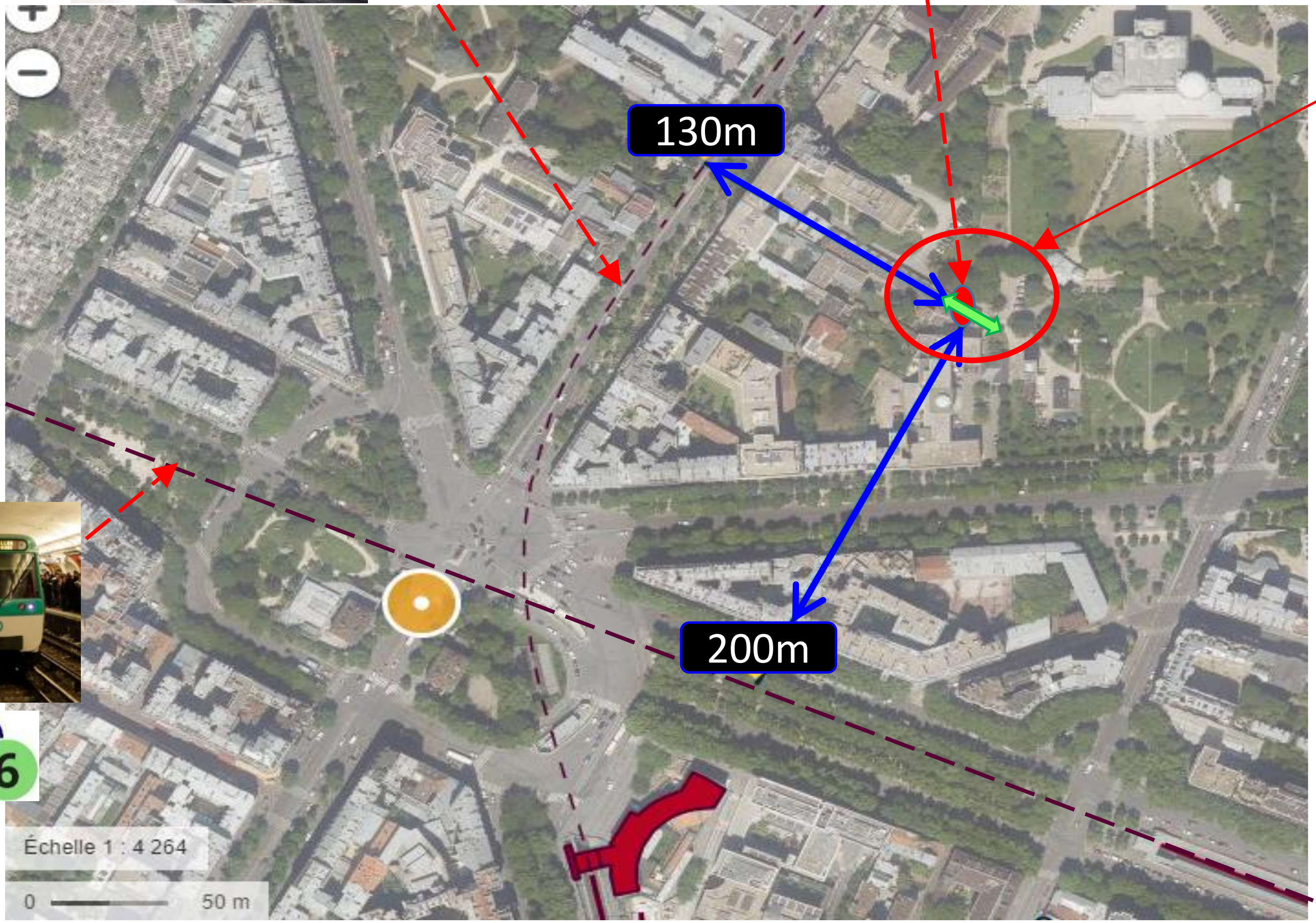
This frequency stability was obtained only after improvements about short and long term stability but without magnetic shield adding.

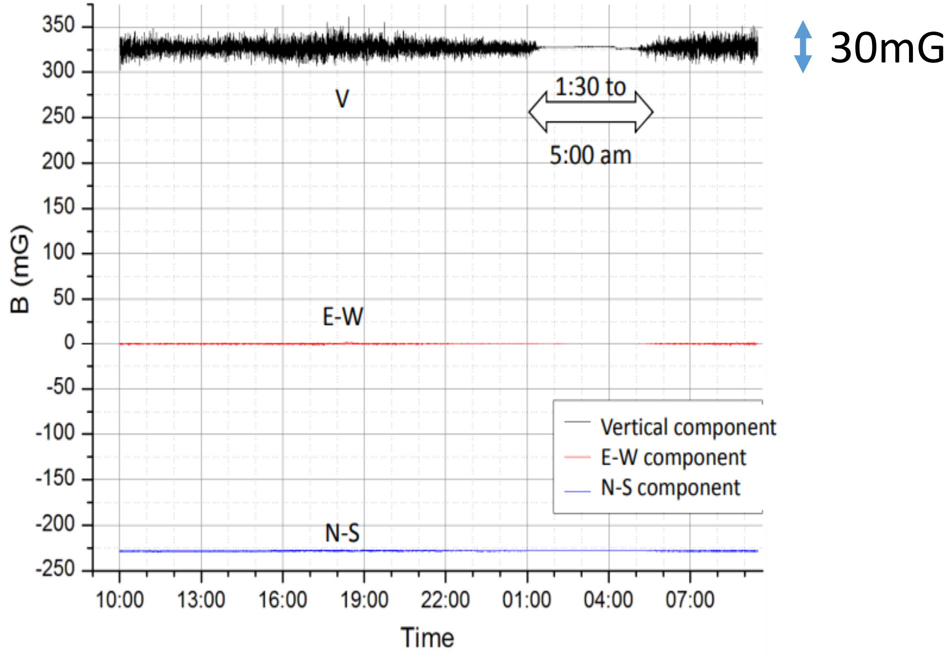
Outline

Study of the Zeeman effect

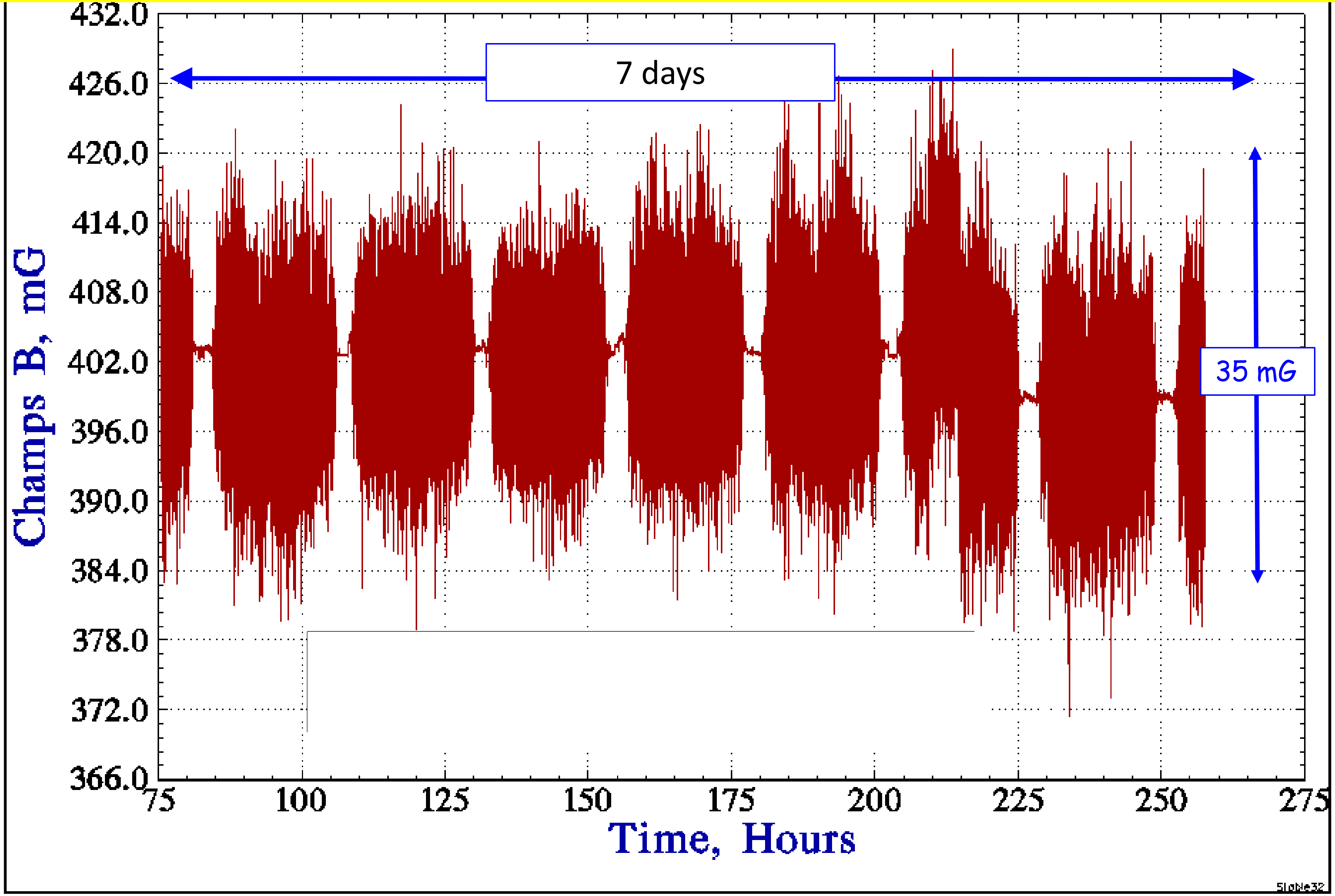
Iodine frequency stabilization experiment





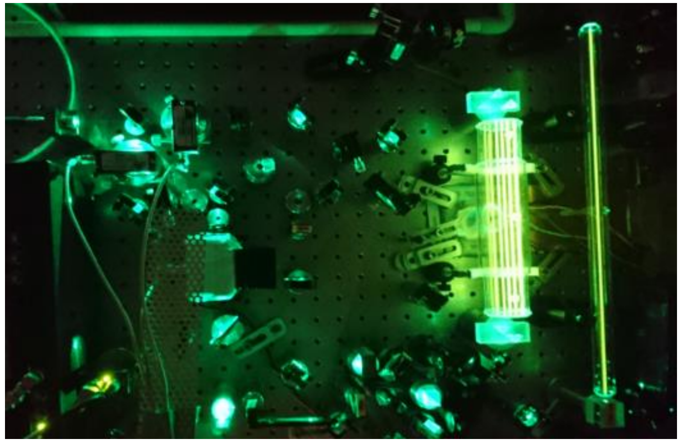


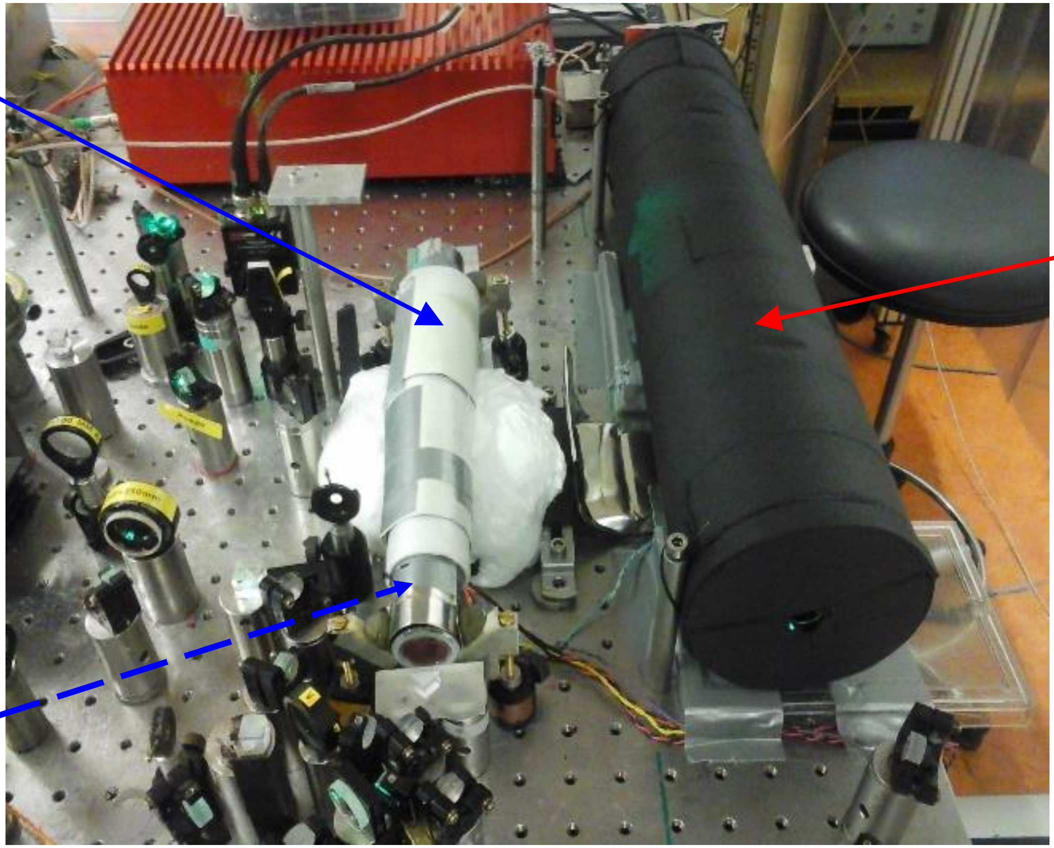
Study of the Zeeman effect



Study of the Zeeman effect

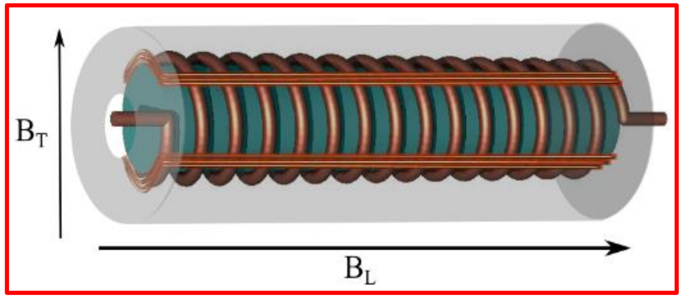
30 cm Iodine Cell
4 optical passes
Cold finger @ -11°C





