

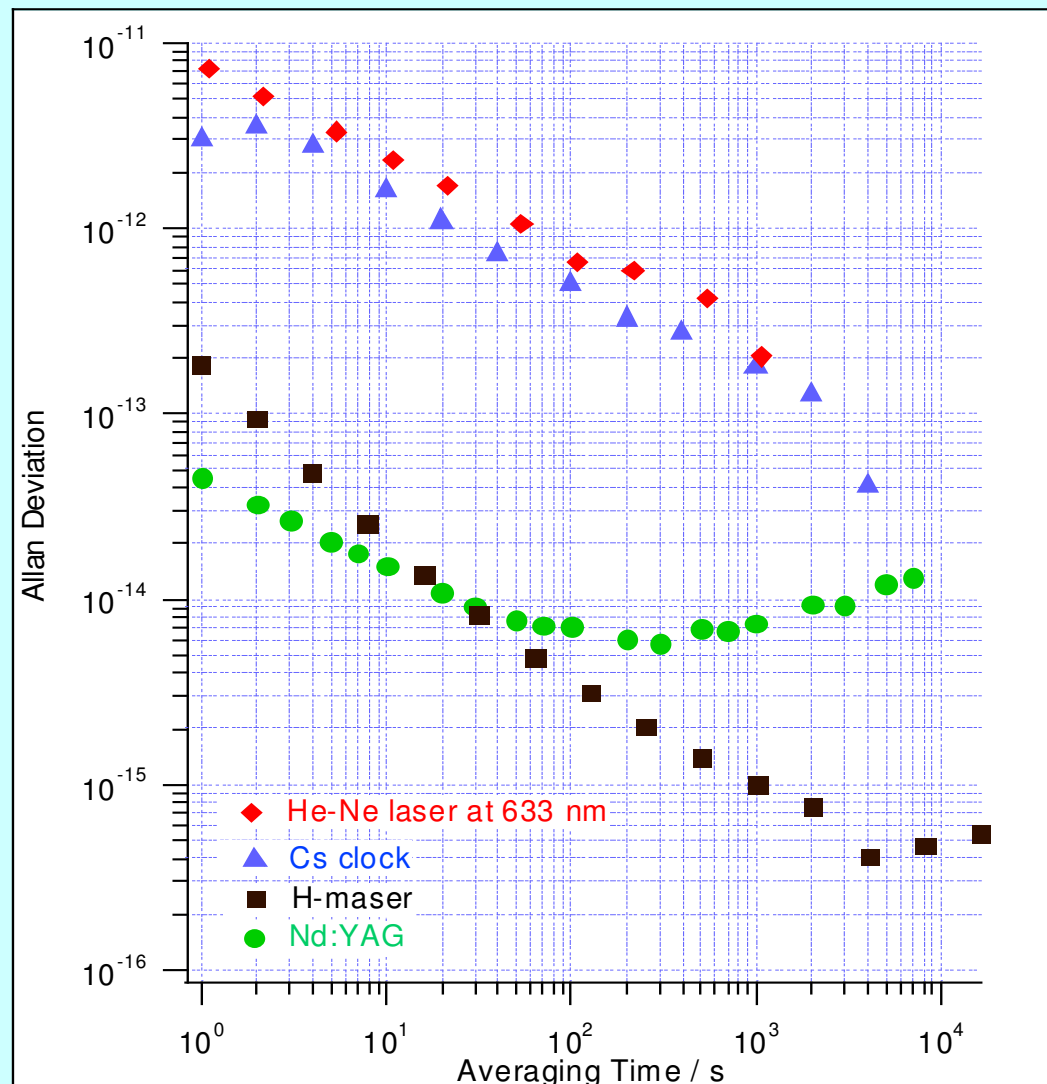
The BIPM Femtosecond Laser Comb

**Long-Sheng Ma, Susanne Picard,
Lennart Robertsson and Massimo Zucco**

- **Performance of the BIPM comb (Long-Sheng Ma)**
- **Frequency measurements (Lennart Robertsson)**

