

Absolute Frequency Measurements of Stabilized Lasers at the BIPM

I₂ stabilized He-Ne Laser at 633 nm

Institute	Model
BIPM	BIPM 4
	BIW 167
CEM	WEO 116
JV	WEO 121
Winter	WEO 001
NMi	WEO 169
	NMi/TUE 2
UME	L3
SPRING	WEO
CENAM	WEO
COM	Jaeger
NRC	WEO
CMI	PLO3
BFI-INM	home made

stabilized He-Ne Laser at 543 nm

Institute	Model
BIPM	Home made
DFM	Home made
MIKES	Home made
CMI	Home made
NIM	Home made 1
	Home made 2
CENAM	TESA SG-L
SPRING	NPL type

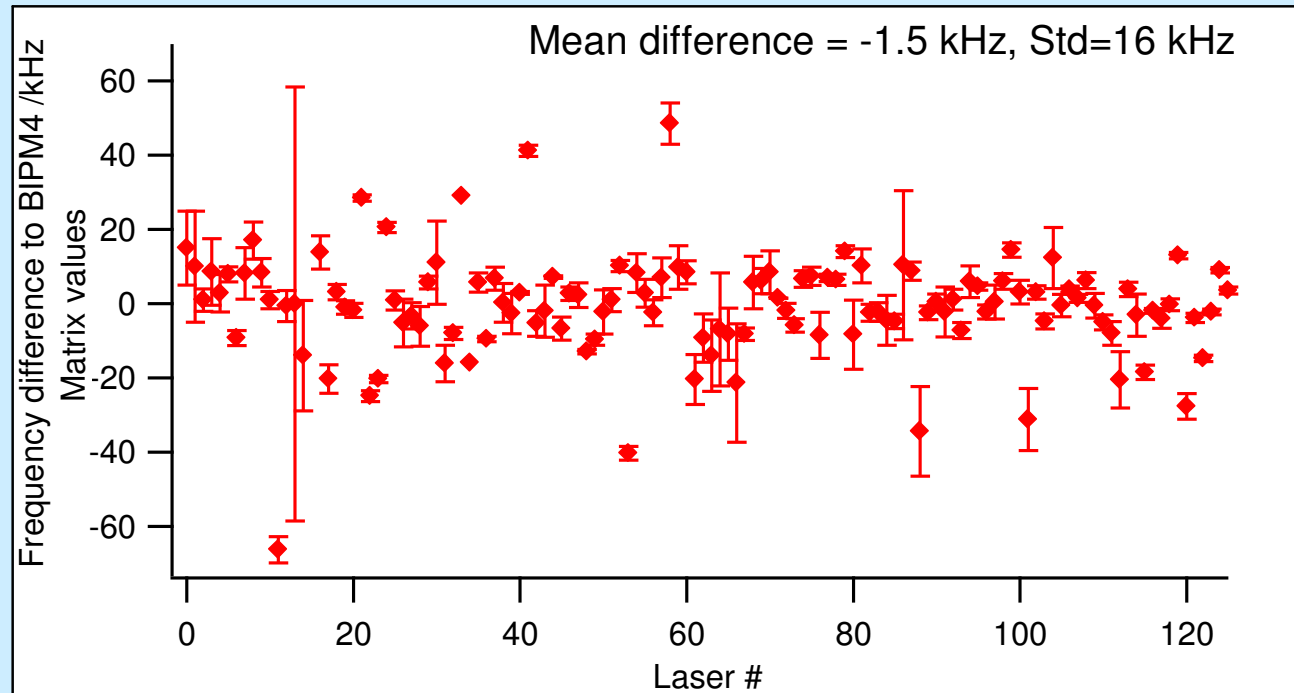
I₂ stabilized Nd:YAG laser at 532 nm

Institute	Model
BIPM	Laser A & B
(other laser connected through comparisons)	

Has the comb actually done any good to the **implementation** of the *metre*?



About 130 laser comparisons relative to **BIPM 4** has been made since 1972 (**Matrix** values)