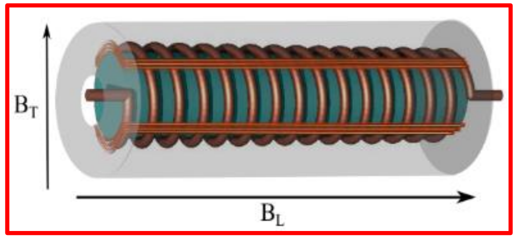
Thermal protection

40 cm iodine cell
2 optical passes
T ambient
Magnetic shield
Solenoid

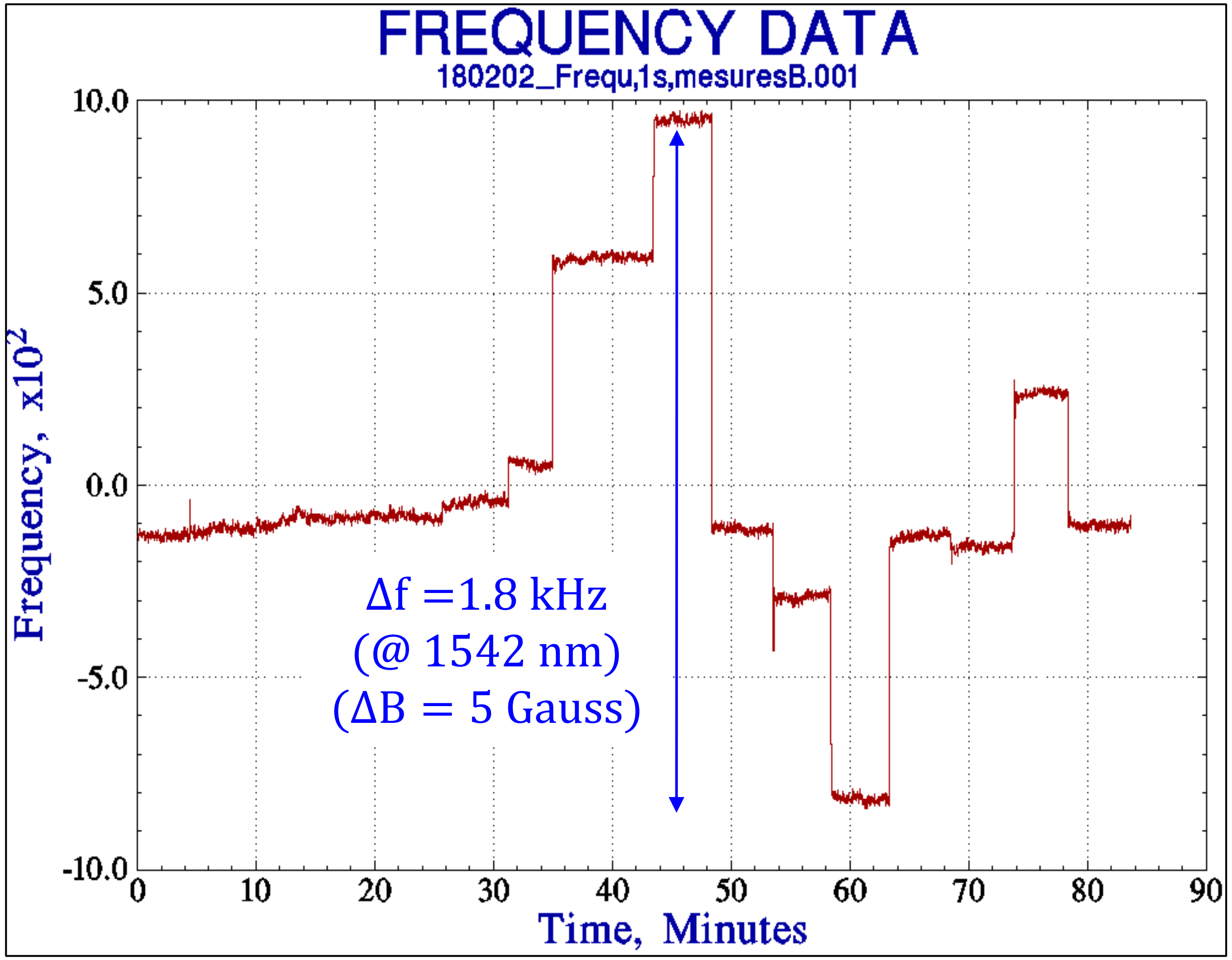


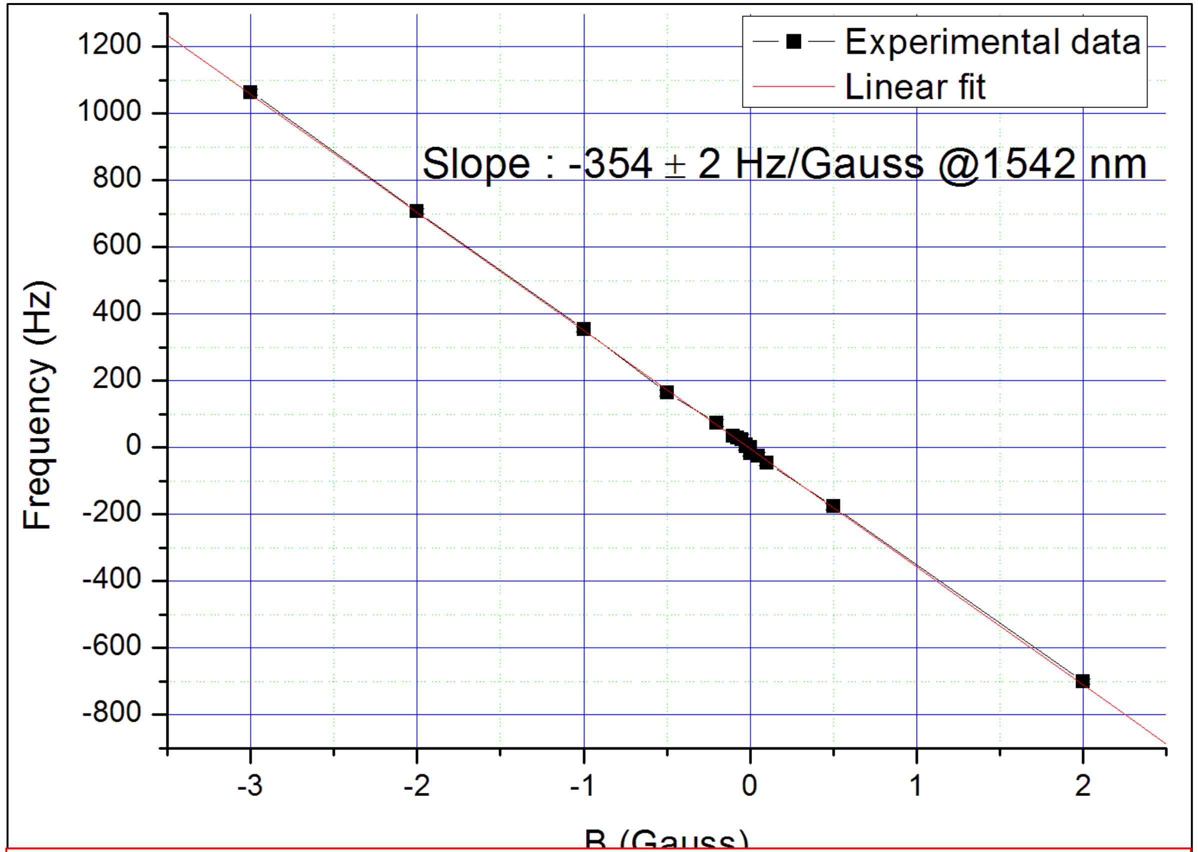
Magnetic shield attenuation factor = 200

Study of the Zeeman effect



7 Gauss / Ampere





Frequency shift : $\Delta\nu \sim 1$ kHz / Gauss @ 514.03 nm

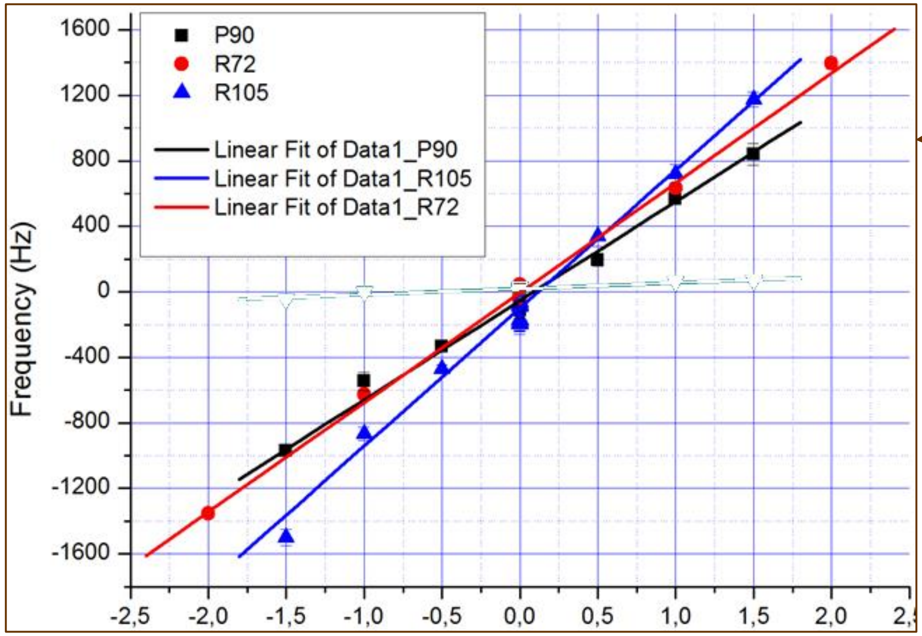
$^{127}I_2$ R 34 [44-0] a_1 component

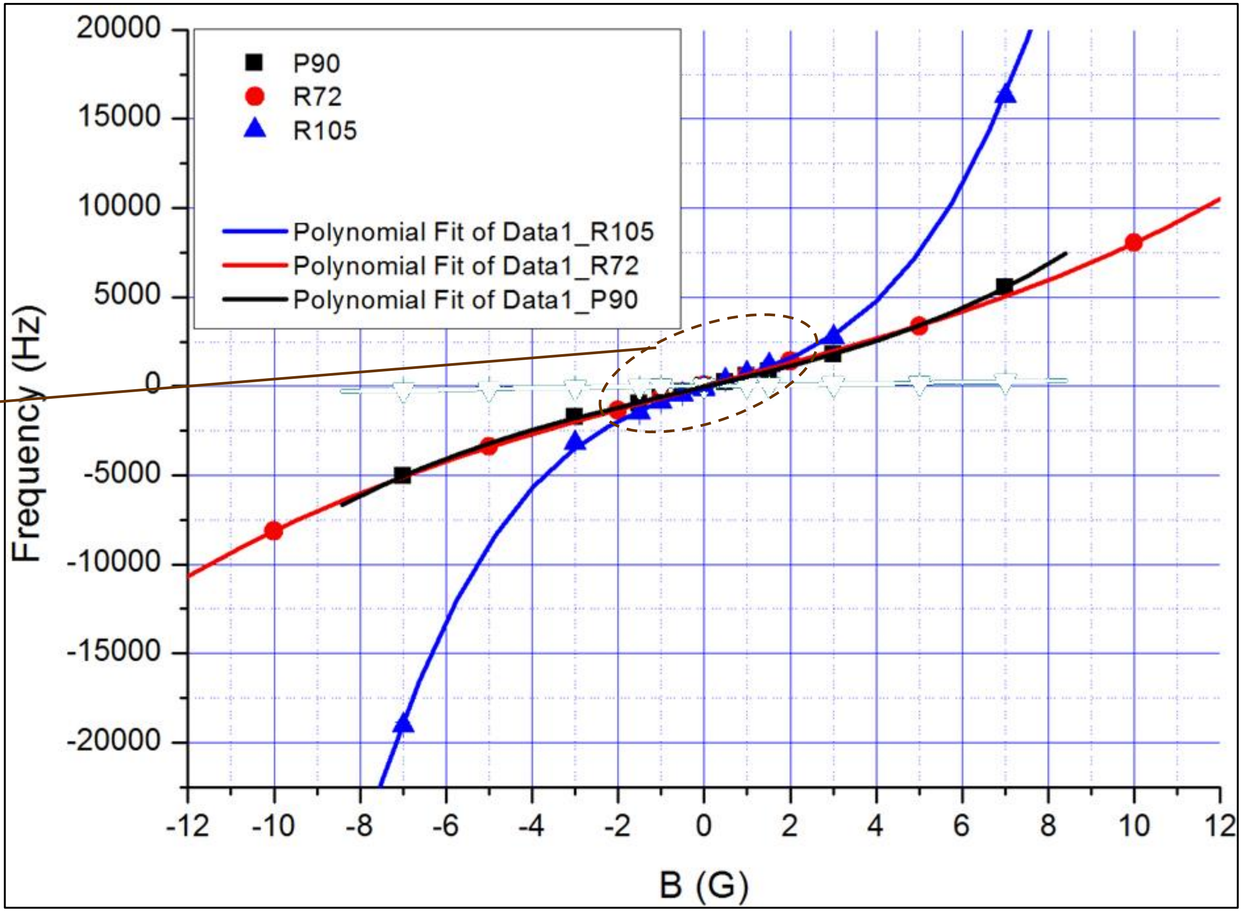
Sensitivity @ 514 nm: **$\delta\nu/\nu \sim 10^{-15}$ /mG** (this work, for laser beams with linear polarization)

Previously estimated as **10^{-18}/mG** (Goncharov, 1996)

Study of the Zeeman effect

Values of fit slopes @ 514 nm:
R34 (44-0) $a_1 \approx$ [354 Hz/G] **x 3**
R72 (46-0) $a_1 \approx$ [670 Hz/G] **x 3**
P90 (48-0) $a_1 \approx$ [605 Hz/G] **x 3**
R105(50-0) $a_1 \approx$ [842 Hz/G] **x 3**

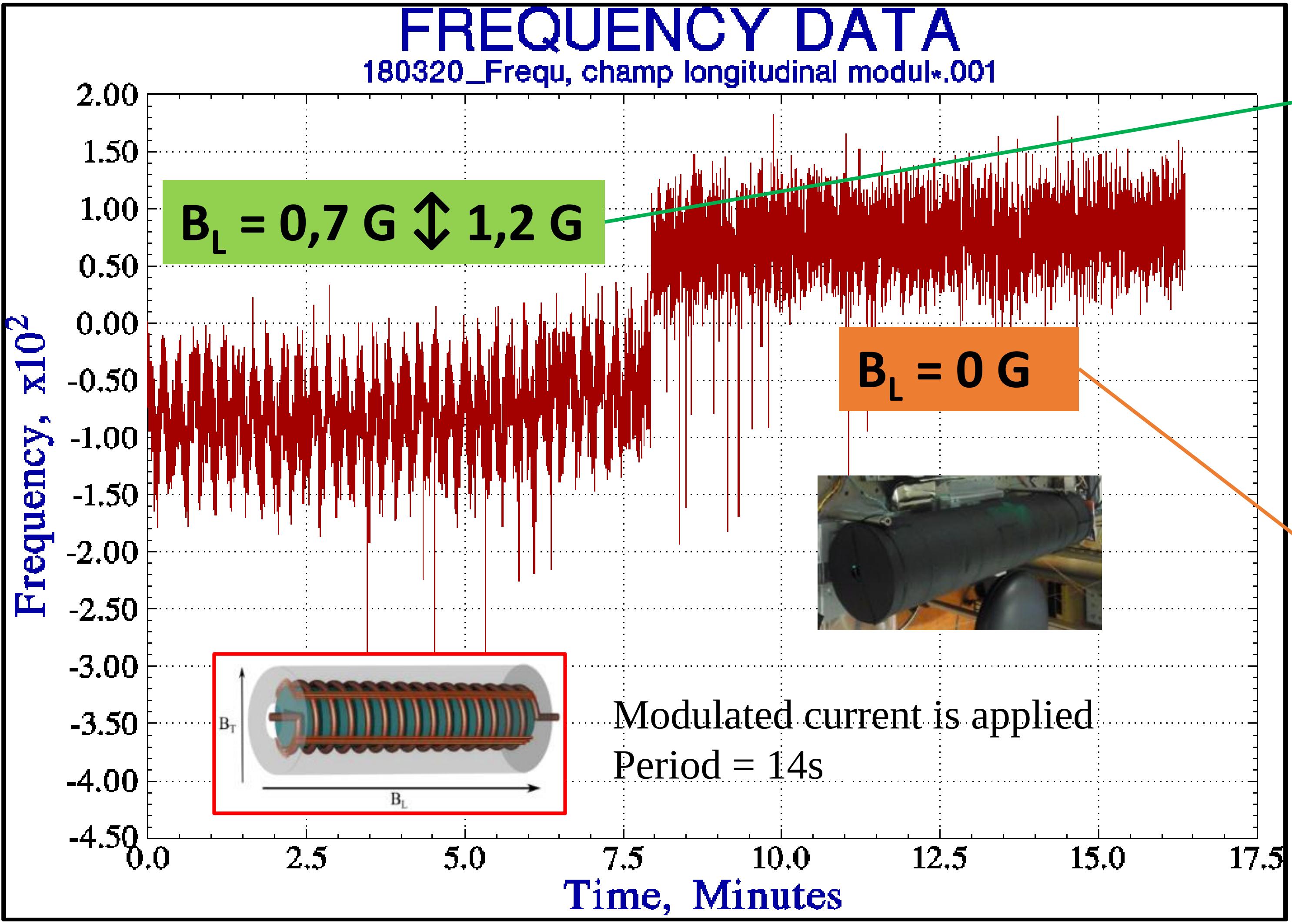


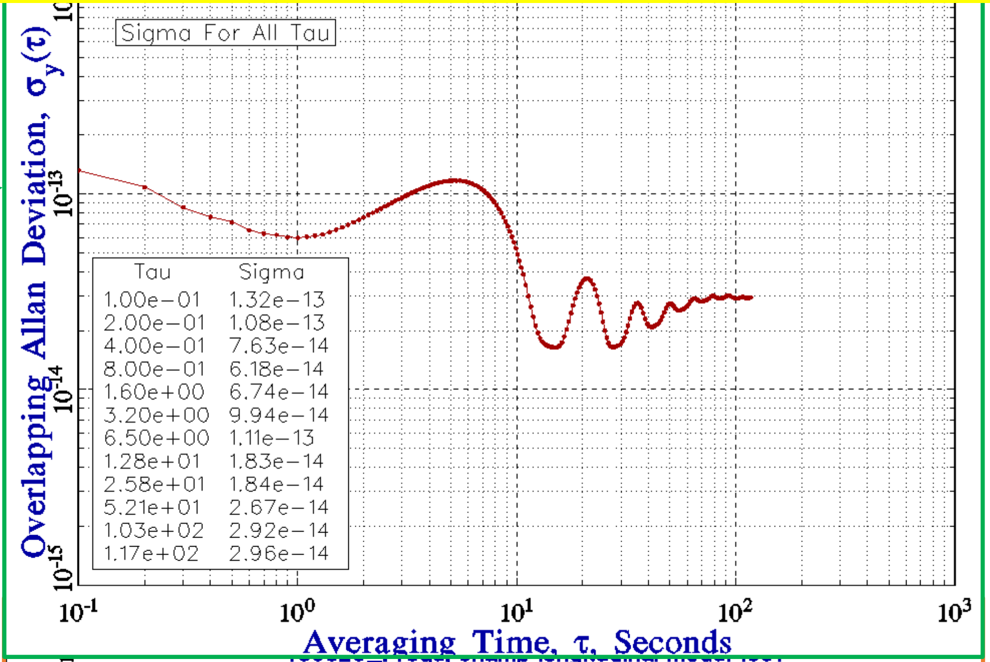


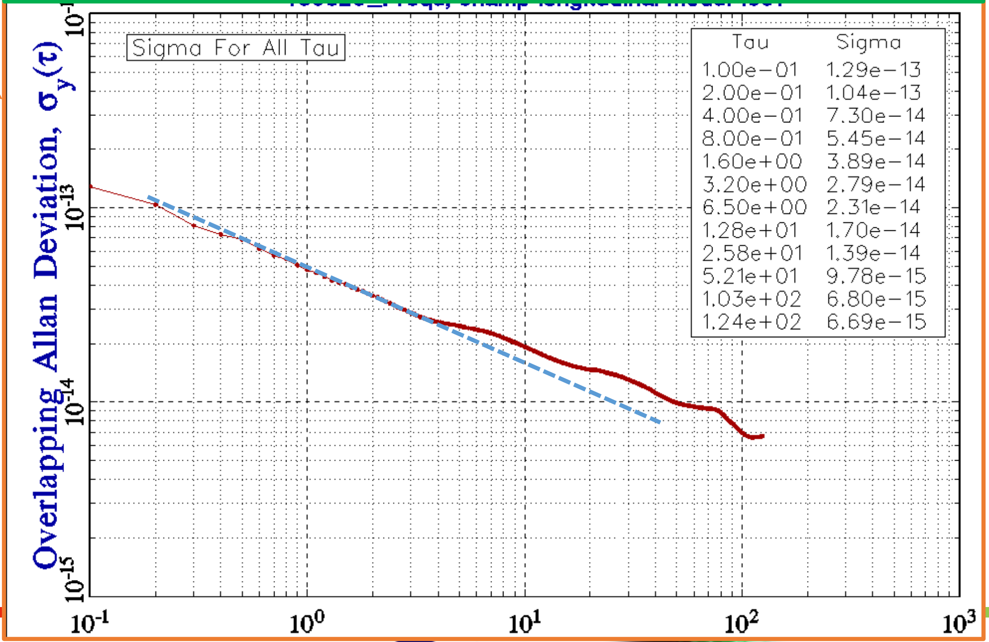
- Depends on the J value
- Linear for small magnetic fields (B<2G)