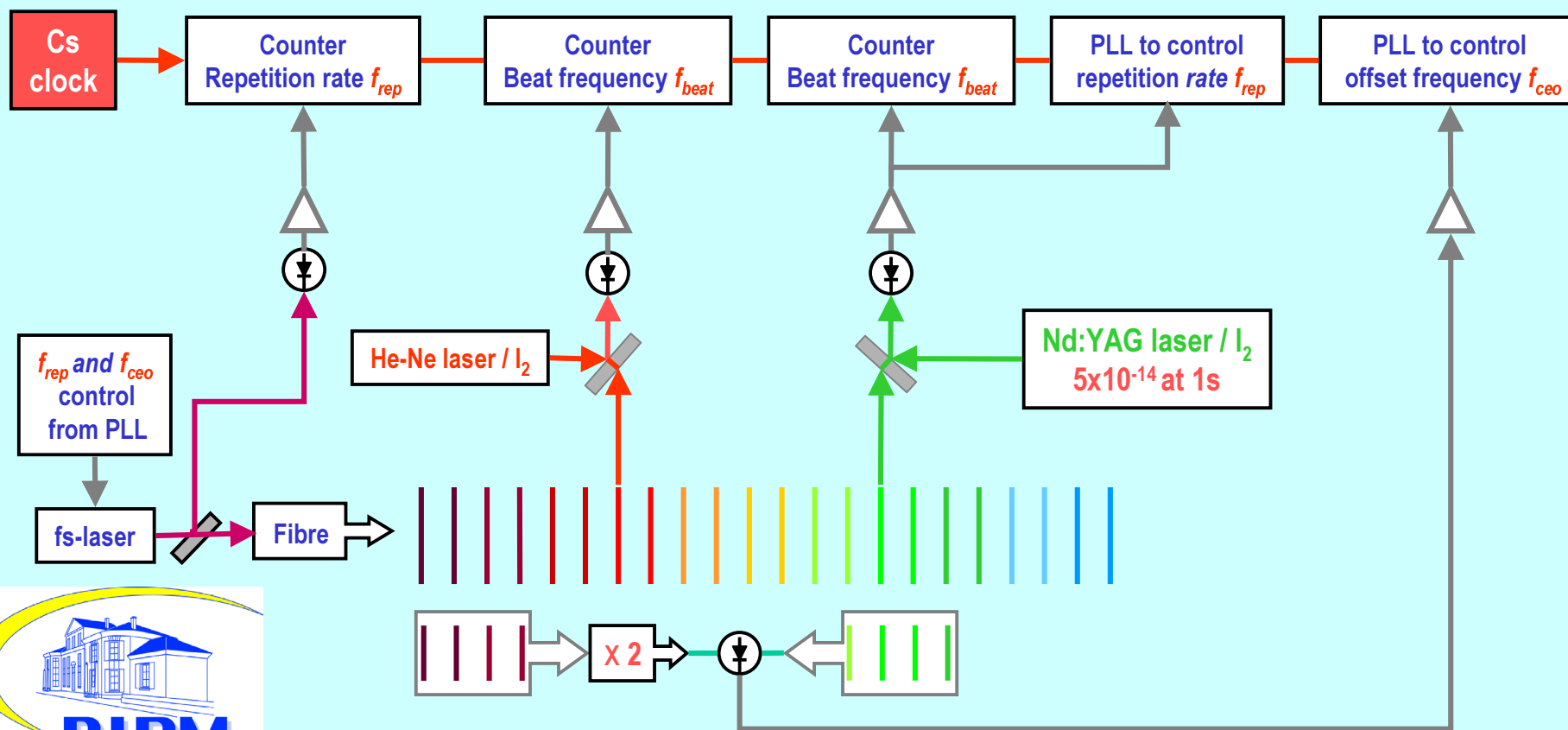


Optical and RF frequency standards at the BIPM

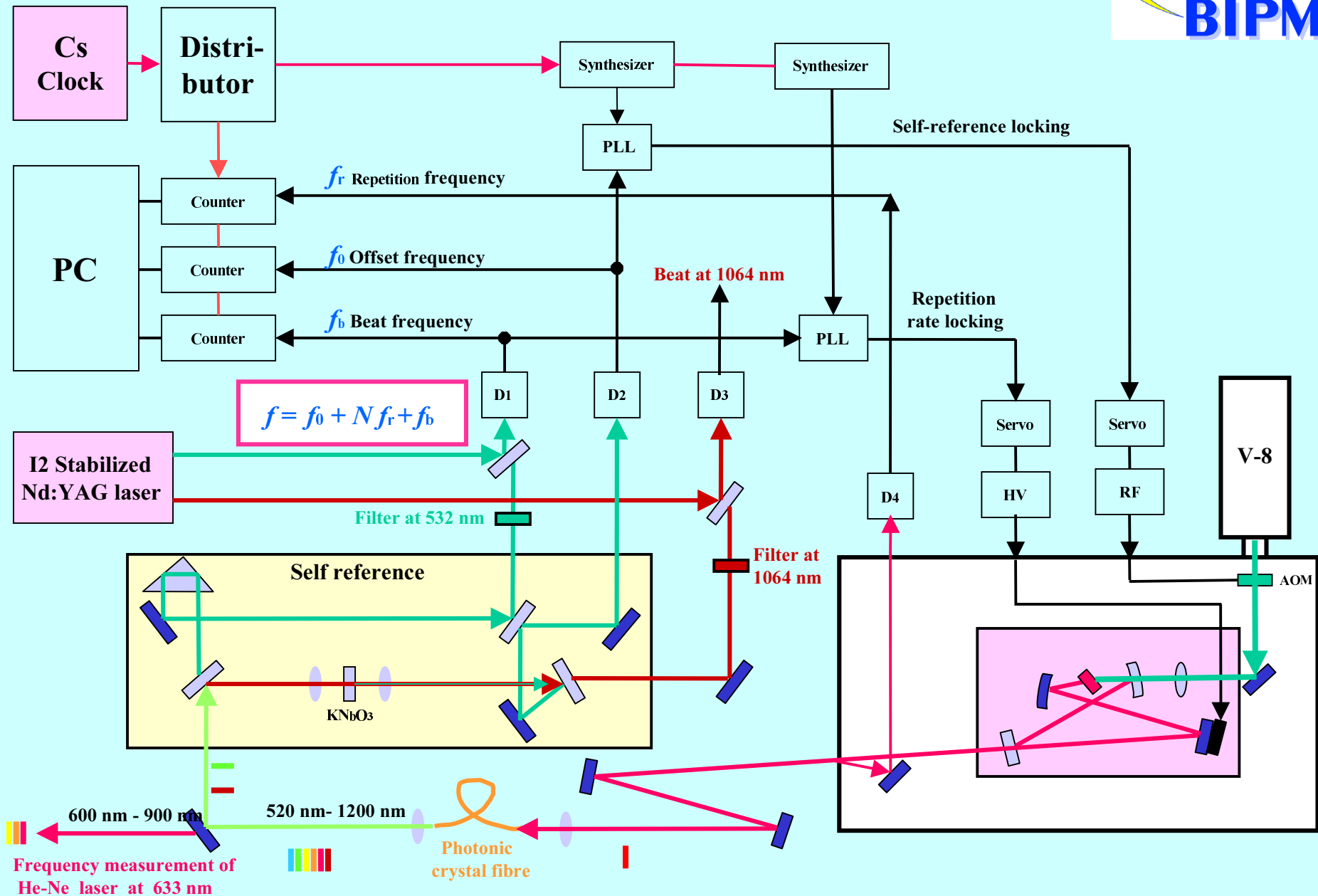


Optical frequency measurements at 633 nm and 532 nm simultaneously using optical clock configuration