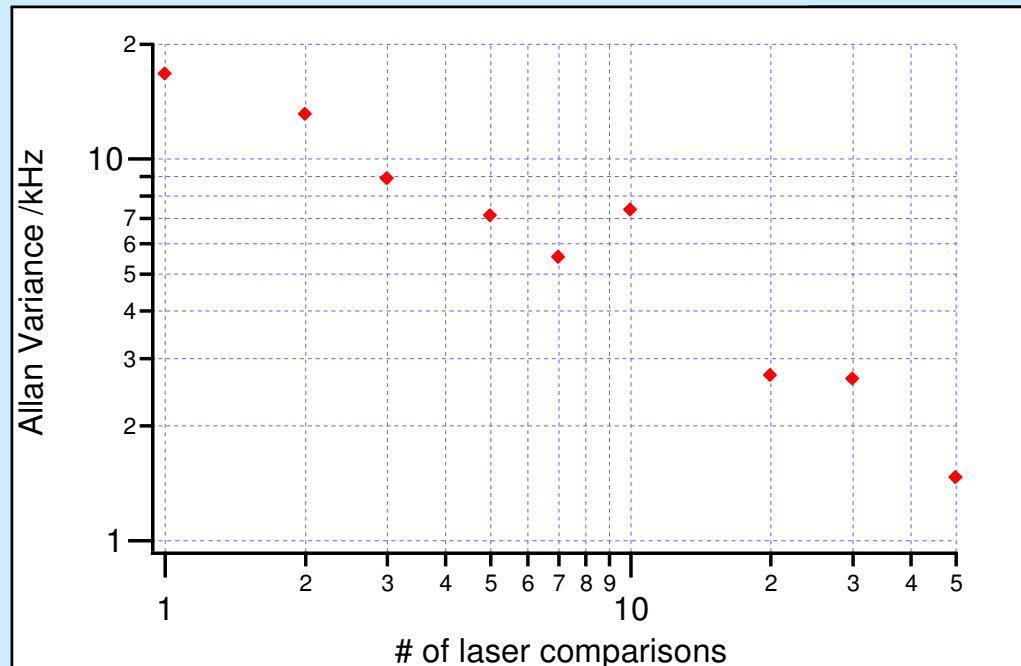


Average value close to zero => **BIPM 4** good representative





“Stability” of 633 nm comparisons



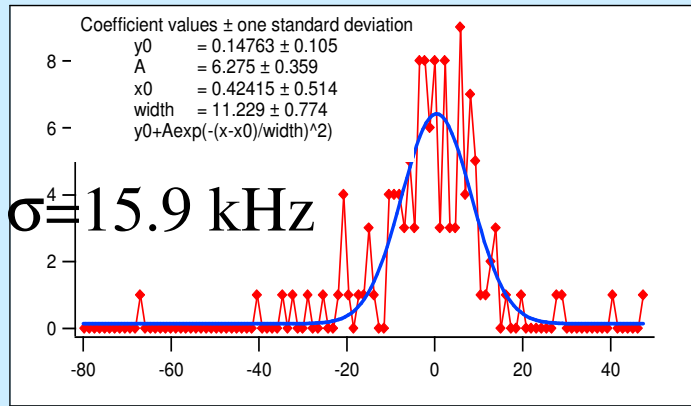
Allan	Tau
16.6806	1
13.0808	2
8.87435	3
7.08697	5
5.51947	7
7.32752	10
2.70246	20
2.64778	30
1.46214	50

Either

- Both BIPM 4 and other realisations stable or
- BIPM 4 and other realisations drift in the same way (mental lockin-effect!!)

Integrating nicely down to a stable average value of few kHz

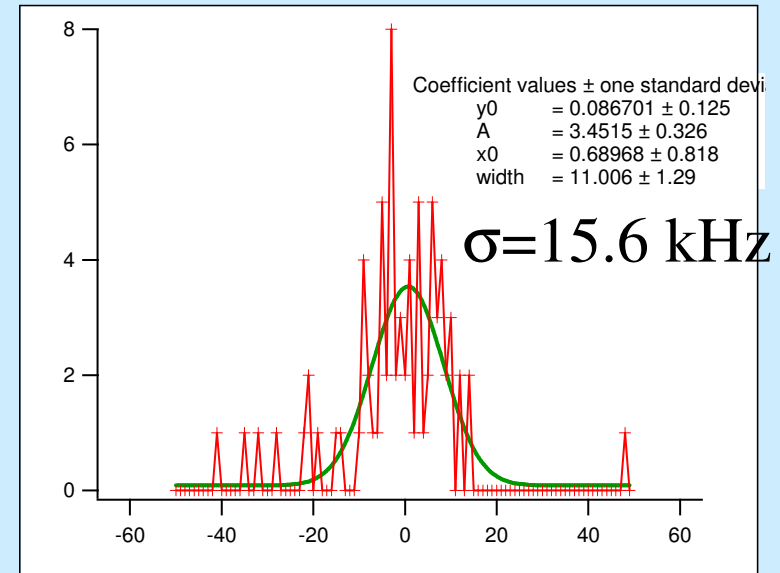
What this value is, is the **task of absolute measurements** to find out



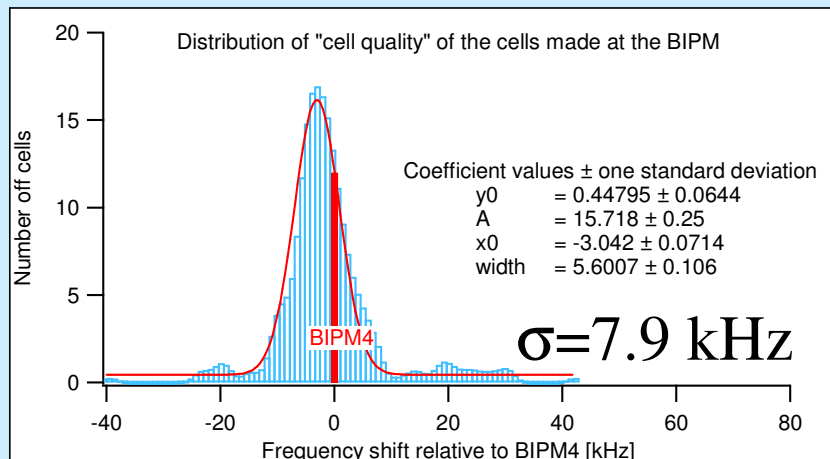
← Distribution of all lasers compared to the BIPM 4 laser since 1974