For B > 2 G, the dependency is nonlinear

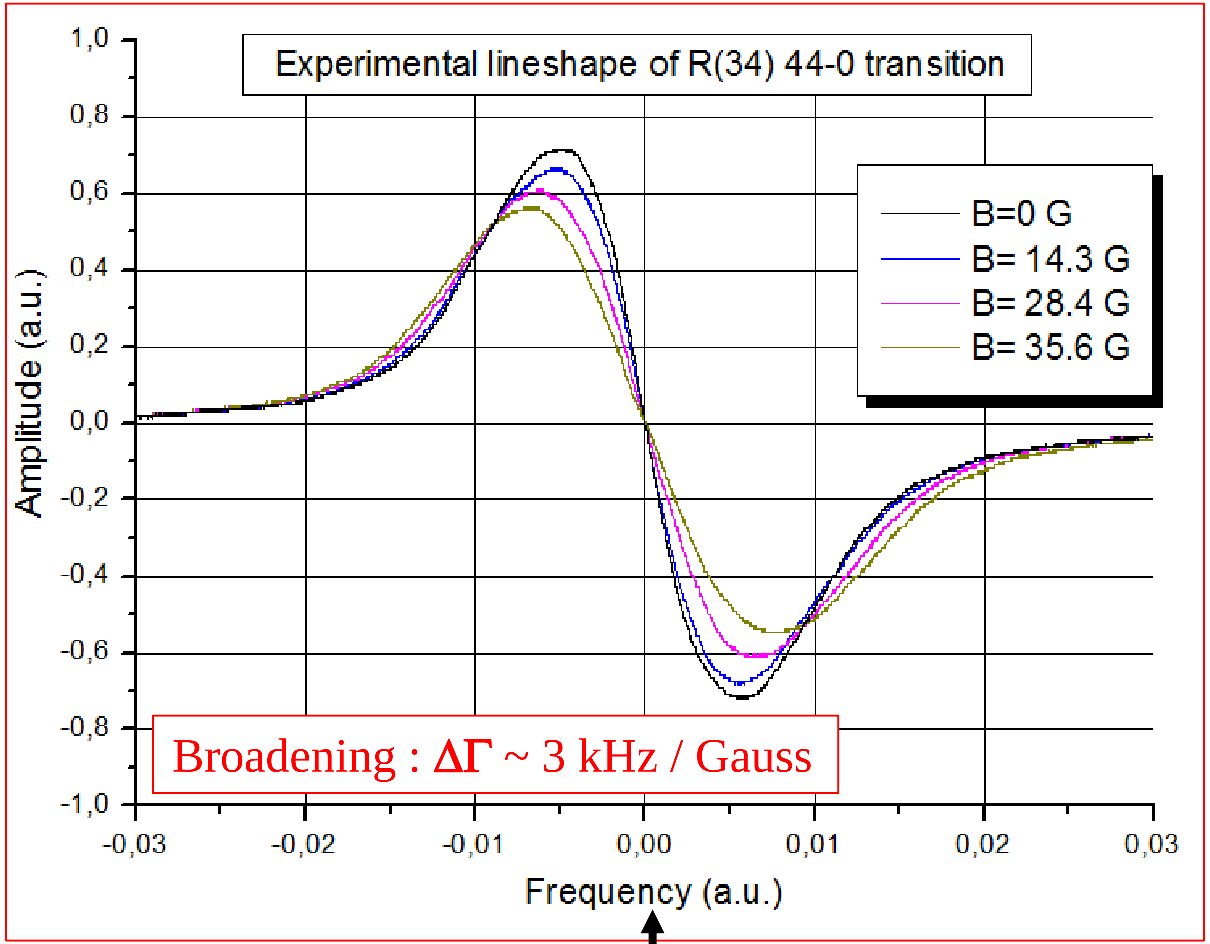
Study of the Zeeman effect

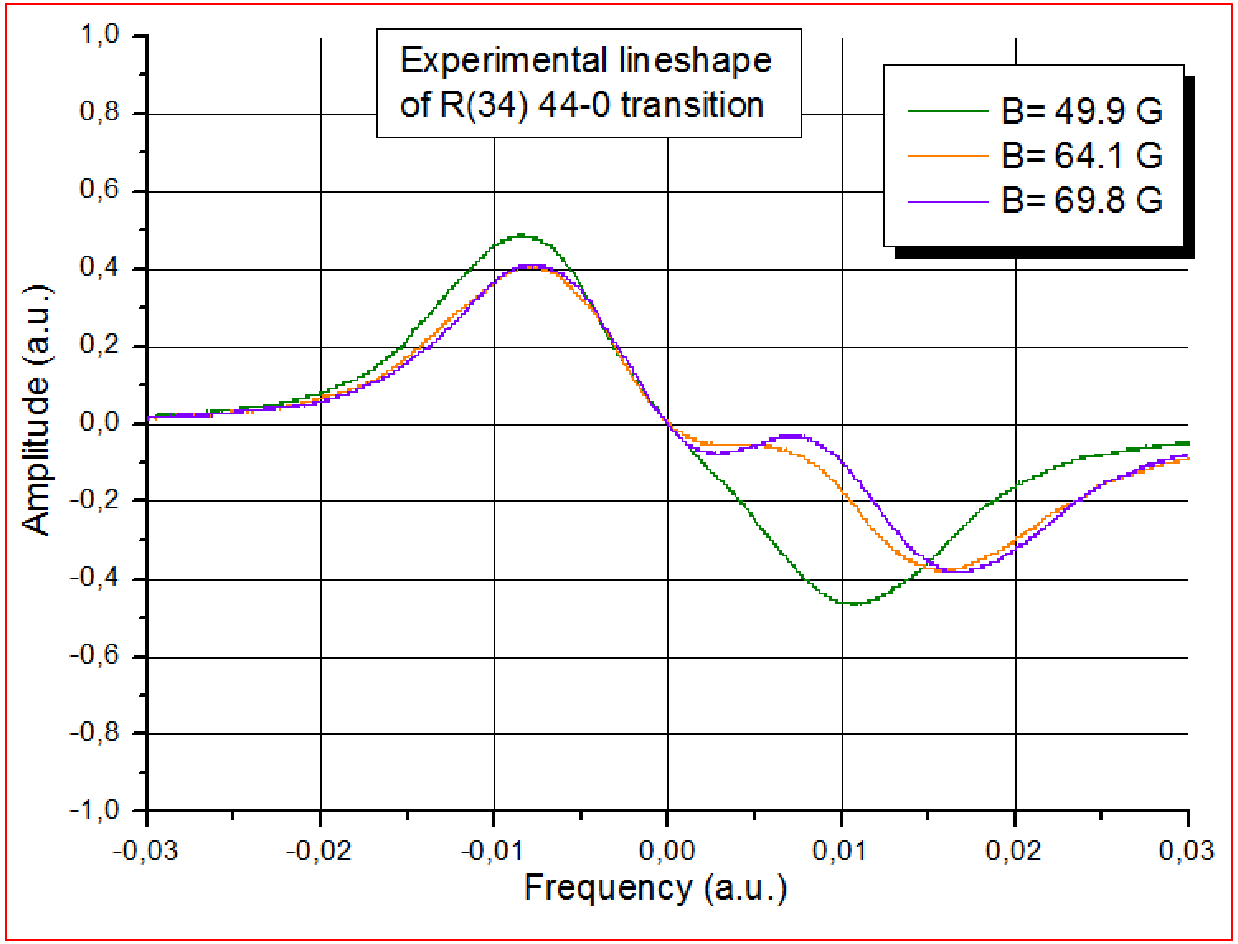






Study of the Zeeman effect



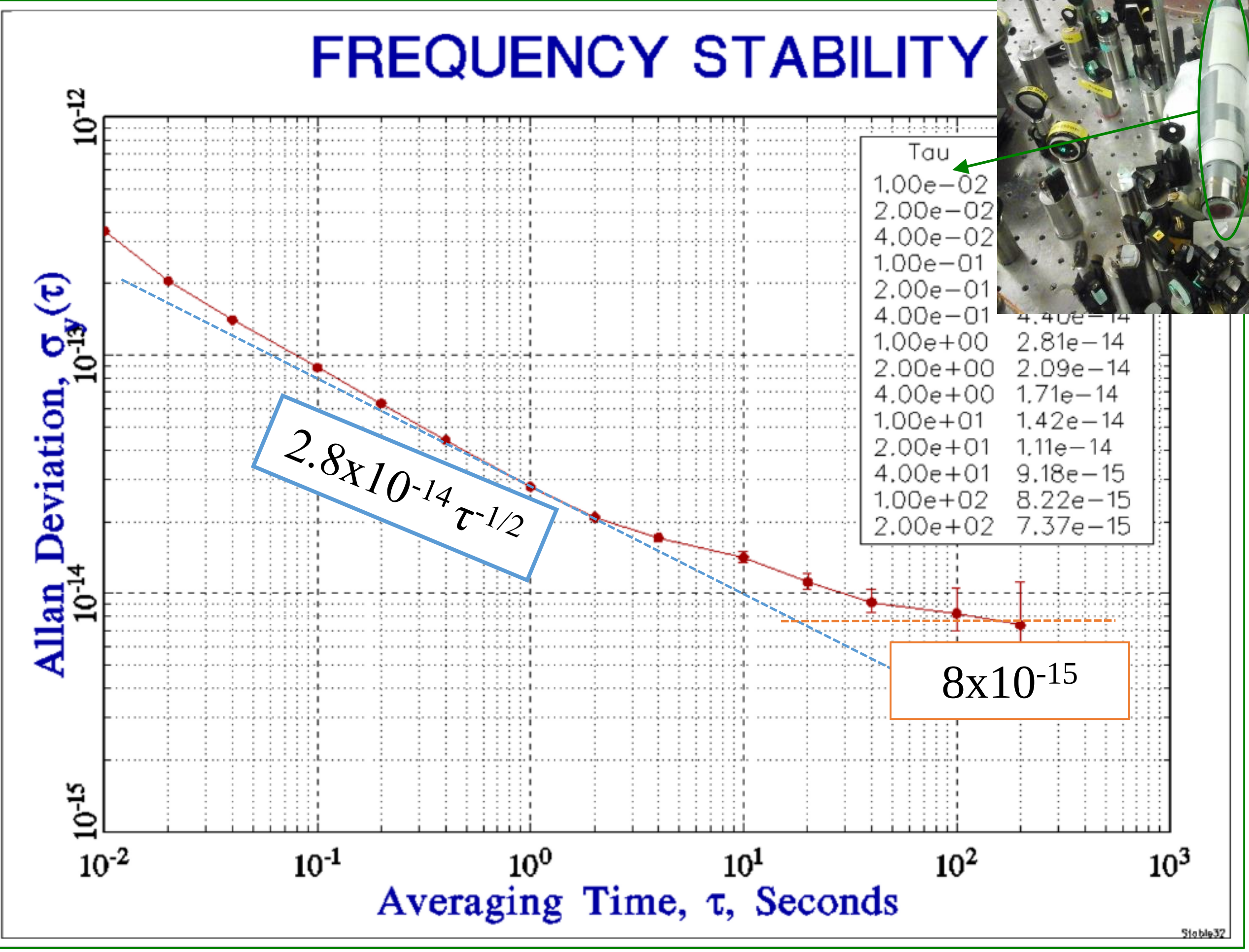


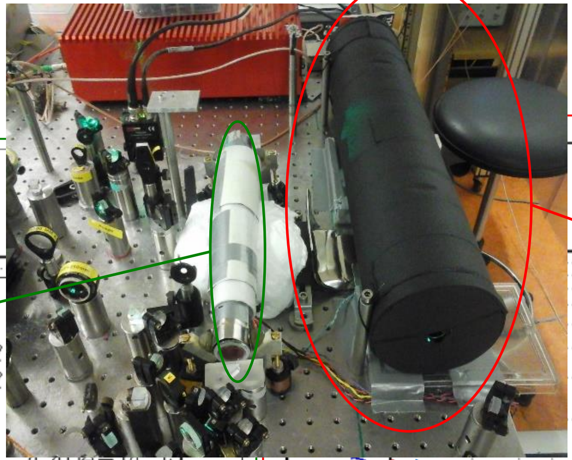
The center of the lines are superimposed to emphasize the Zeeman broadening
The iodine linewidth is increased by 30% when the magnetic field is varied from 0 to 35G
Broadening : $\Delta\Gamma$ ~ 3 kHz / Gauss

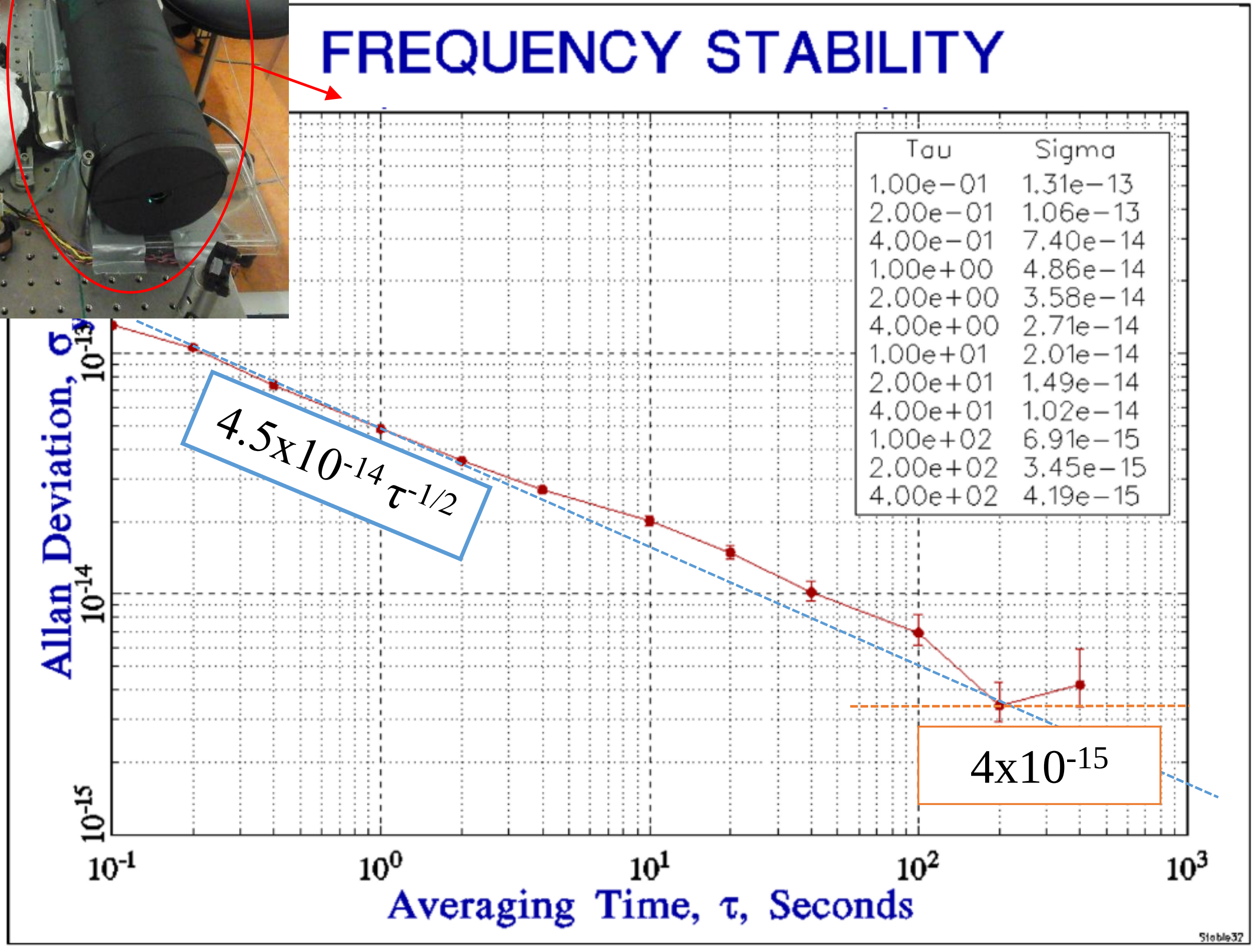
Study of the Zeeman effect

Without magnetic shield around the iodine cell

With magnetic shield around the iodine cell







J. Barbarat et al., IFCS-EFTF'2019, Orlando, Florida, USA, April 2019

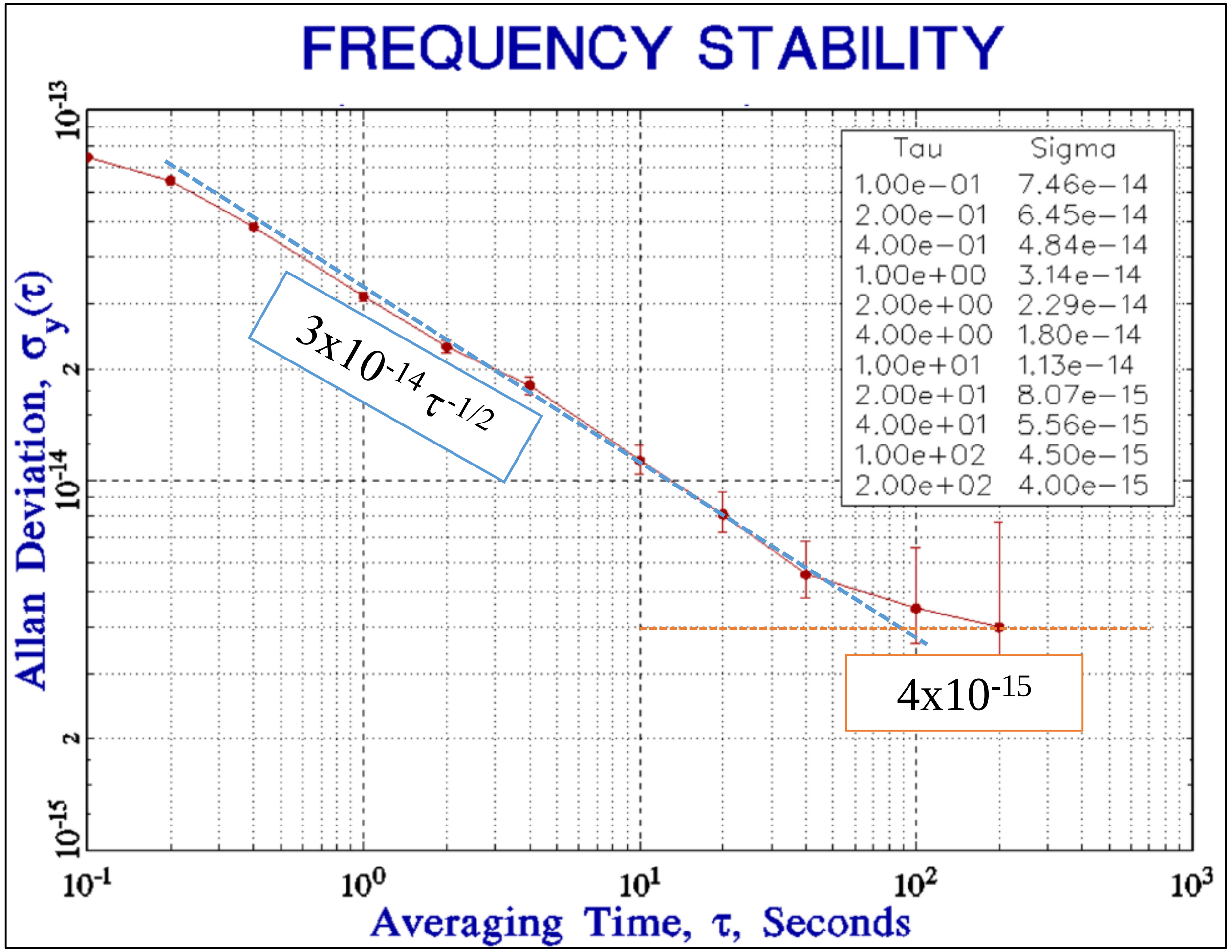
Outline

New frequency modulation architecture

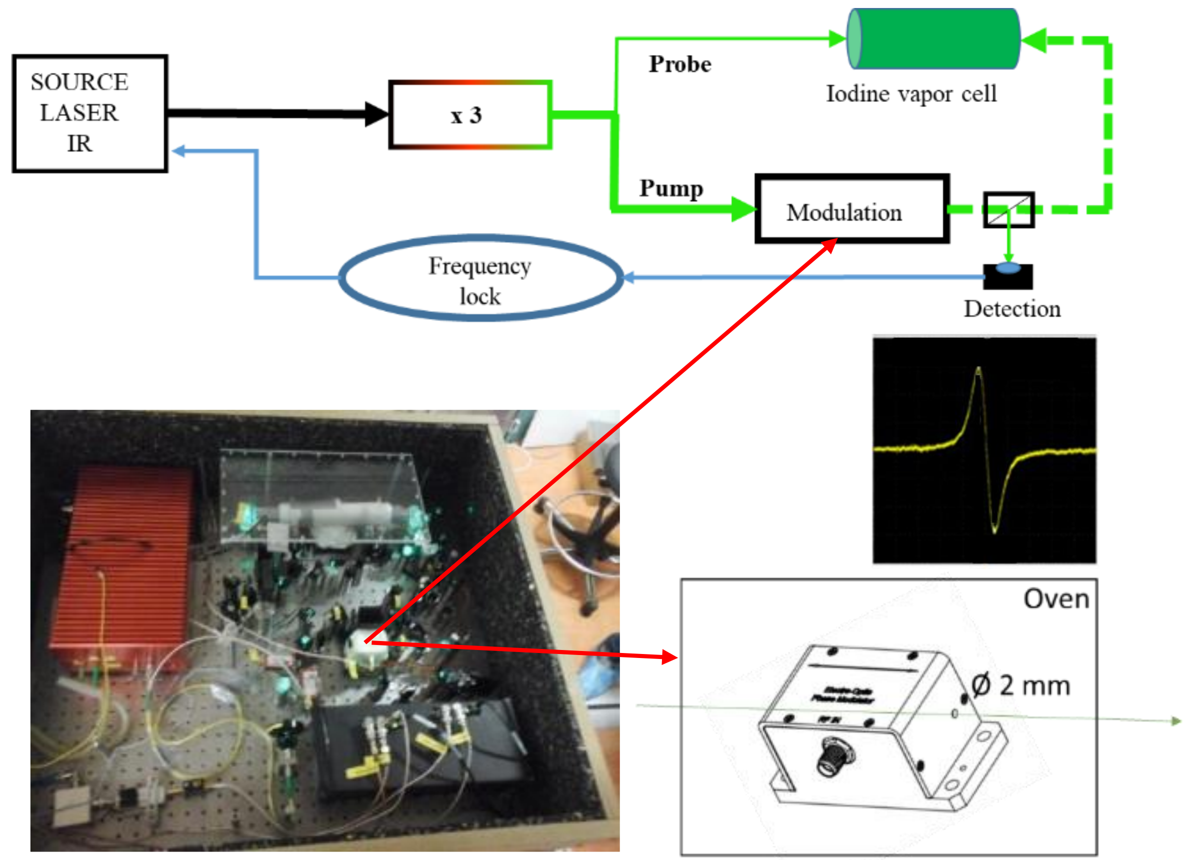
- Modulation transfer spectroscopy
- **With** Optical power stabilization
- Using cooled iodine cell (-11°C)
- Interaction length = **120 cm**