Distribution of all lasers compared to the BIPM 4 laser since 1993

$15.6 / \sqrt{75} = 1.8 \text{ kHz}$

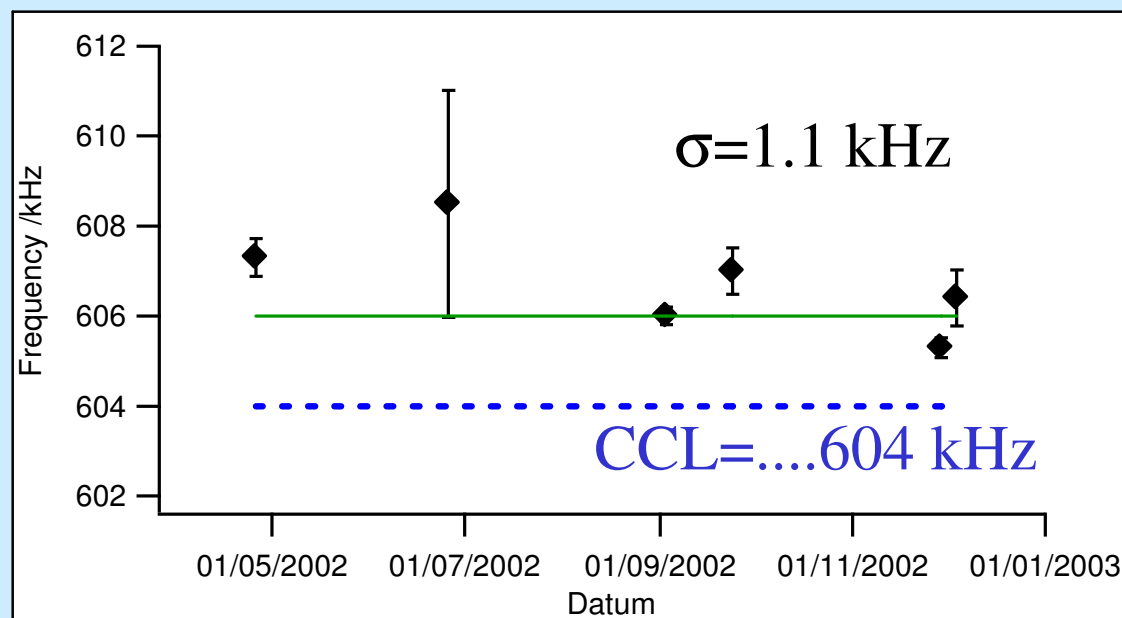


← Iodine cells at the BIPM



Absolute frequency measurements on BIPM 4 in 2002

Mean frequency 473612353605.4 kHz $u_{k=2}=3.8$ kHz
(-0.6 kHz modulation correction)

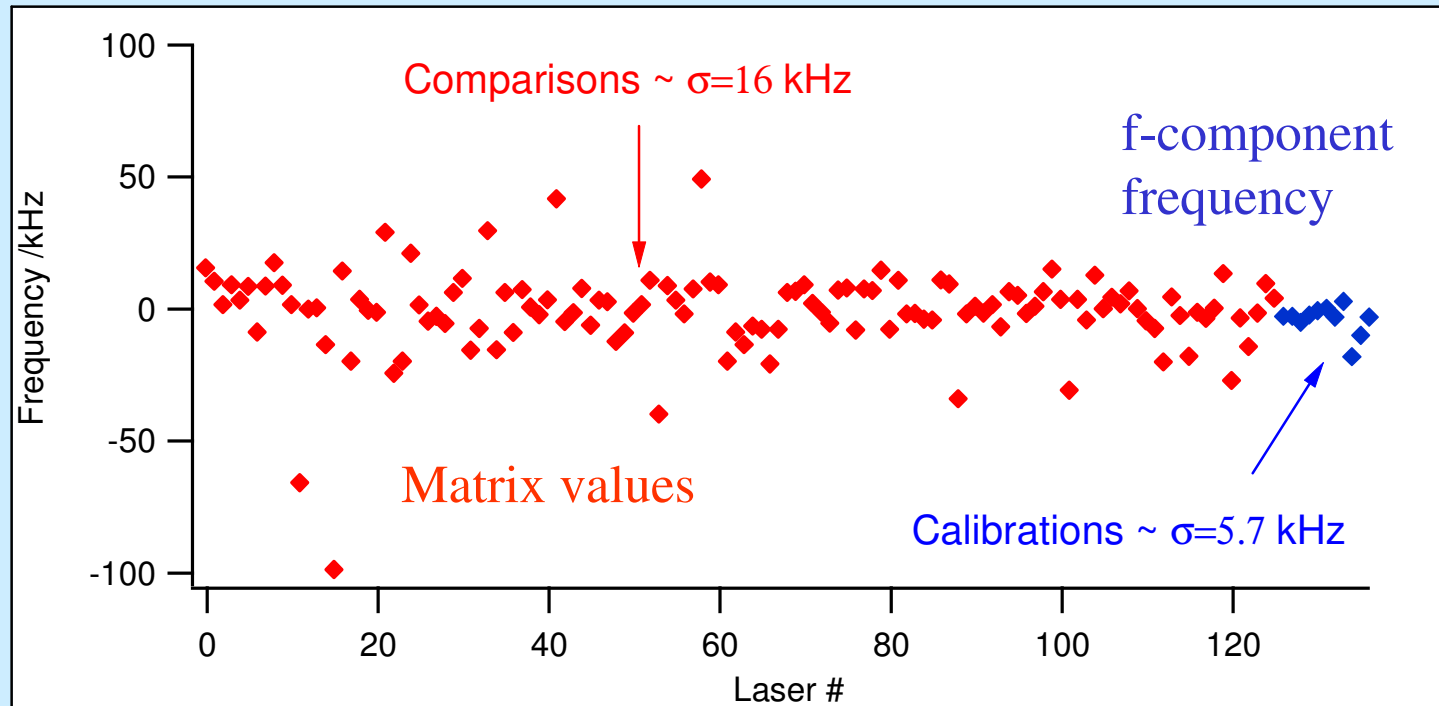


CCL - BIPM 4 = -1.4 kHz

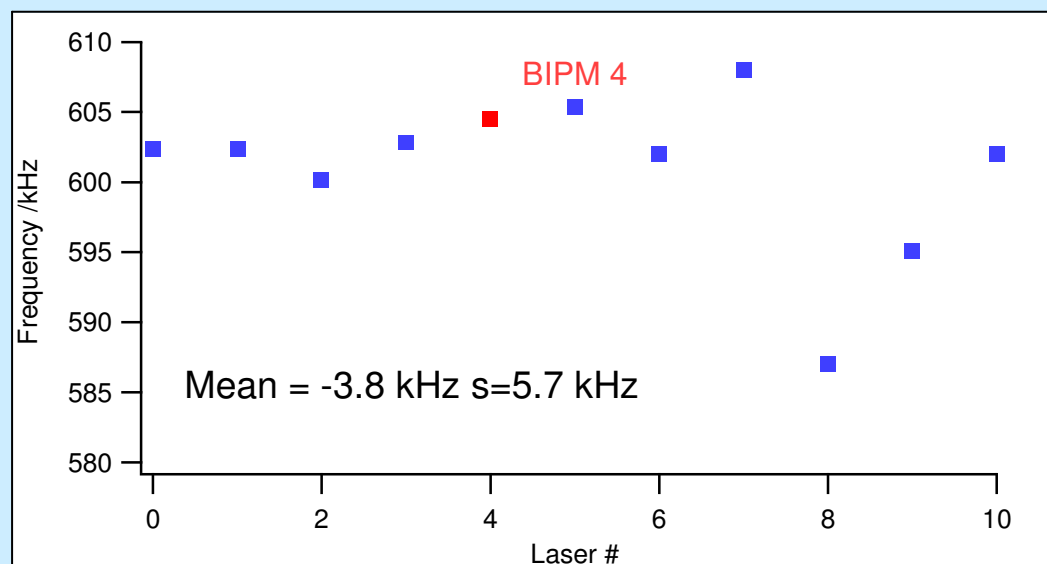
All lasers - BIPM 4 = -1.5 kHz



Going from comparisons to calibrations



633 nm standards measured at the BIPM



$$5.7 / \sqrt{11} = 1.7 \text{ kHz}$$

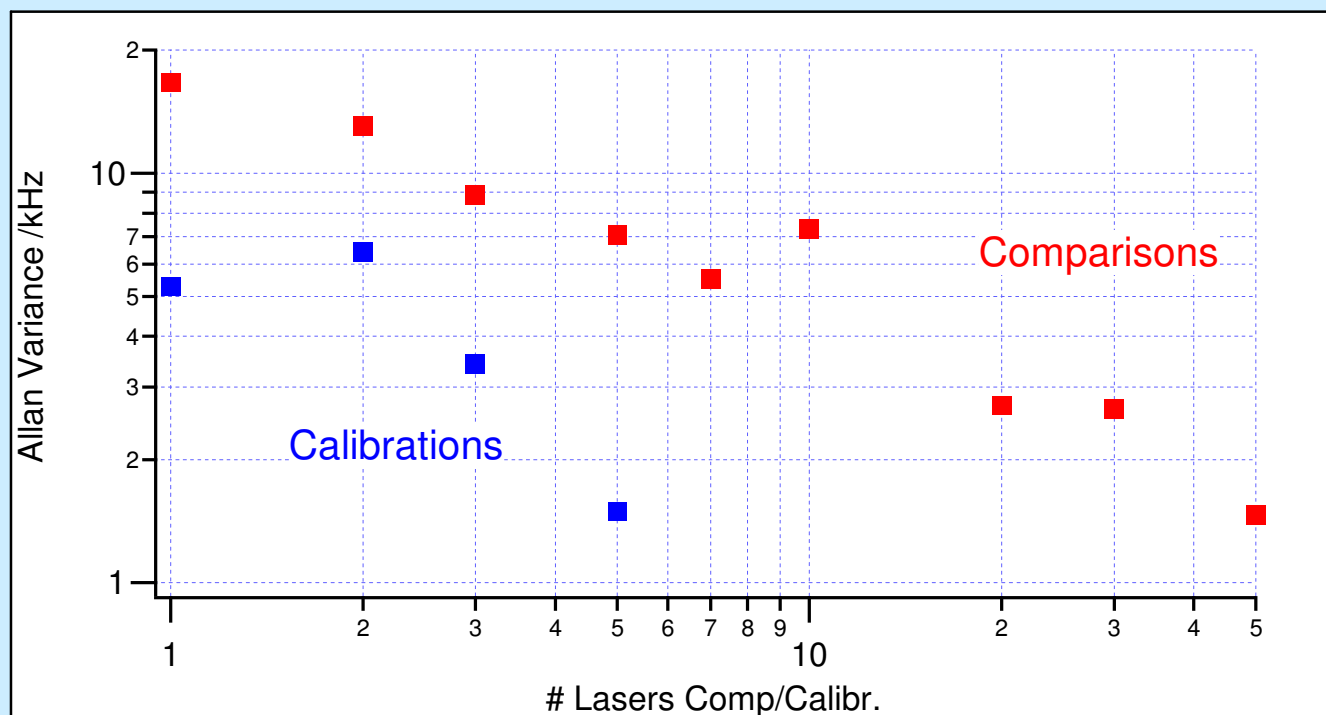
Apparent reduction in scatter

- Direct frequency measurements eliminates intermediate standards.
- “Instrumental cloning”, many Winters lasers.
- Frequency average now lower.

Absolute frequency measured within a day makes more frequent verification of standards possible. *Accelerated program of calibrations*



Averaged “stability” over realisations





Accelerated program of comparisons/measurements

Actual status and proposed future comparisons for the 633 nm frequency standard					
BIPM4 used as frequency reference					
Comb					
Laboratory (laser)	last comp.	Country	543	633	532
DFM (DK1)	93-10	Denmark			
SP (SP2)	93-10	Sweden			
SMU (SMU-B2)	94-04	Slovakia			
IPQ (IPQ2)	94-07	Portugal			
UME (UME-L3)	94-11	Turkey		Mars 2003	
BNM-INM (INM9)	95-03	France		Mars 2003	
CEM (CEM2)	95-03	Spain		April 2002	
IGM (AIM2)	95-03	Belgium			
IMGC (IMGC4/5)	95-03	Italy			
NMI-VSL (NMI/TUE2)	95-03	Holland		Dec. 2002	
NPL (NPLS)	95-03	UK			
PTB (PTB01/89)	95-03	Germany			
OFMET (EAM1)	95-05	Switzerland			
CSIR-NML (CSIR3)	95-07	South Africa			
CSIRO-NML (CSIRO1)	95-07	Australia			
MSL (PELB)	95-07	New Zealand			
SISIR (SISIR1****) SPRING	95-08	Singapore	Sept-2002	Mars 2003	
JV (NMS/122)	95-09	Norway		April 2002	
NCM (NCM2)	95-09	Bulgaria			
NIST (NIST/96)	97-03	USA			
NIST/JILA (JILA145)	97-03	USA			
KRISS (KRISS-R701)	97-07	Korea			
NRLM (NRLM-P1)	97-07	Japan			
MIKES (MIKES-M3)	98-09	Finland			
NIM (NIM-N1)	98-09	China			
VNIIM (VNIIM-V2)	98-09	Russia			
CMI (PLD1)	99-09	Czech Rep.		Mars 2003	
GUM (GUM1)	99-09	Poland		Mars 2003	
NILPRP (RO1)	99-09	Rumania			
OMH (OMH1)	99-09	Hungary			
BEV (BEV1)	99-09	Austria			
CENAM (CENAM1)	00-07	Mexico	17/09/2002	Mars 2003	
INMETRO (INMETRO1)	00-07	Brazil		Mars 2003	
INMETRO (INMETRO2)	00-07	Brazil			
INTI (INTI1)	00-07	Argentina			
NRC (INMS2)	00-07	Canada			
NIS		Egypt		14-18 Oct-02	
SCL		Hong Kong			
BIPM					
Winter					

Objective!