Limitations of the free space setup for transportability

X Use of the EOM in the green range in free space configuration needs a perfect alignment (2×2 mm² over 90 mm length)

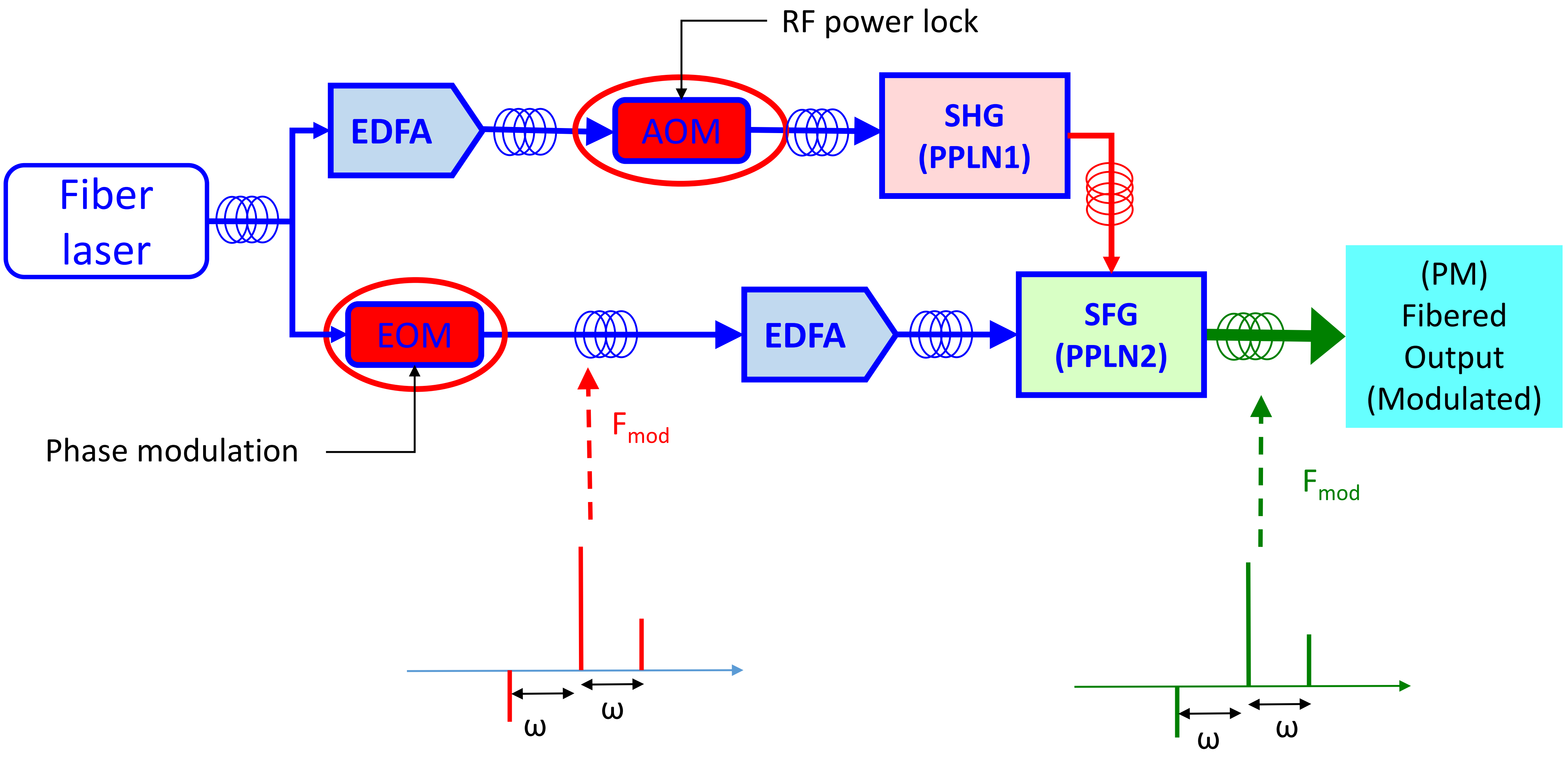


Tau	Sigma
1.00e−01	7.46e−14
2.00e−01	6.45e−14
4.00e−01	4.84e−14
1.00e+00	3.14e−14
2.00e+00	2.29e−14
4.00e+00	1.80e−14
1.00e+01	1.13e−14
2.00e+01	8.07e−15
4.00e+01	5.56e−15
1.00e+02	4.50e−15
2.00e+02	4.00e−15

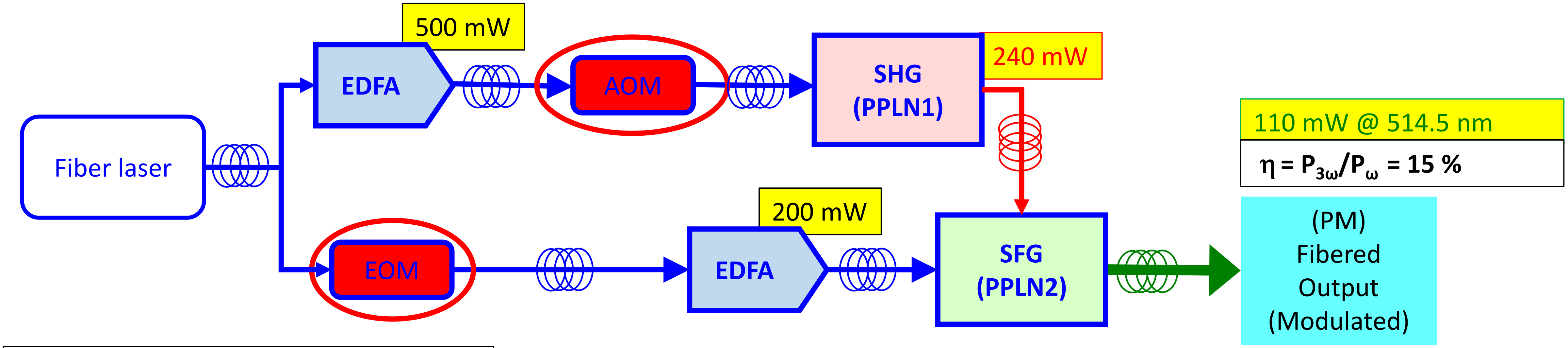


80 x 80 x 20 cm^3 (~ 130 liters)

New optical architecture

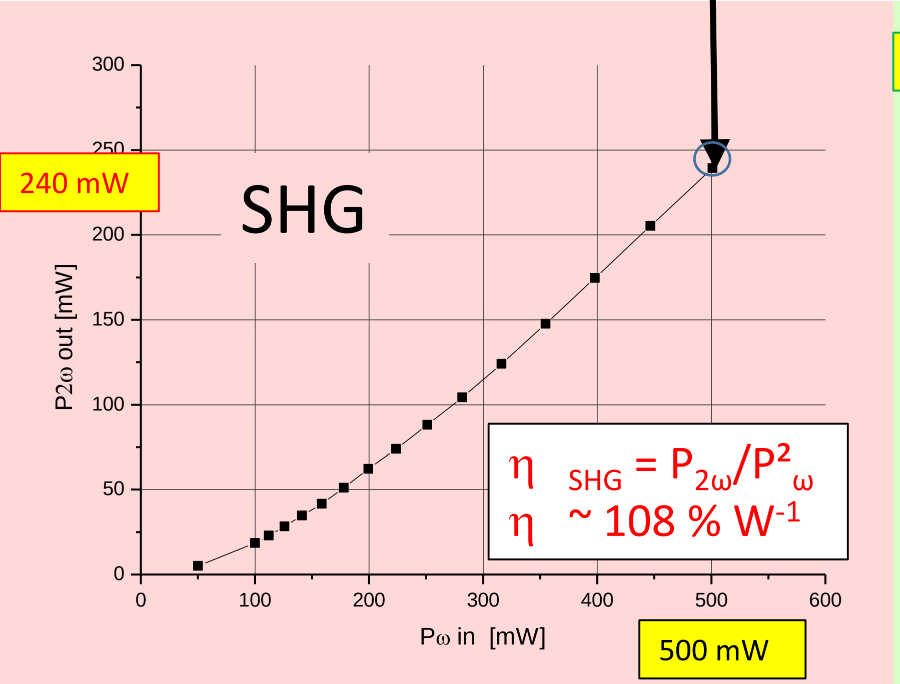


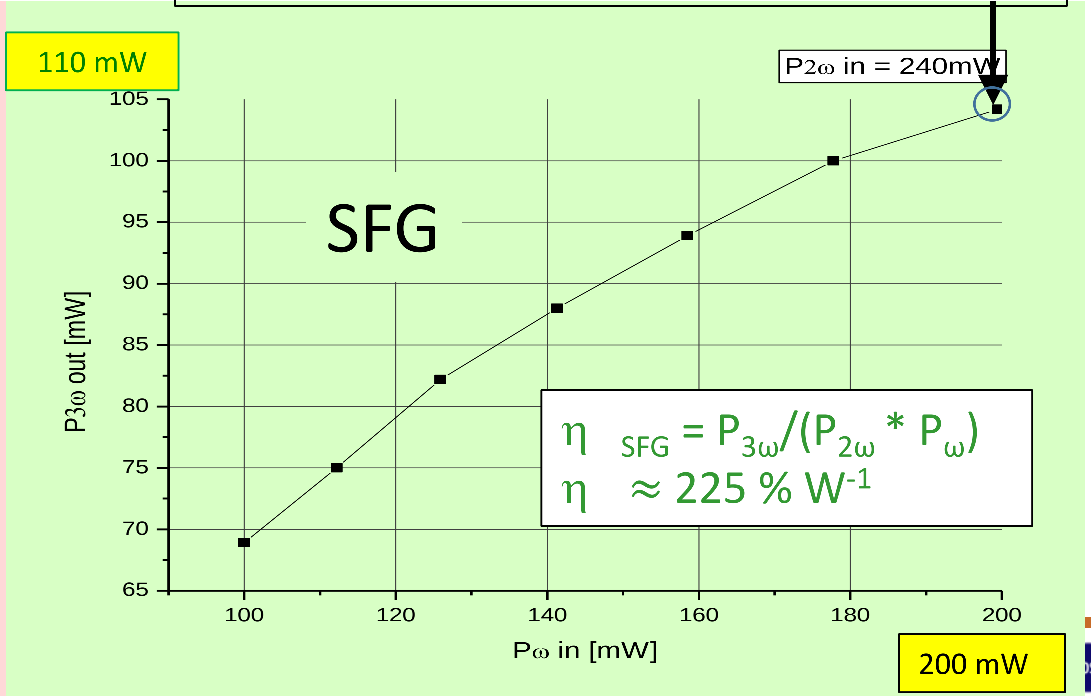
Development of a new compact transportable laser setup



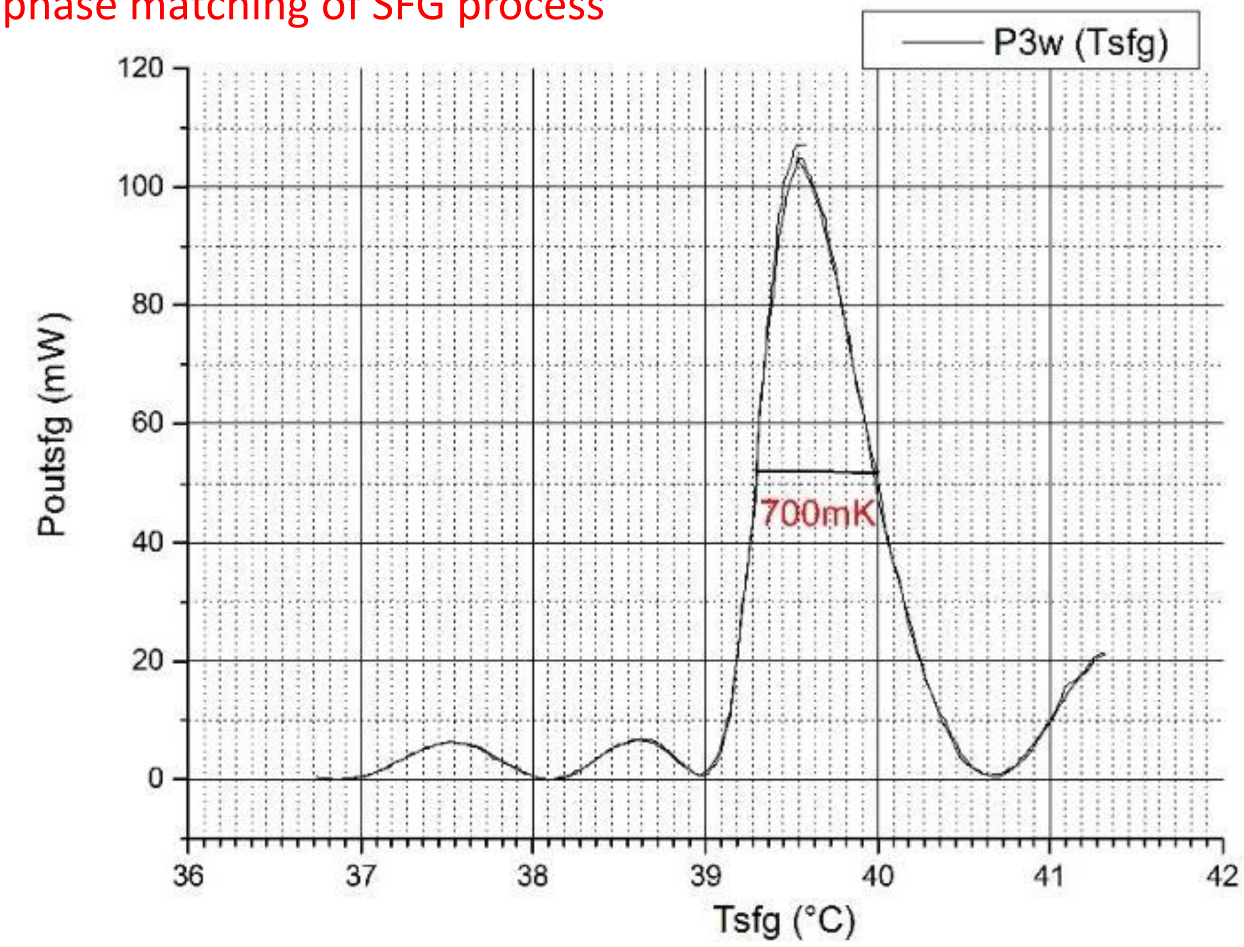
Optical conversion 2ω: $P_{2\omega} / P_\omega = 65\ \%$

Optical conversion à 3ω: $P_{3\omega} / (P_\omega + P'_\omega) = 15\ \%$



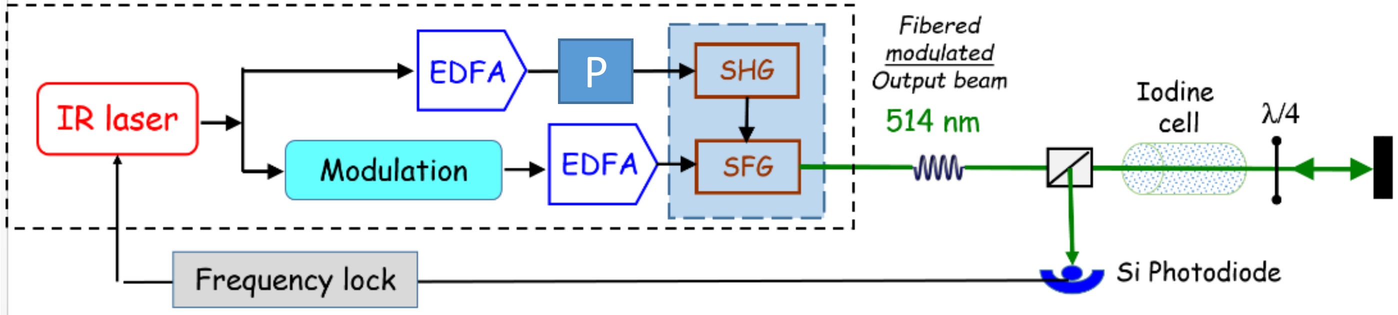


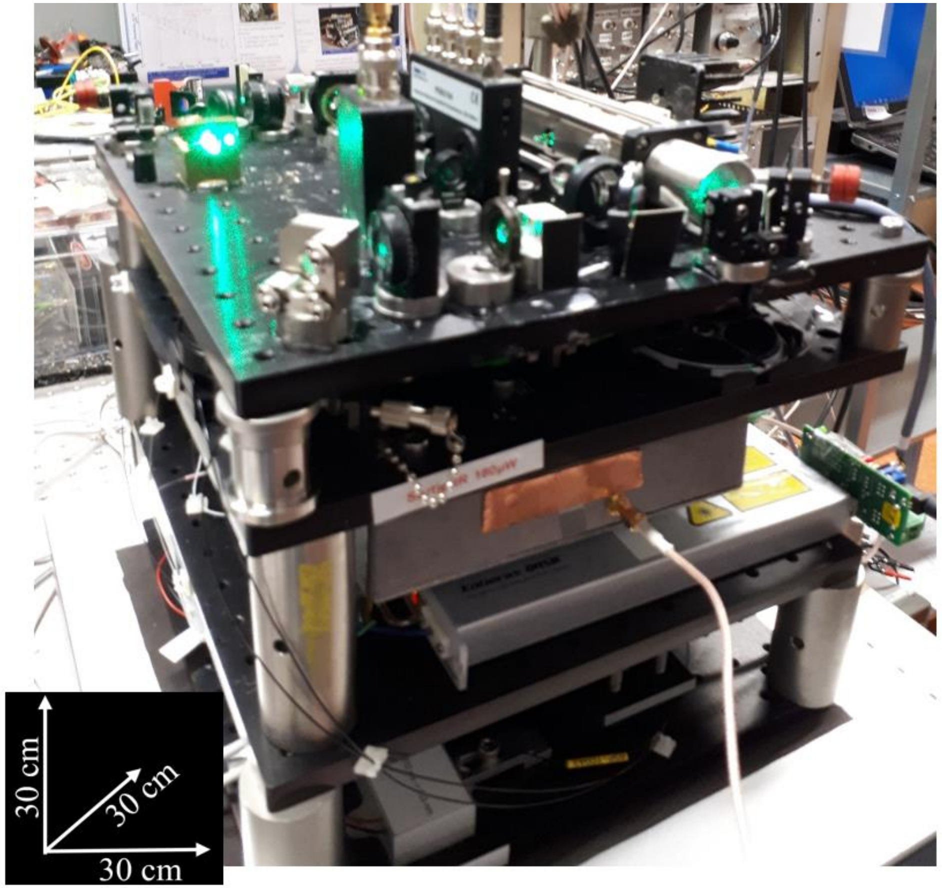
Temperature phase matching of SFG process



The home made temperature stabilization device allow residual fluctuations at ≈mK level (SYRTE electronic workshop)

Development of a new compact transportable laser setup





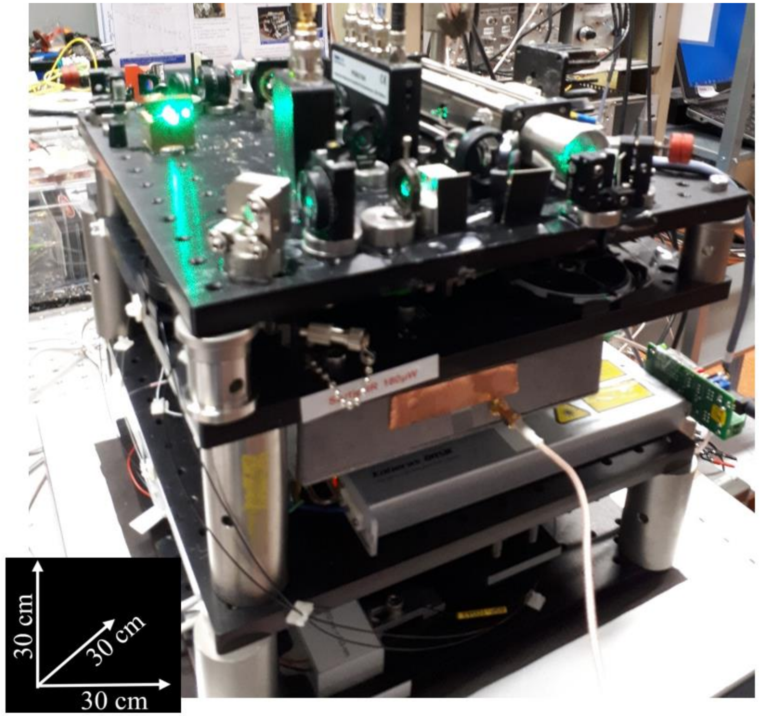
- Compact setup : 30 x 30 x 30 cm^3 = 27 liters

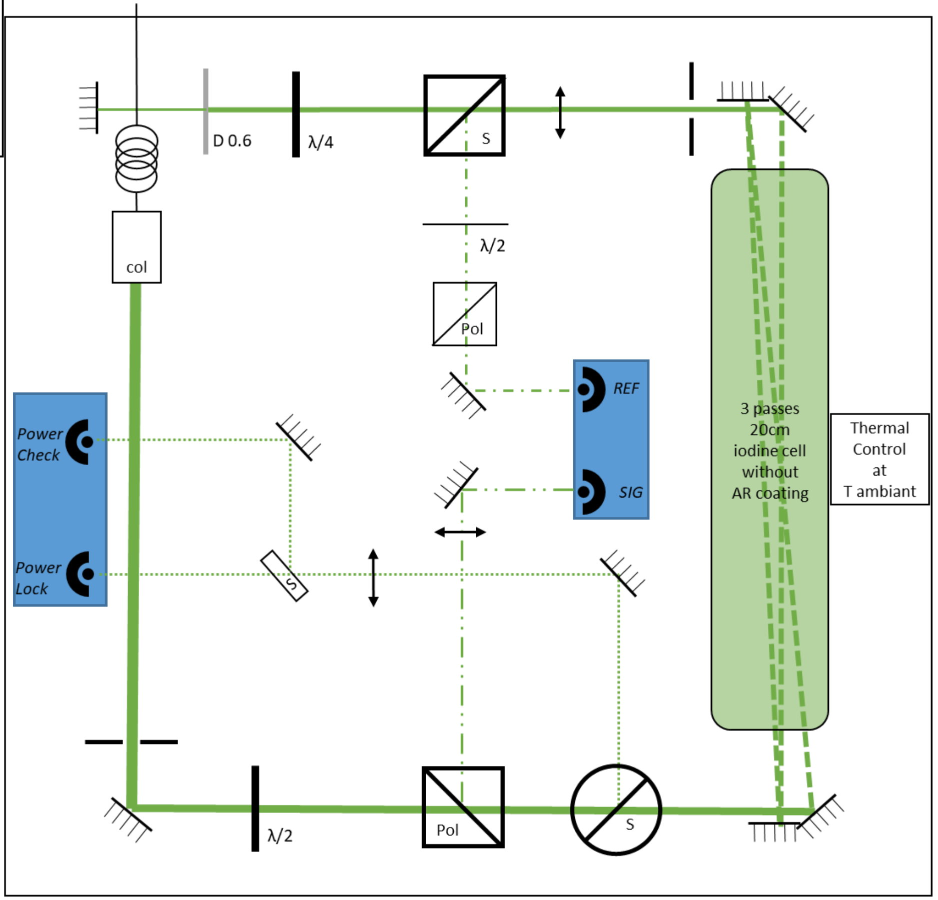
Fibered:
- Fiber laser
- 2 x EDFA
- 2 x LiNbO3 NL crystals (THG process)
- 1 x EOM (Phase modulation)
- 1 x AOM power stabilization in the green

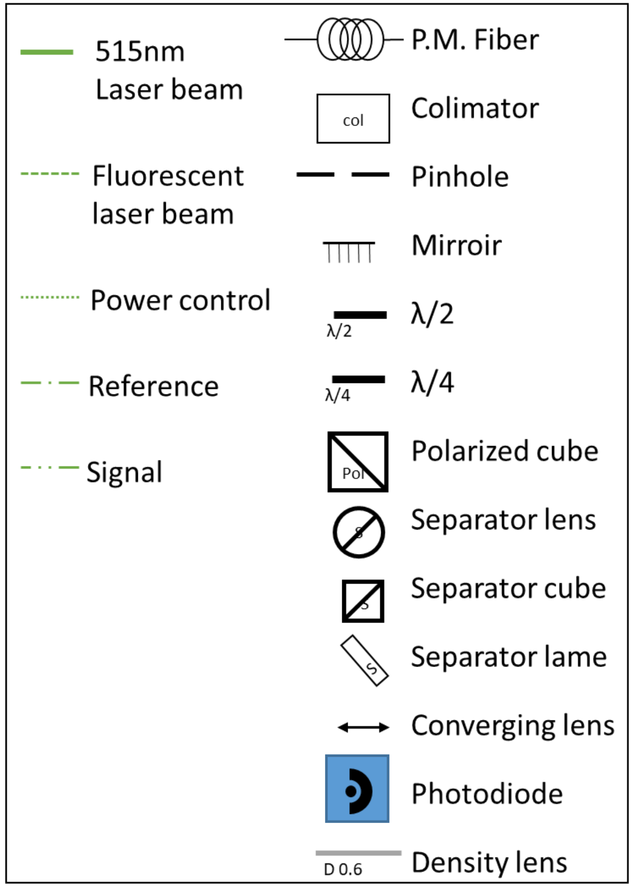
Free space:
- 1 x Iodine cell
- 2 x Photodiodes

J. Barbarat et al., ICSO 2018, Chania Greece, Oct. 2018

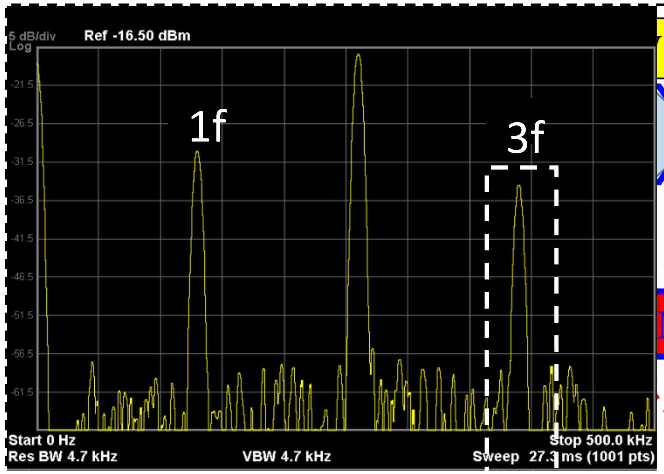
- Frequency Modulation Spectroscopy
- Using Uncooled iodine cell (+20°C)
- Interaction length: 3 x 20 = **60 cm**
- **Without** optical power stabilization
- Frequency modulation by an AOM at 70 kHz

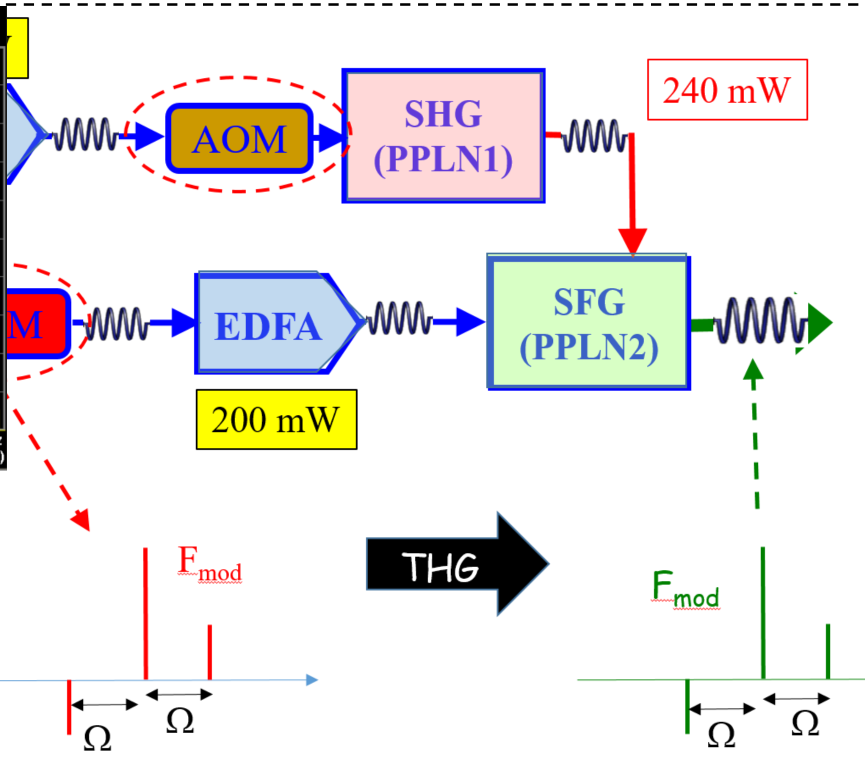






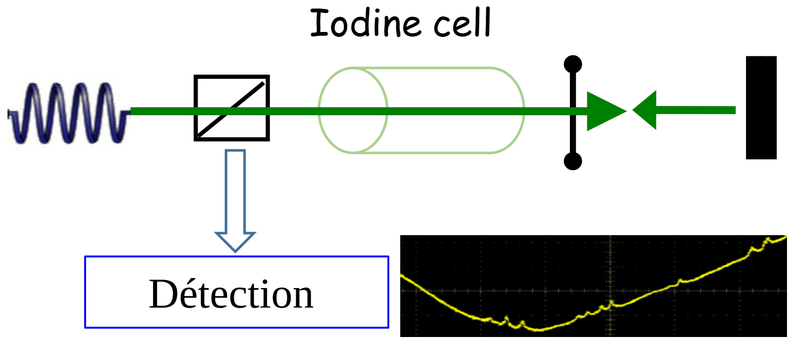
Development of a new compact transportable laser setup



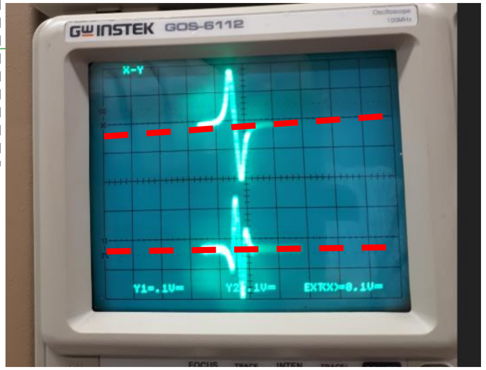


110 mW @ 514.5 nm

$\eta = P_{3\omega}/P_{\omega} = 15\ \%$

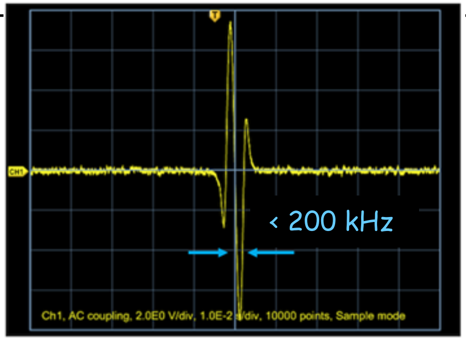


Third derivative of the iodine line is used to frequency stabilize the fiber laser



$\sqrt{10}/\sqrt{3} \approx 1{,}8$

$a_1/a_3 \sim 3 - 4$

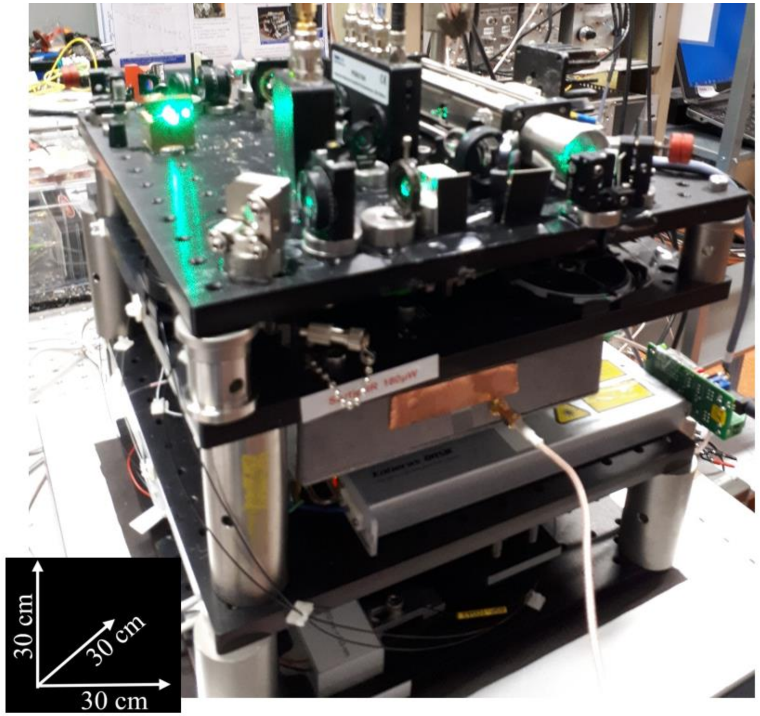


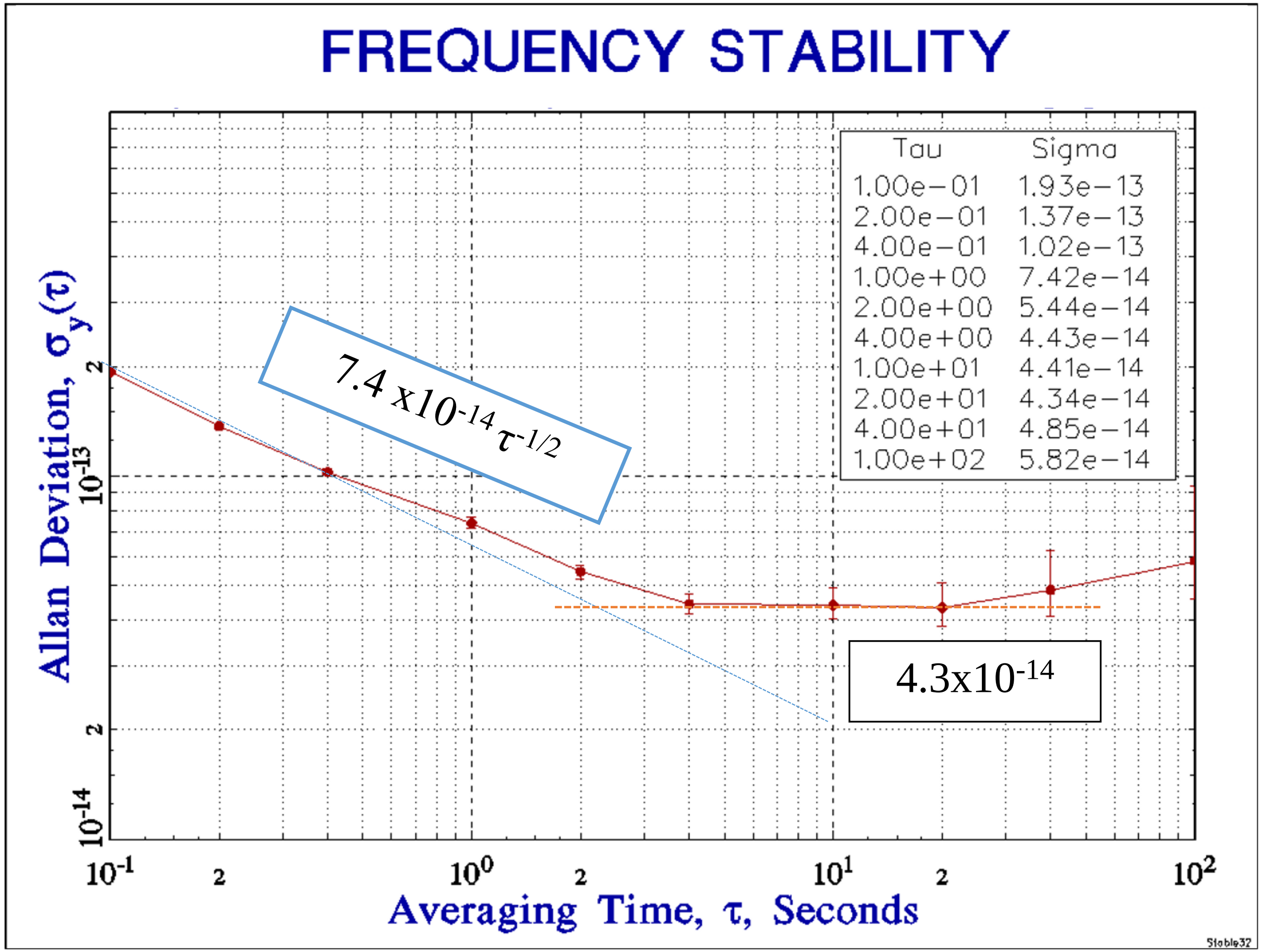
~ σ / 2

$$\sigma \propto \frac{1}{S/_B * Q}$$

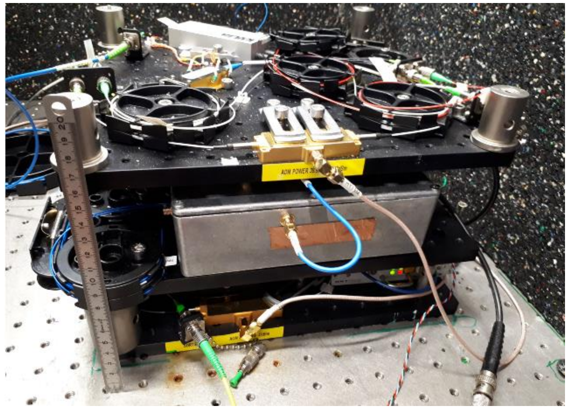
Development of a new compact transportable laser setup