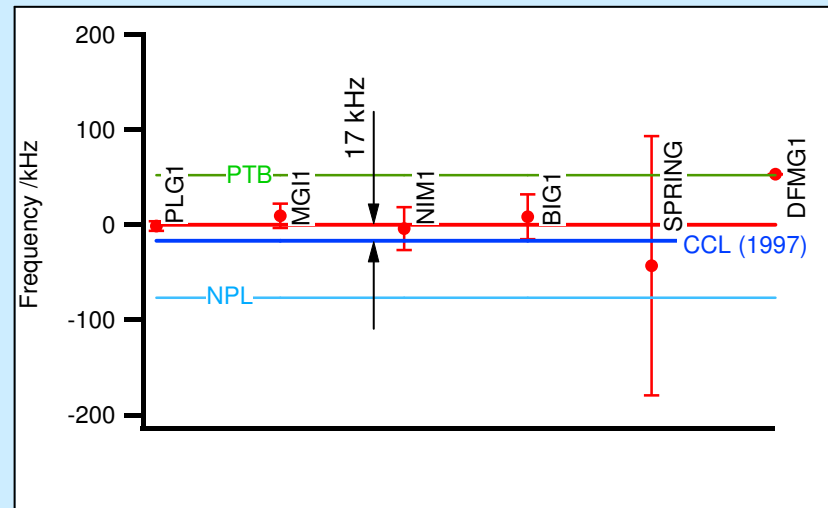
- To measure the absolute frequency of most lasers in the 633 nm list within the next few years
- Two campaigns per year planned

Calibrations of 543 nm standards

The CCL value of the 543 nm radiation was based on two interferometric measurements

- PTB 52 kHz high (uncertainty 46 kHz)
- NPL 77 kHz low (uncertainty 72 kHz)

Institute /country	Laser	Stabilization- scheme
CSU/ Czech rep.	PLG 1	3 rd harm
DFM/Denmark	DFMG1	3 rd harm
NIM/China	NIM1	
MIKES/Finland	MGI2	3 rd harm
SPRING/Singapore	08A01/G10	FM
BIPM	BIG 1	3 rd harm
NIM/China	NIM2	2 mode
CENAM/ Mexico		2 mode



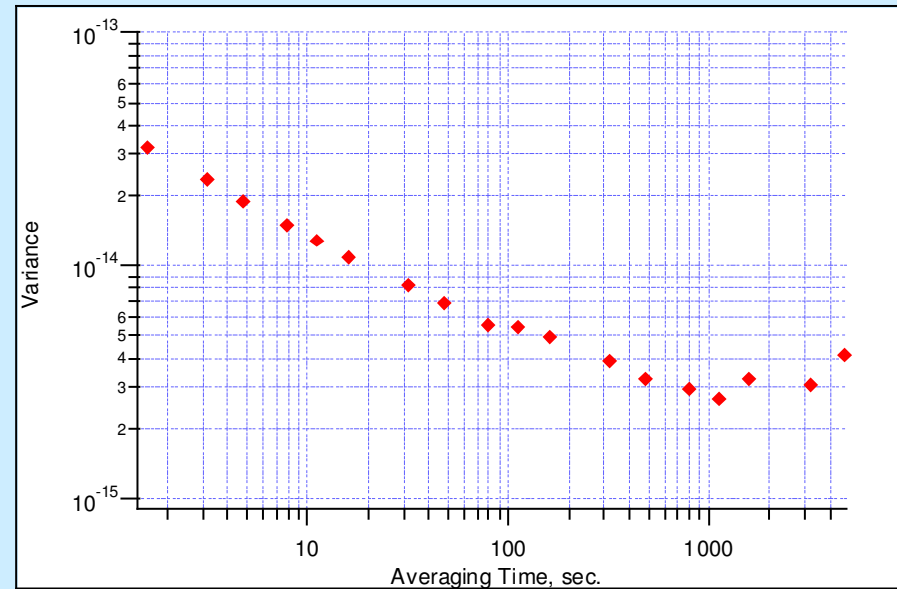
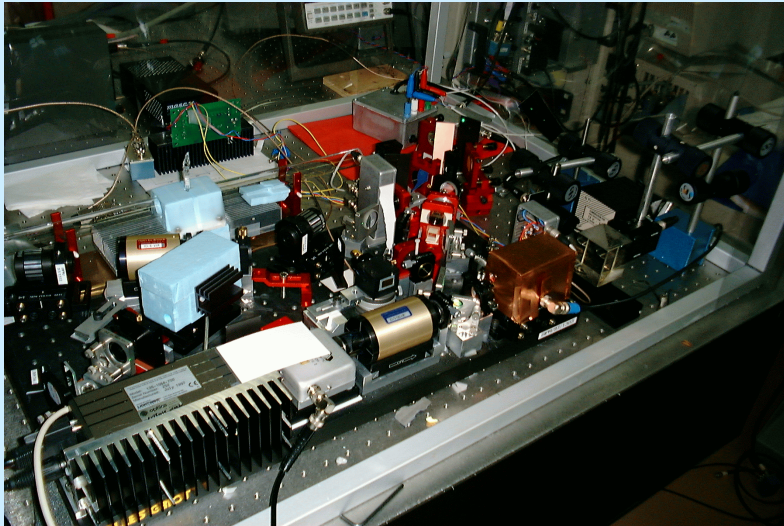
CCL value 551580162.38 MHz $u=2.2 \cdot 10^{-10}$ (120 kHz)

New value 551580162397.1 kHz $u=8.3 \cdot 10^{-12}$ (4.6 kHz)

BEV=> ..396.6 kHz



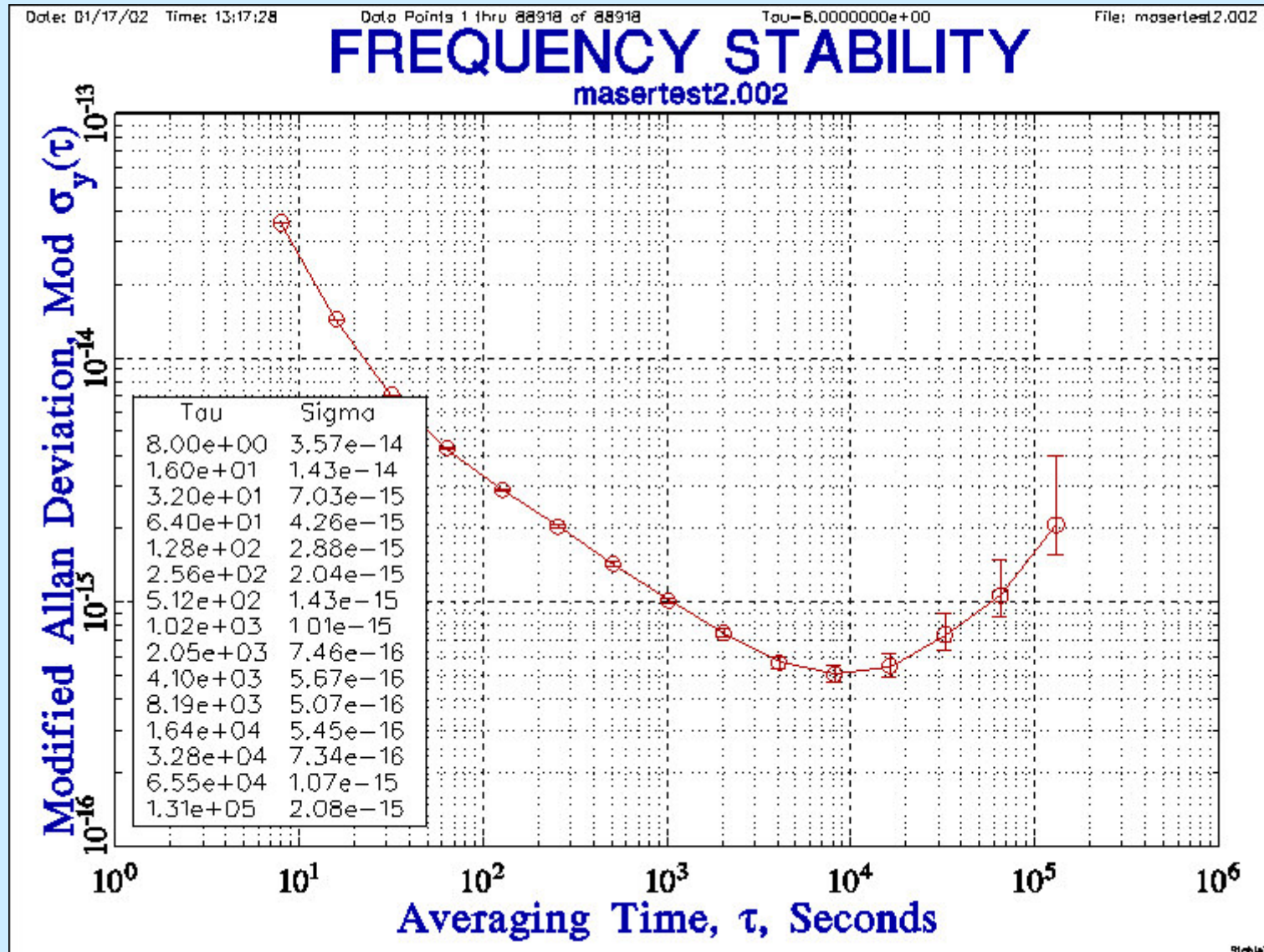
Optical frequency measurements of I_2 stabilized Nd:YAG laser at 532 nm



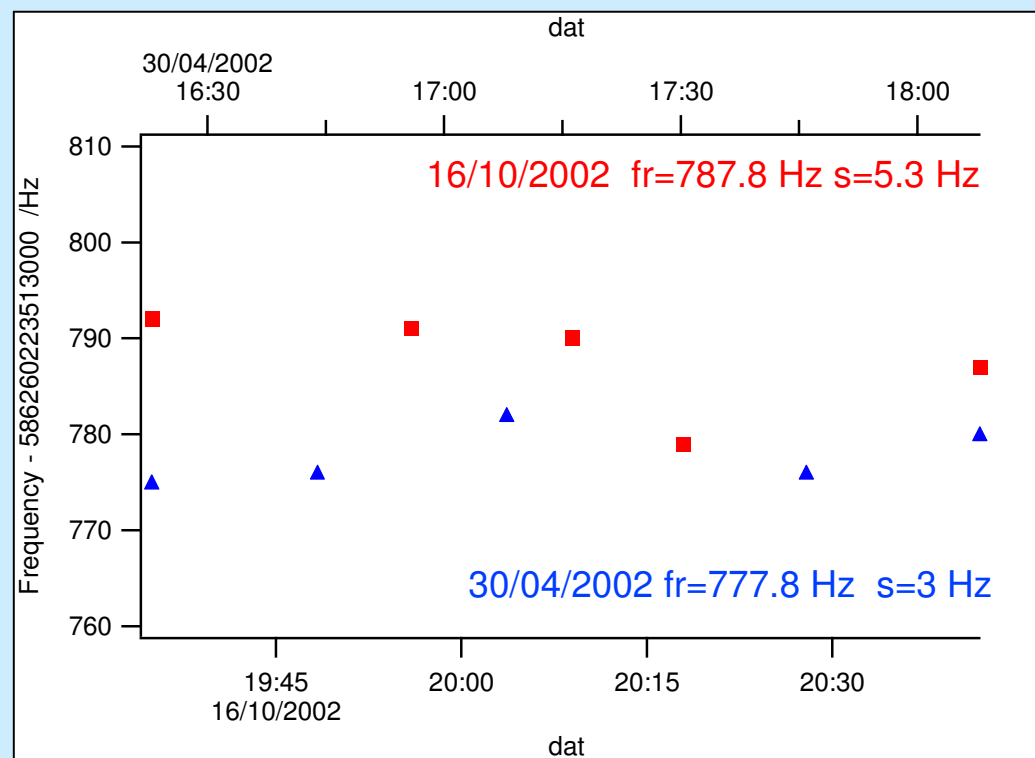
The good short term stability and the 532/1064 nm emission of the Nd:YAG laser makes this type of laser an interesting candidate as a **comb flywheel**.