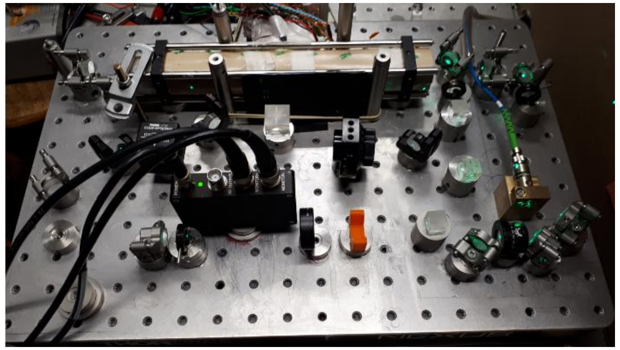
- Frequency Modulation Spectroscopy
- Using Uncooled iodine cell (+20°C)
- Interaction length: 3 x 20 = **60 cm**
- **Without** optical power stabilization
- Frequency modulation by an AOM at 70 kHz

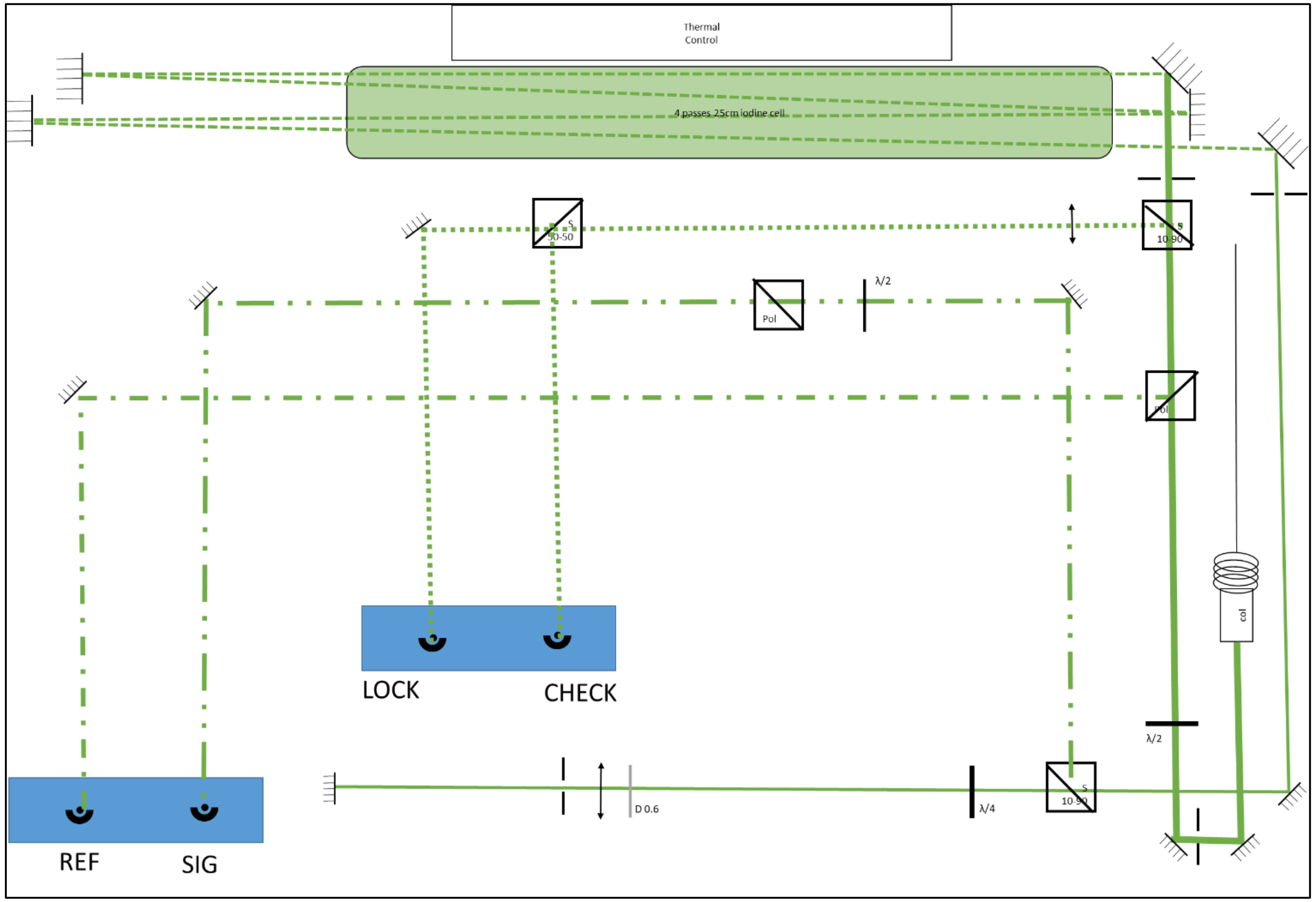




- Frequency Modulation Spectroscopy
- Using a cooled iodine cell (-15°C)
- Interaction length: 4 x 25 = **100 cm**
- **With** Optical power stabilization
- Phase modulation by an EOM at 130 kHz

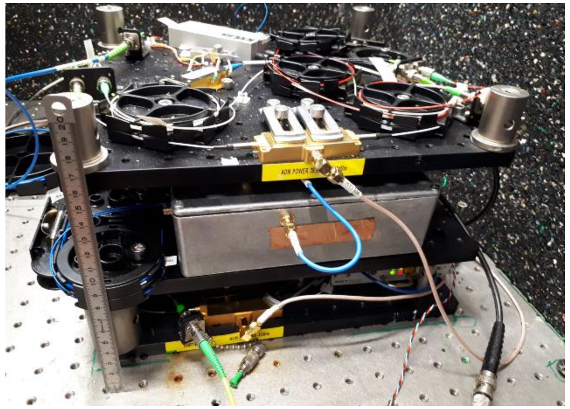


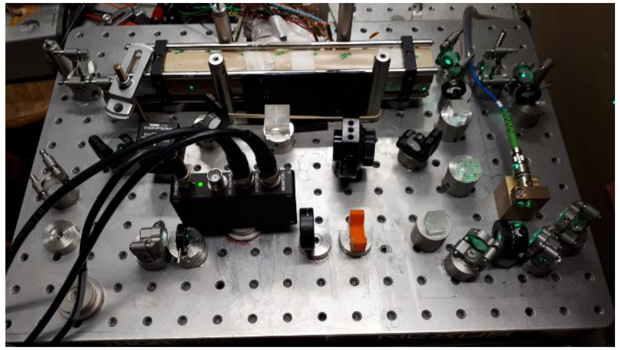


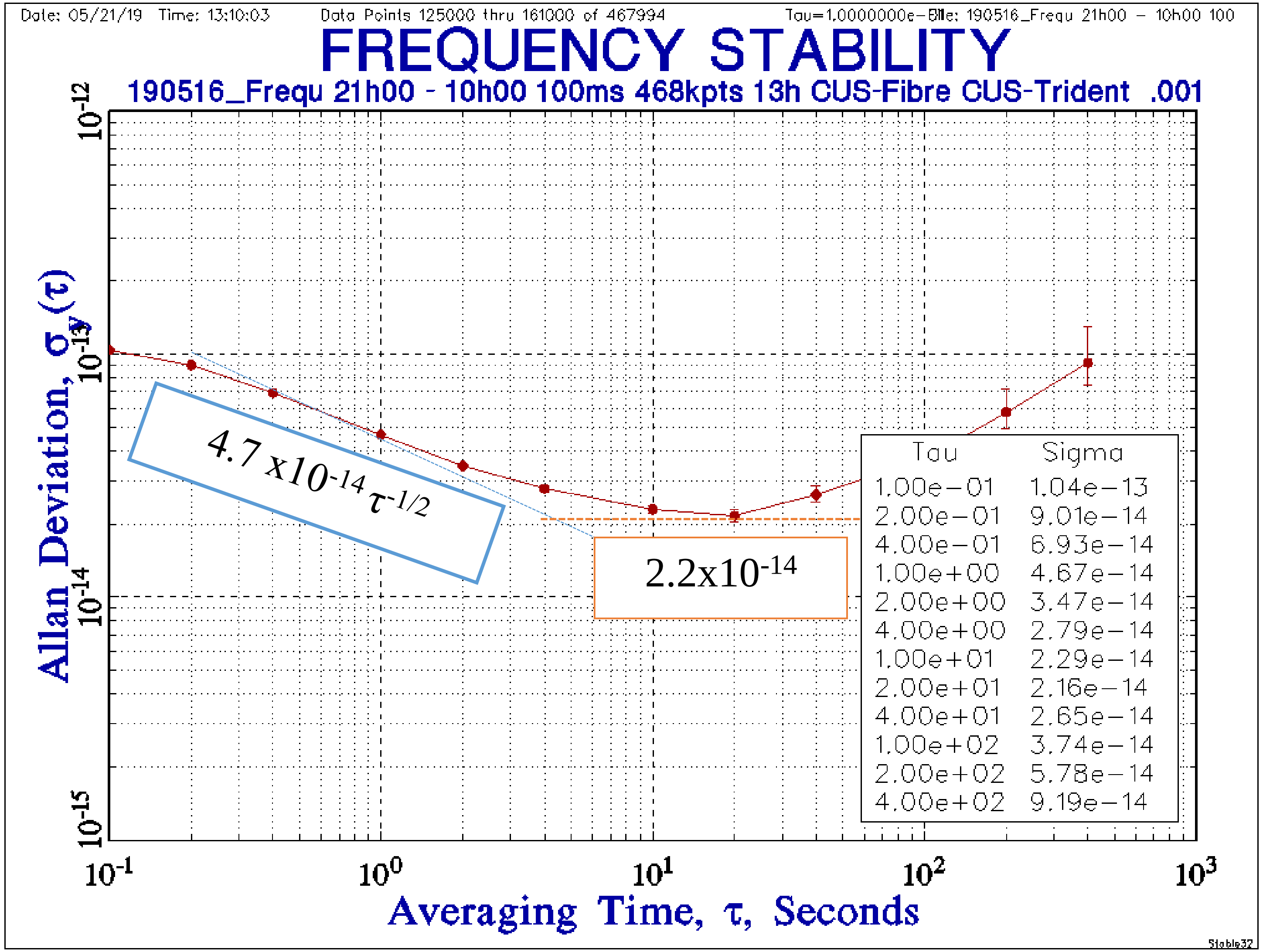


Development of a new compact transportable laser setup

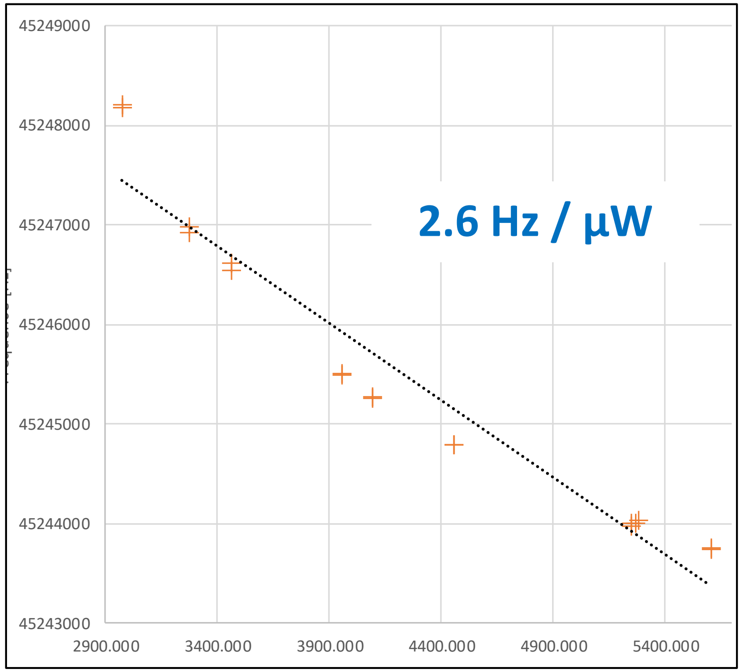
- Frequency Modulation Spectroscopy
- Using a cooled iodine cell (-15°C)
- Interaction length: 4 x 25 = **100 cm**
- **With** Optical power stabilization
- Phase modulation by an EOM at 130 kHz

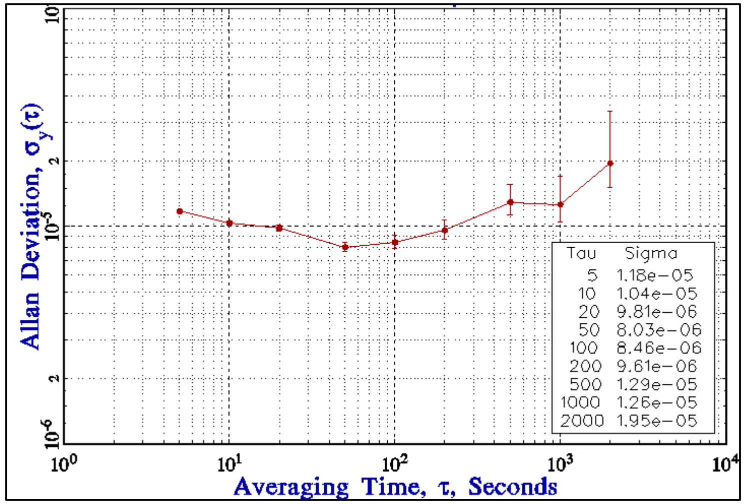






Power sensitivity





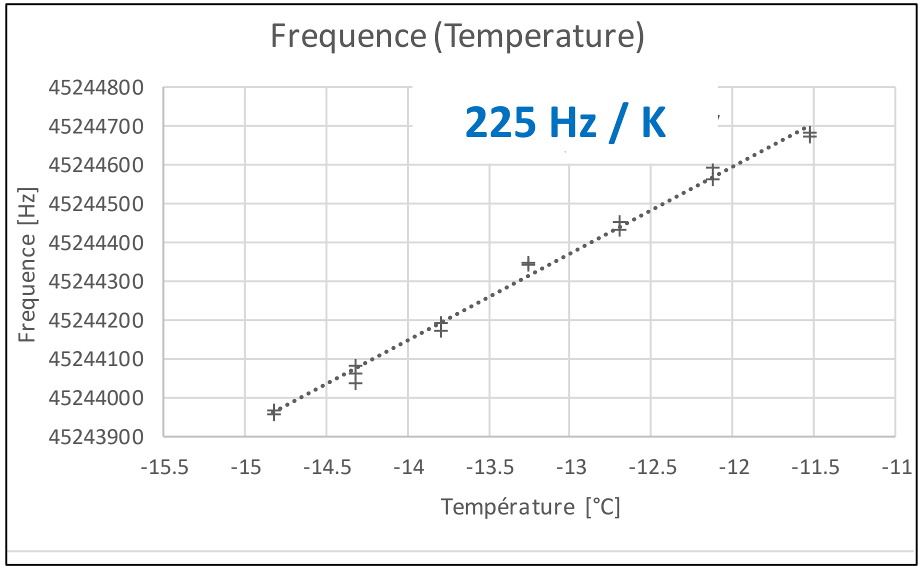
Mean: 6 mW

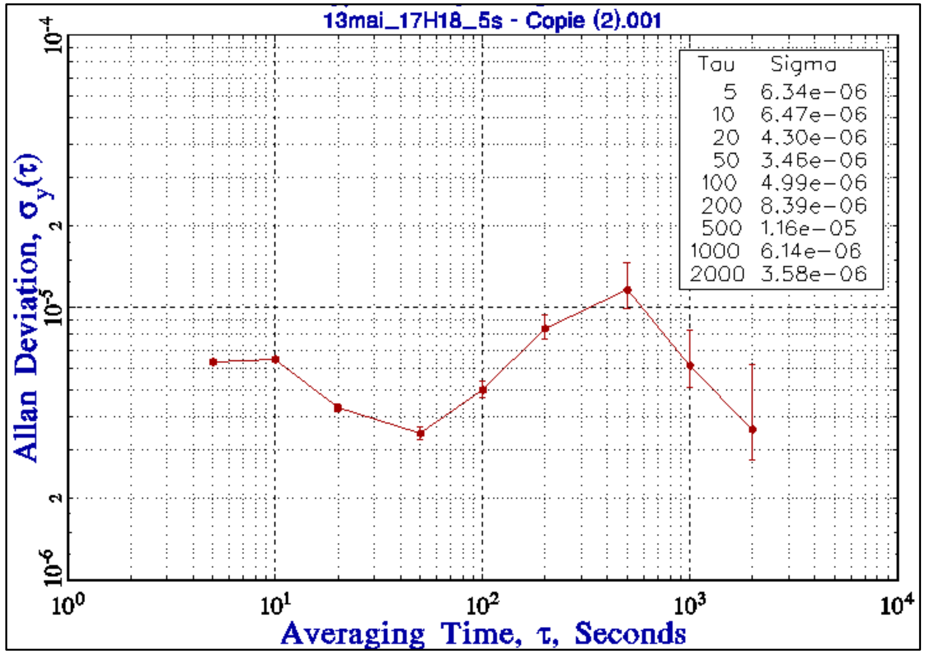
ΔP = 0.06 µW

Δν = 0.2Hz

Δν/ν = 1.10^{-15} ((contribution to residual frequency instability)