H-maser stability



Measurements on the 532 nm BIPM standard, Laser B



4 Hz $\sim 7 \cdot 10^{-15}$

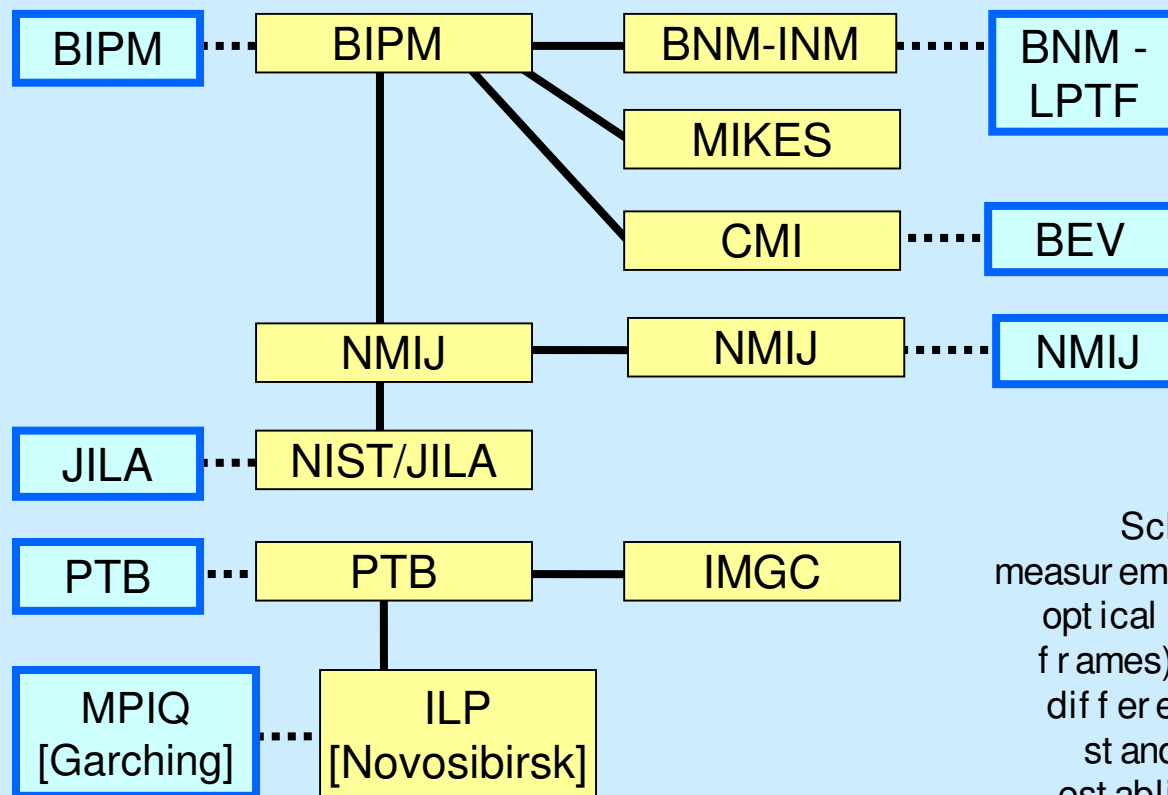
Laser $\sim 3 \cdot 10^{-15}$

Maser $\sim 1 \cdot 10^{-15}$

Distribution amplifier ?