Iodine pressure cell sensitivity





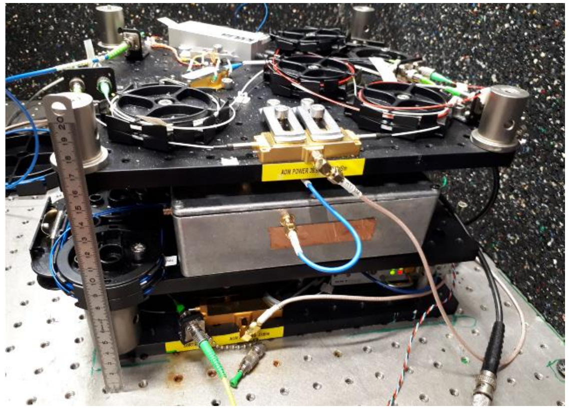
Mean: -14°C

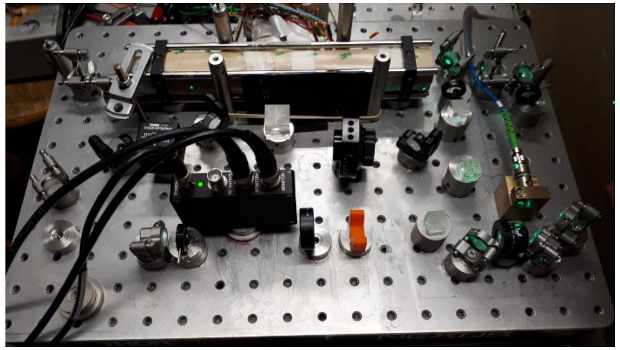
ΔT = 0.2mK

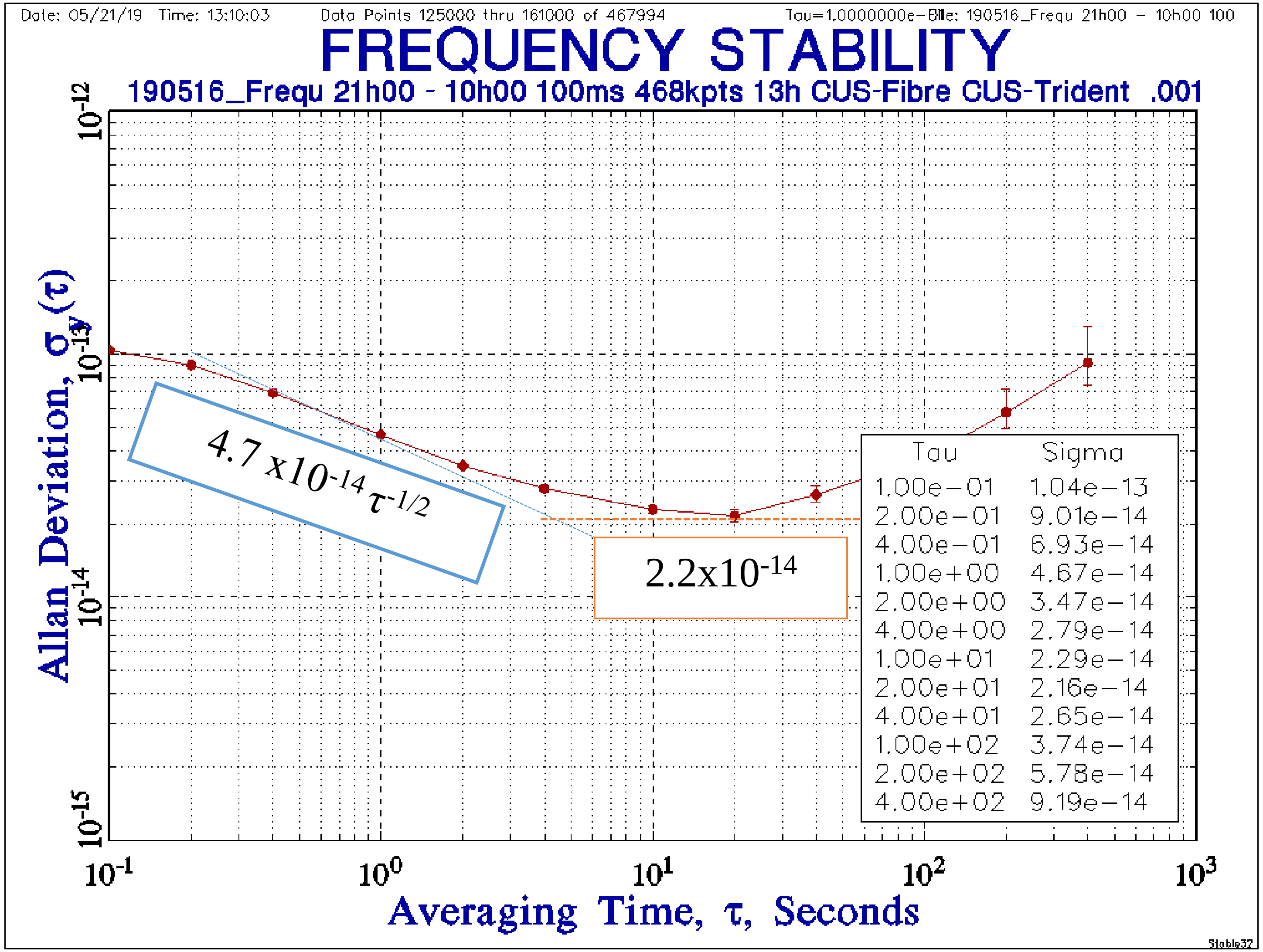
Δν = 0.05Hz

Δν/ν = 3.10^{-16} (contribution to residual frequency instability)

- Frequency Modulation Spectroscopy
- Using a cooled iodine cell (-15°C)
- Interaction length: 4 x 25 = **100 cm**
- **With** Optical power stabilization
- Phase modulation by an EOM at 130 kHz





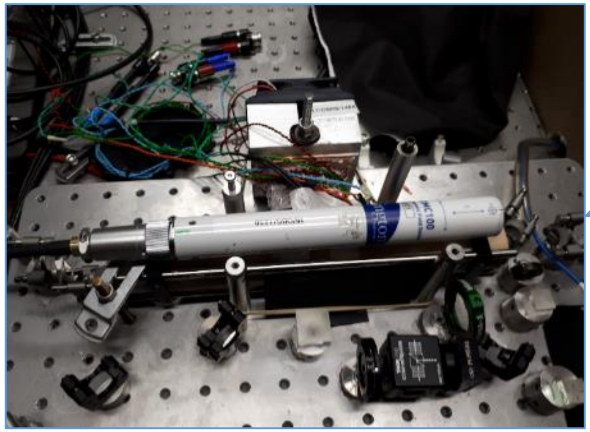


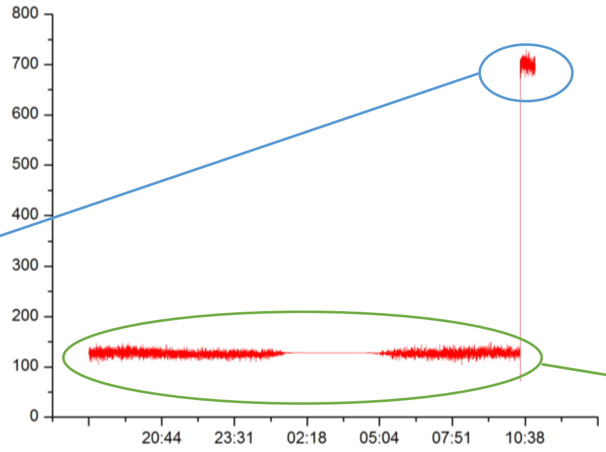
Zeeman effect sensitivity

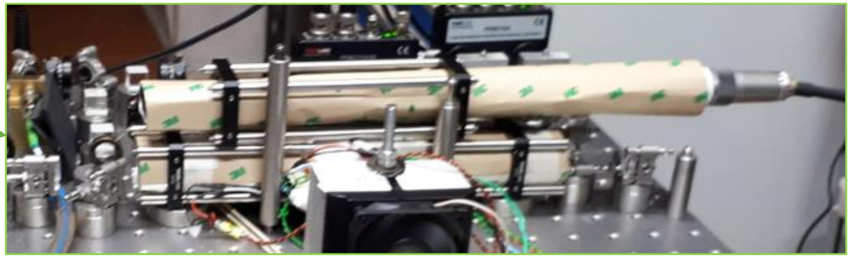
ν (B) = 1.2x10^{-15} / mGauss

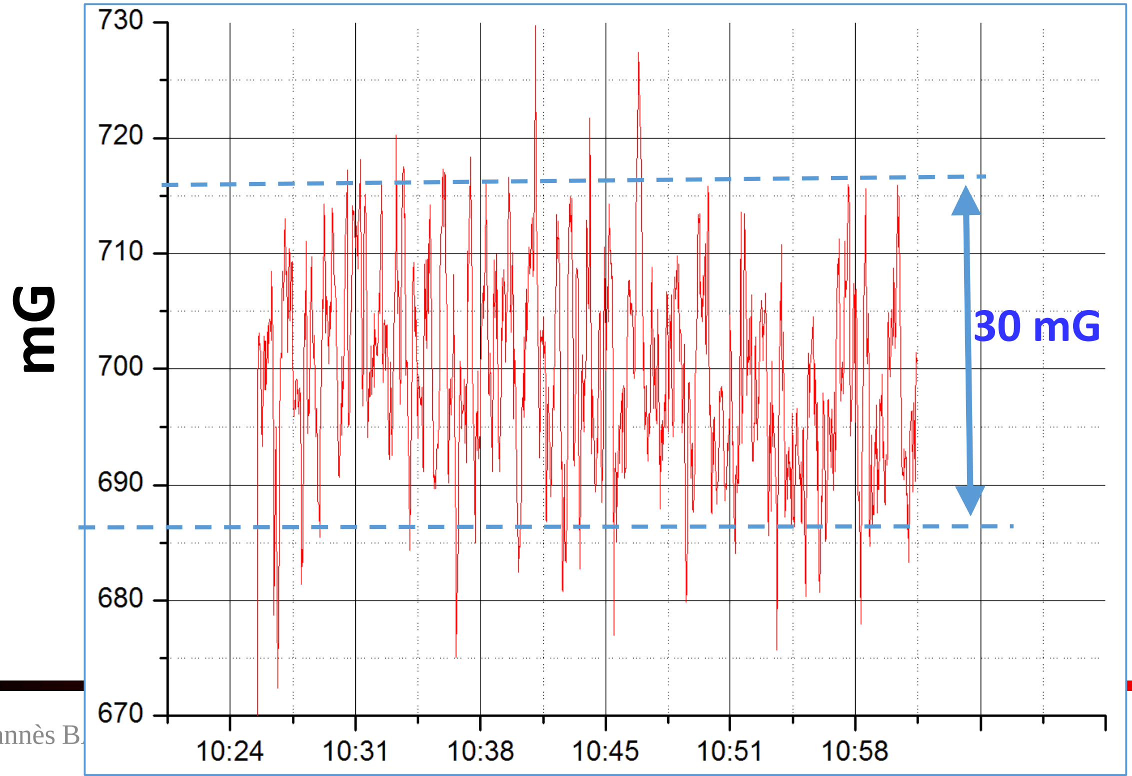
ΔB = 30 mGauss

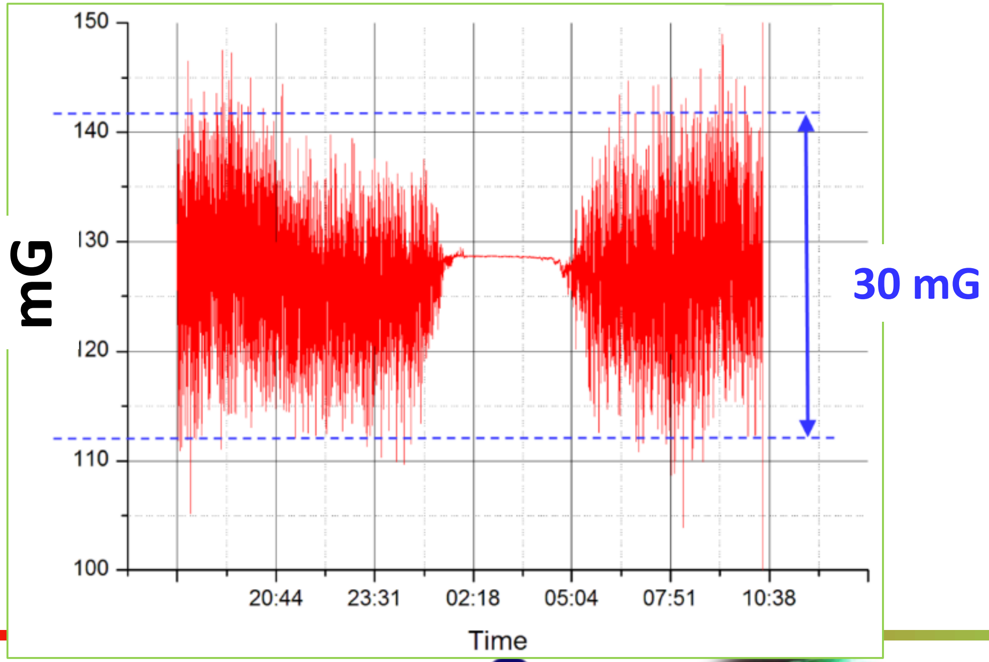
$\Delta\nu/\nu \approx 3.6 \times 10^{-14}$





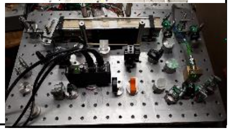


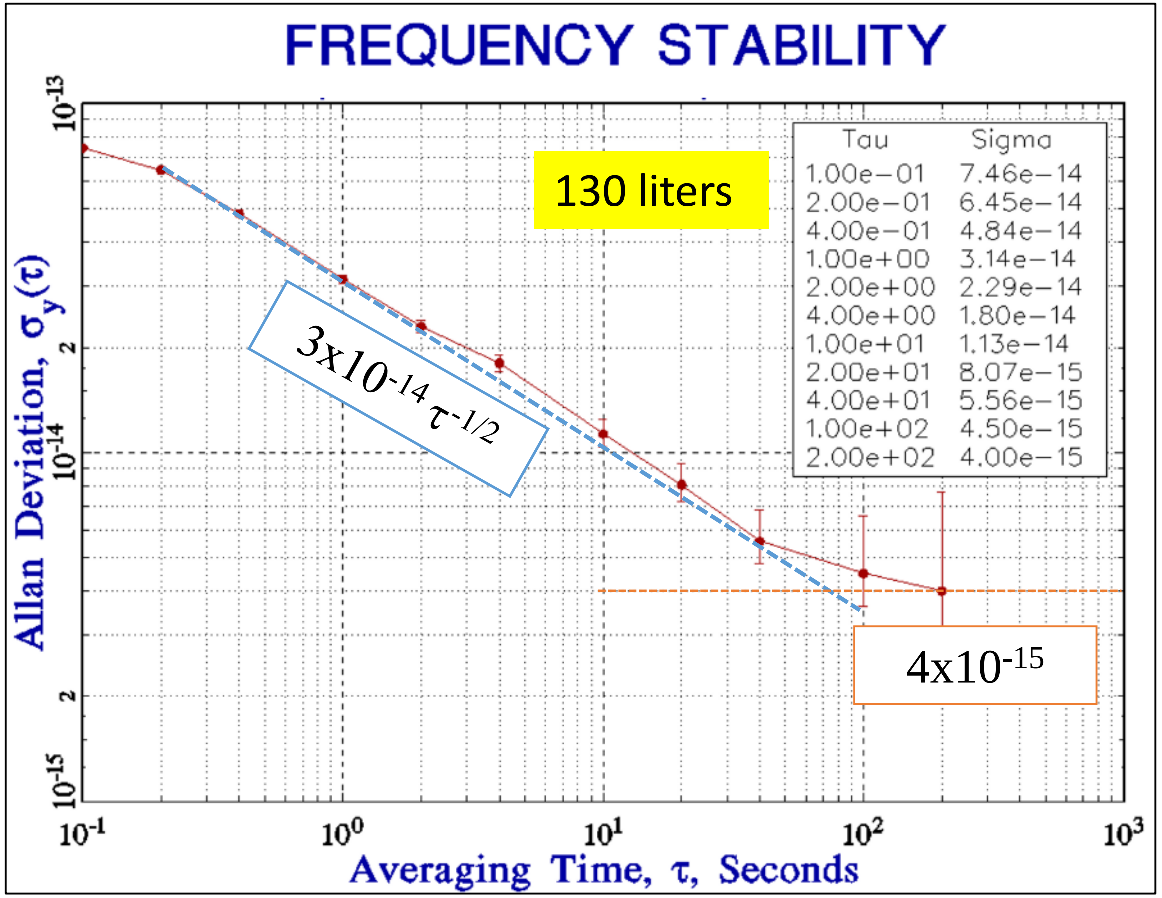


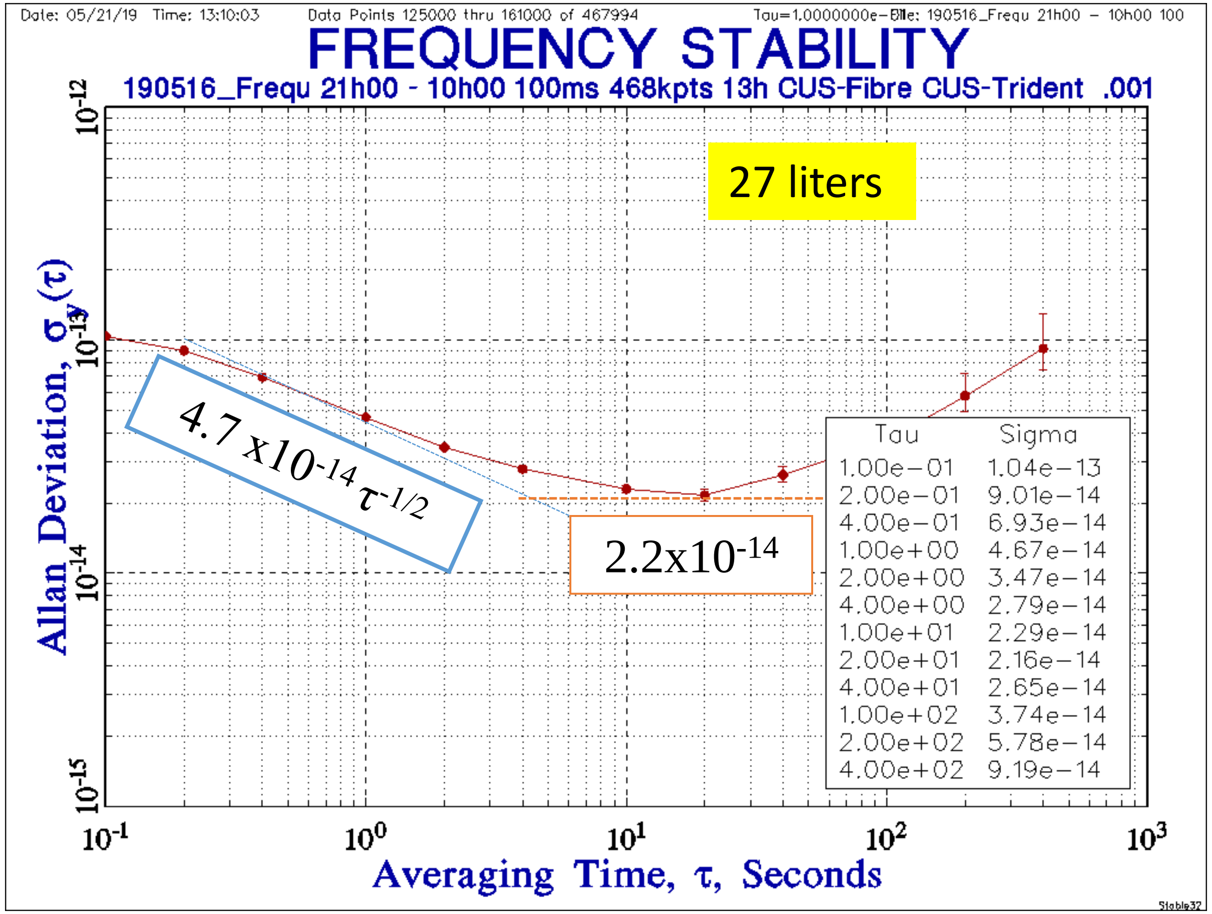


- Modulation transfer spectroscopy
- Using cooled iodine cell (-11°C)
- Interaction length = **120 cm**
- **With** Optical power stabilization