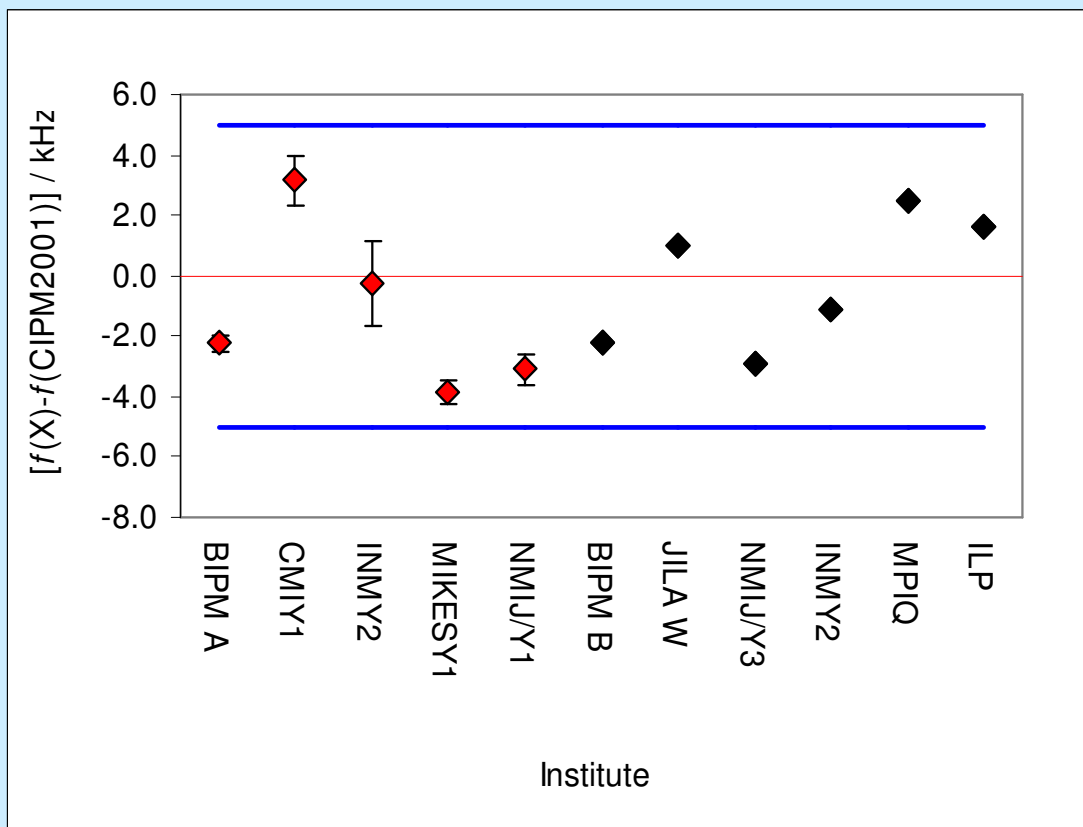


WORLD-WIDE REFERENCE NETWORK OF $^{127}\text{I}_2$ STABILIZED FREQUENCY-DOUBLED Nd:YAG LASERS



Scheme of absolute measurements (dotted lines) using optical comb generators (fat frames) and the link between different 532 nm frequency standards (thin frames) established through direct frequency comparisons (solid lines).

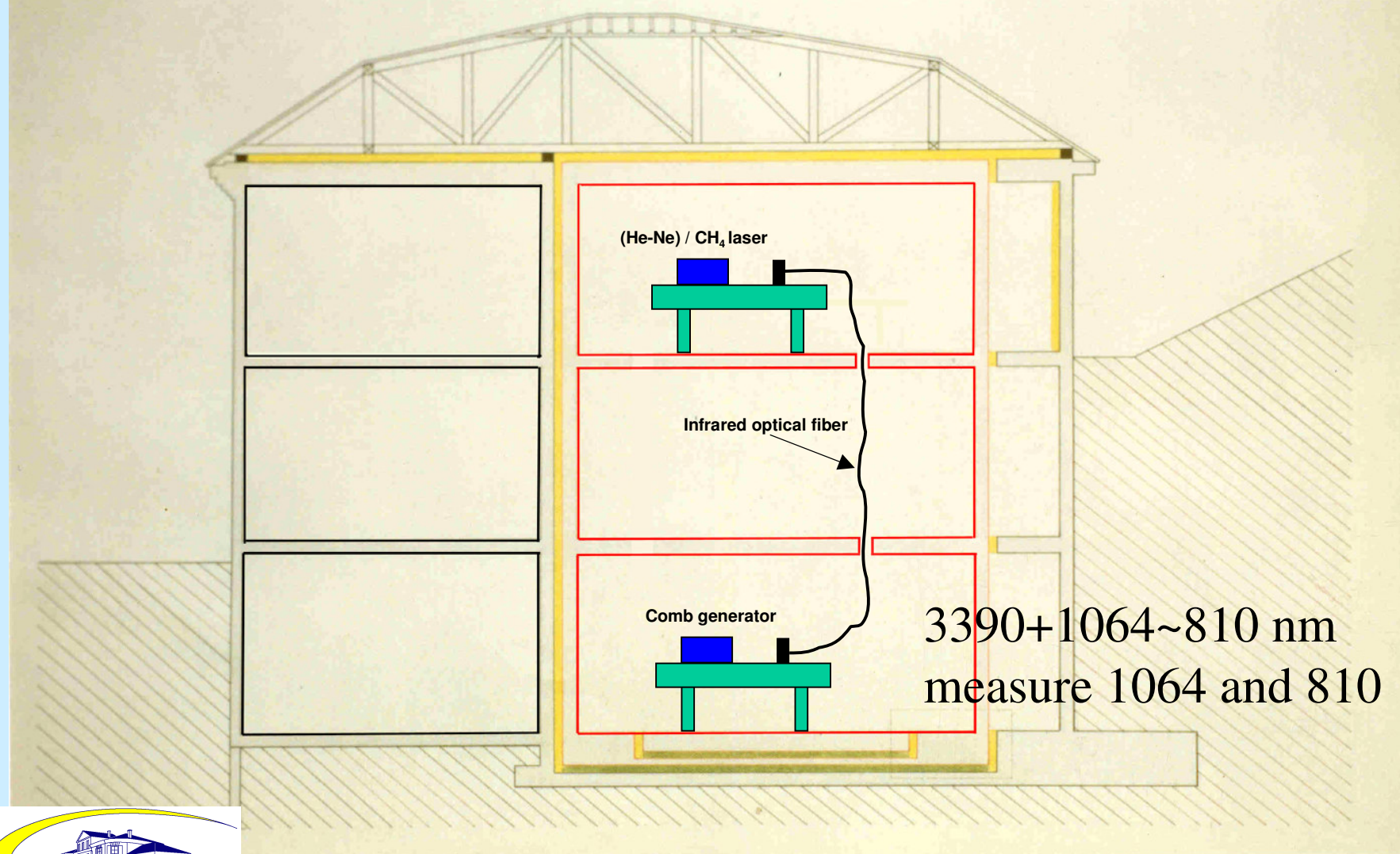
Absolute frequencies of frequency-doubled iodine-stabilized Nd:YAG standards, obtained by a comparison (◆) or by an absolute measurement (◆). The value adopted by the CIPM in 2002 is used as reference. All values lie within the adopted standard uncertainty of 5 kHz.



Mean = -1.2 kHz
 $\sigma = 2.4$ kHz



General view of the set-up for the measurement of absolute frequency of the 3.39 μm laser



Conclusion

- The comb technique has **improved the implementation** of the *metre*
 - by more accurate frequency determinations
 - a wider calibration spectrum
 - makes more frequent calibrations possible
- BIPM provides since October 2002 a **calibration service** for the member states
 - to date we have calibrated ~20 lasers.
 - two calibration campaigns per year are planned
(**next in Nov. 2003**)