- Frequency Modulation Spectroscopy
- Using cooled iodine cell (-15°C)
- Interaction length = **100 cm**
- **With** optical power stabilization





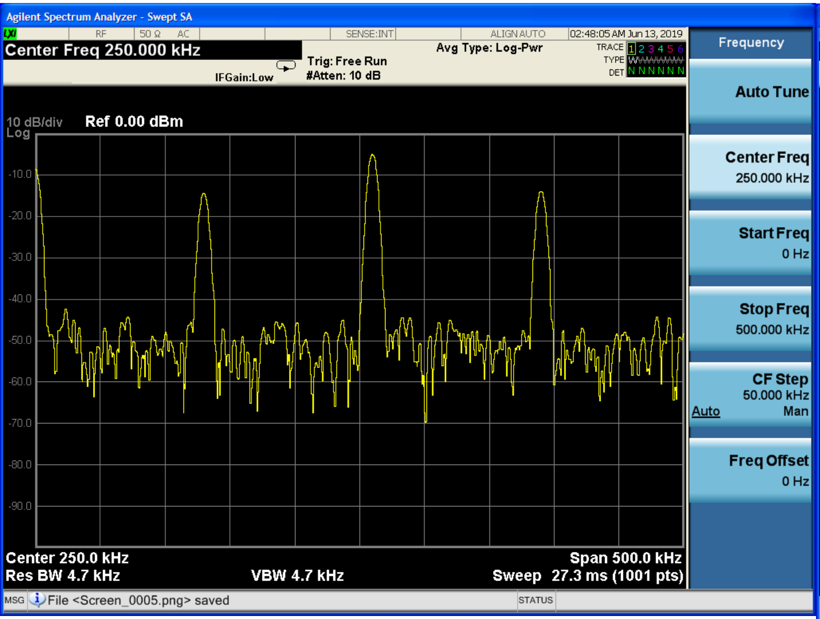


Outline

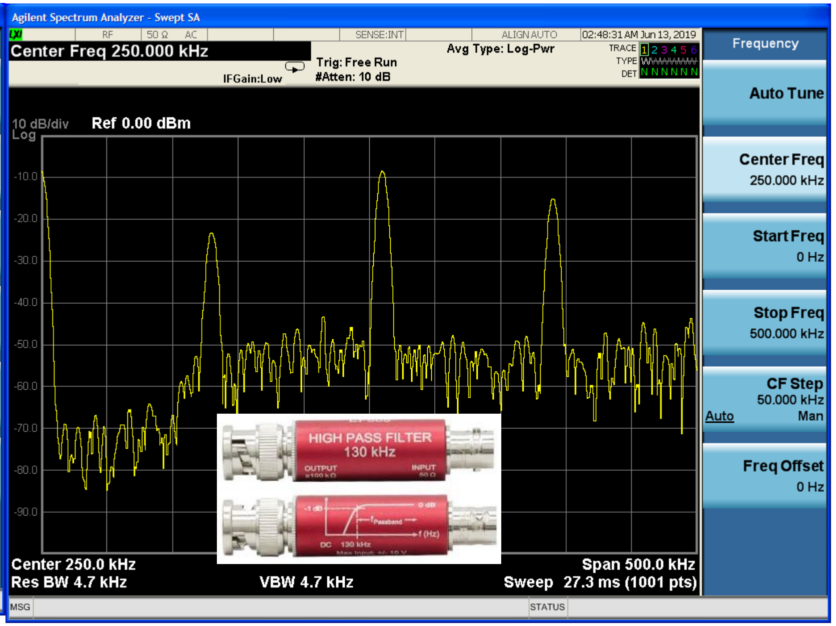
Next step

- **New 3f filter for iodine signal**

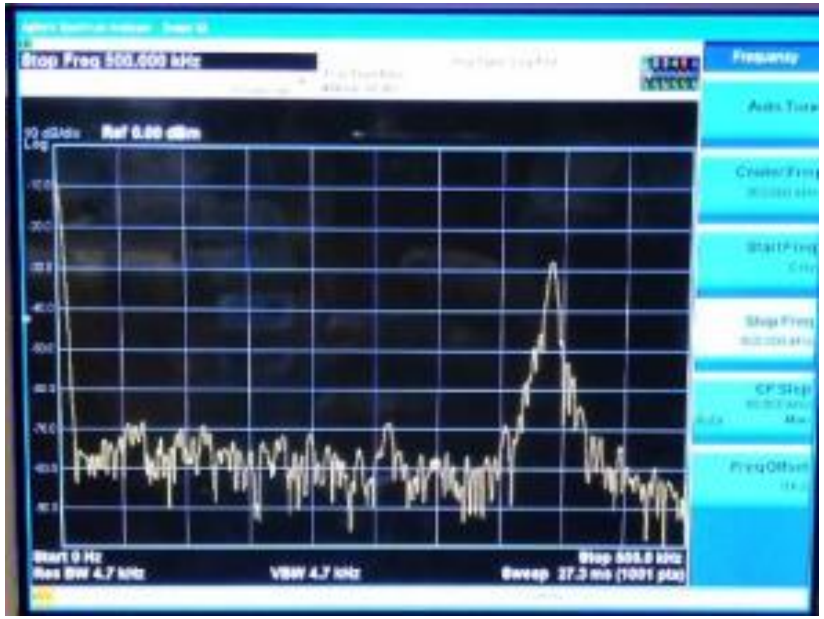
Photodiode output



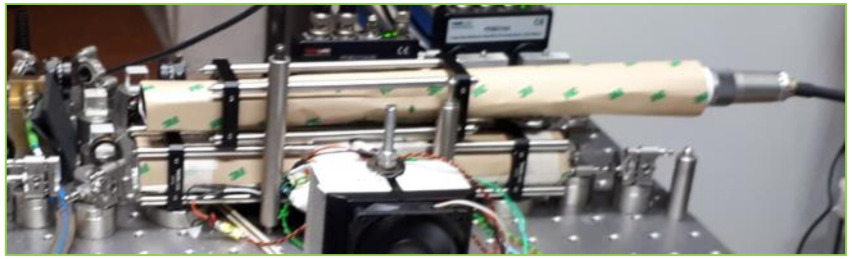
Photodiode output + commercial filters



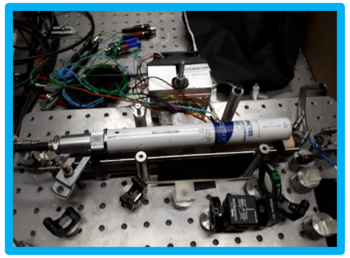
Photodiode output + homemade filters

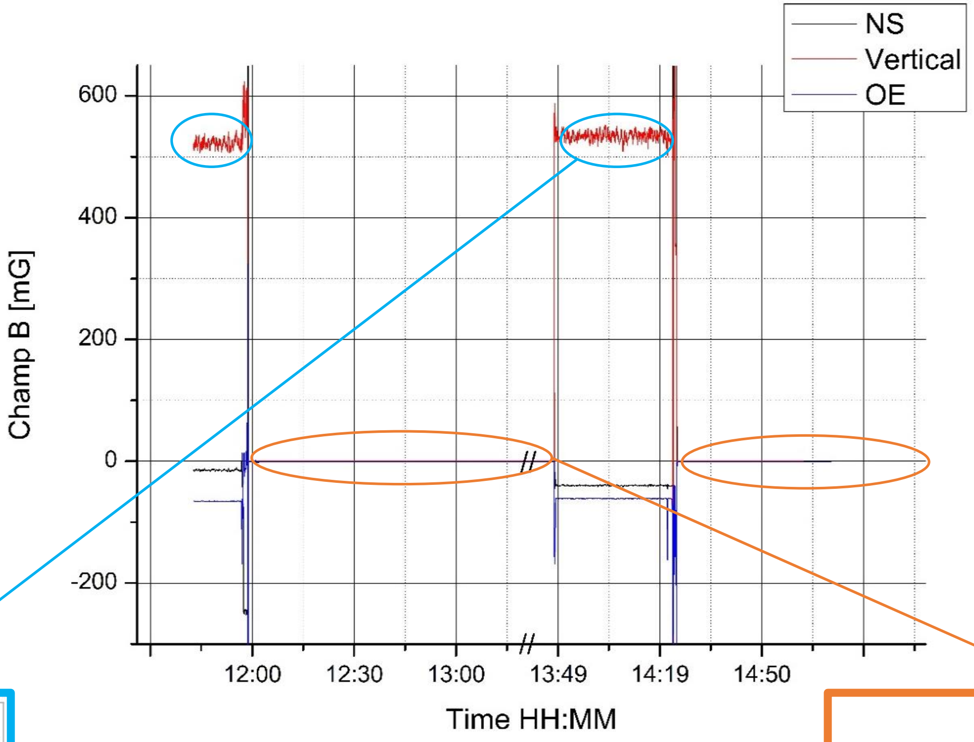


- **Adding an efficient magnetic shield around the iodine cell**

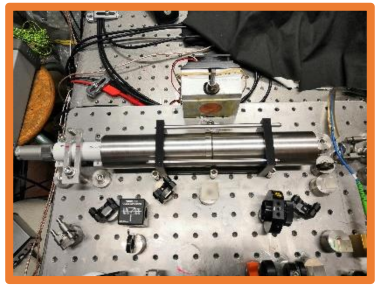


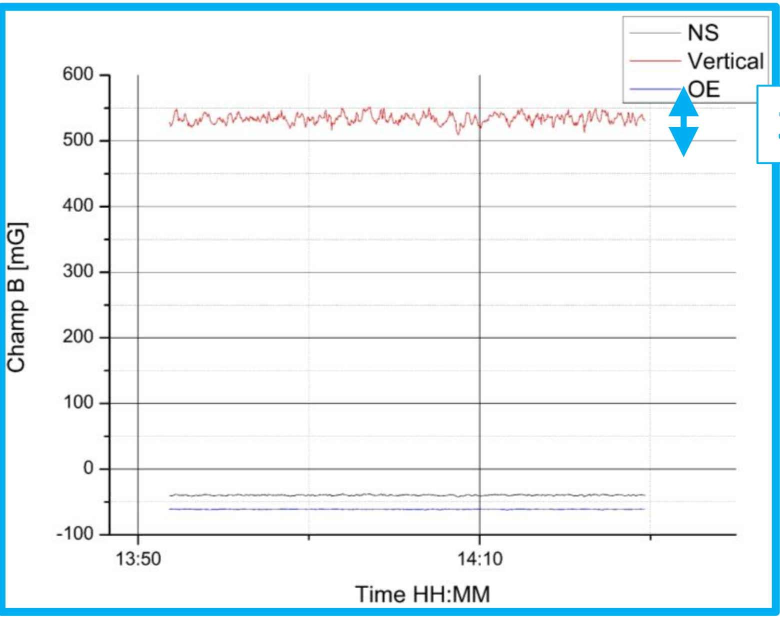
Sans blindage



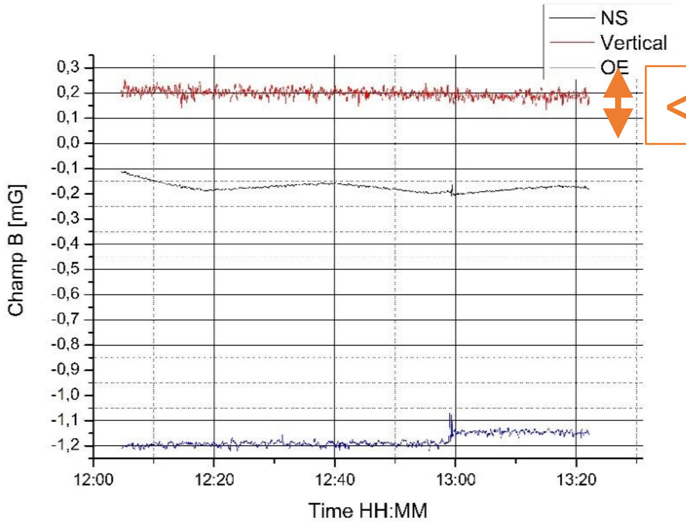


Blidage µ-metal





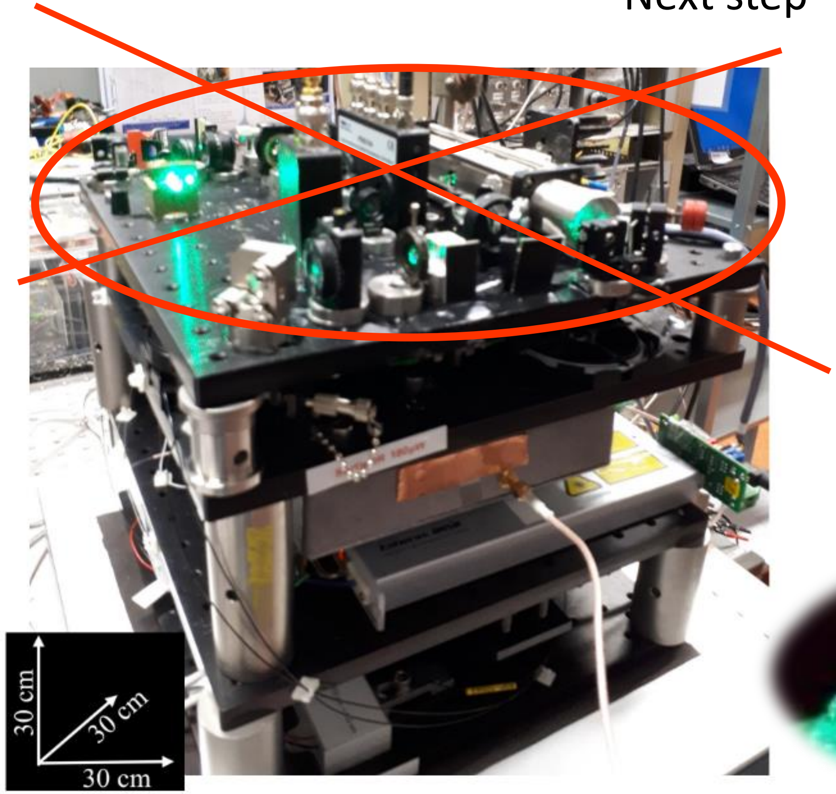
30 mG

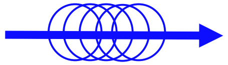


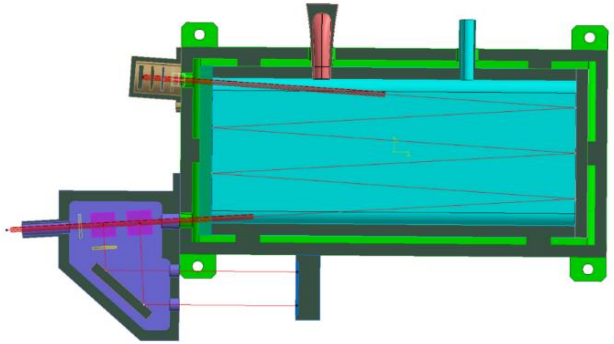
<0,1 mG

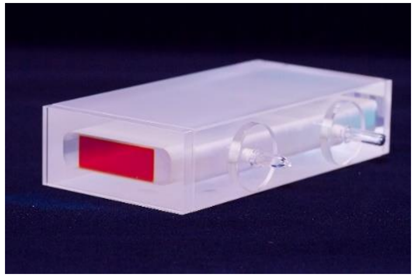
Next step

Next step ⇒ develop a fibered iodine cell module









Loss power of 2% each of 2 x 8 windows crossing that corresponding at a total of 32% power loss.
The loss of 2% is due of the "degradation" of the AR coating during the welding process

New cell:
The AR coating is conserved by the optical contact.
Only 4 windows crossing that corresponding to less than 4 % power loss.
Expect a better short term stability
Compact fibered module

Conclusion

- I improve the day to day short term frequency stability of the free space setup at $3 \times 10^{-14} \tau^{-1/2}$ level.
- I characterize the influence of the Zeeman effect on the hyperfine iodine line.
- I improve the day to day long term frequency stability of the free space setup at the level of 4×10^{-15} @ 200s
- I develop a new Iodine frequency stabilized laser set up of 27 liters.
- This demonstrator has a preliminary day to day frequency stability at $5 \times 10^{-14} \tau^{-1/2}$.
- The long term frequency stability is limited up to now to 2×10^{-14} @ 20s (residual external magnetic field)

<u>Next steps:</u>

- Use of an efficient magnetic shield around the iodine cell
- Development a fibered iodine cell spectroscopy module
- Precise large band Iodine spectroscopy over 1 nm at 1544 nm.

This work was performed with the help of many colleagues:
M. Lours, L. Volodimer, J. Pinto, D. Holleville, B. Venon, J-P. Aoustin, J. Gillot, E. De Clercq, P. Blonde, H-A. Martinez, R. Le Targat, P-E. Pottie and Y. Lecoq
Thesis supervised by O. Acef and P. Tuckey

Thank you