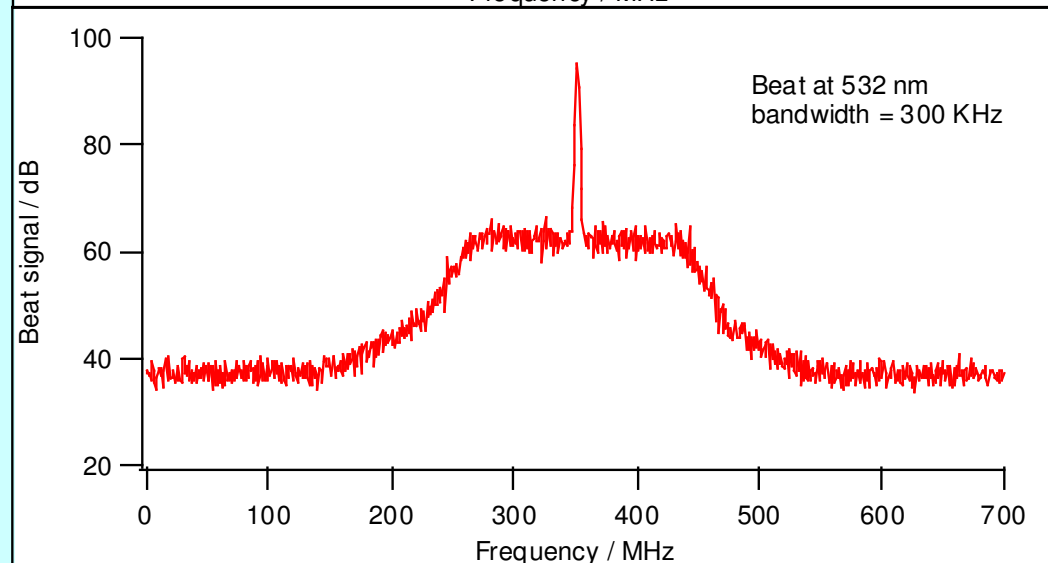
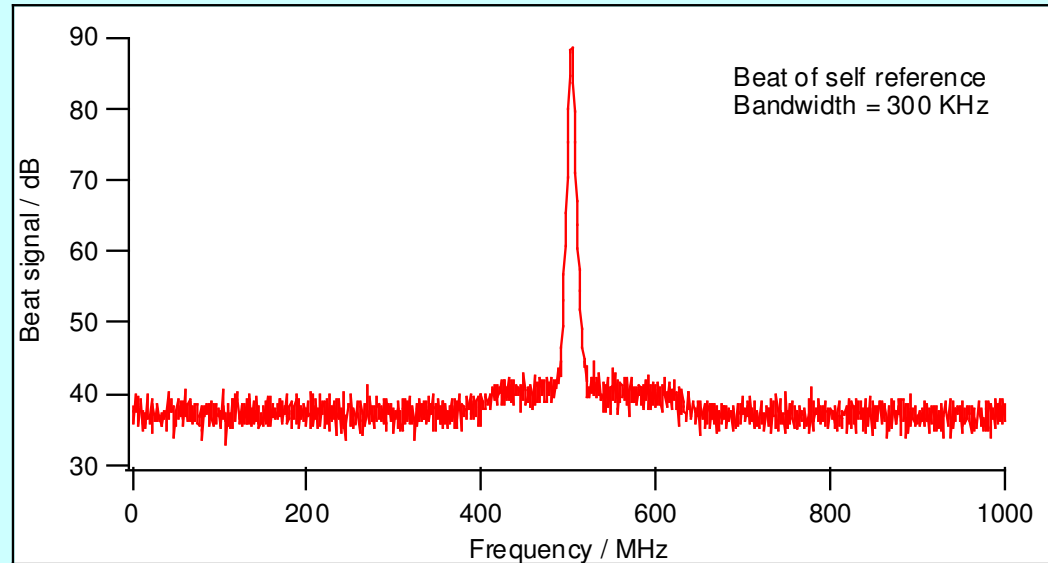
$$f = f_{ceo} + N \times f_{rep} + f_{beat}$$



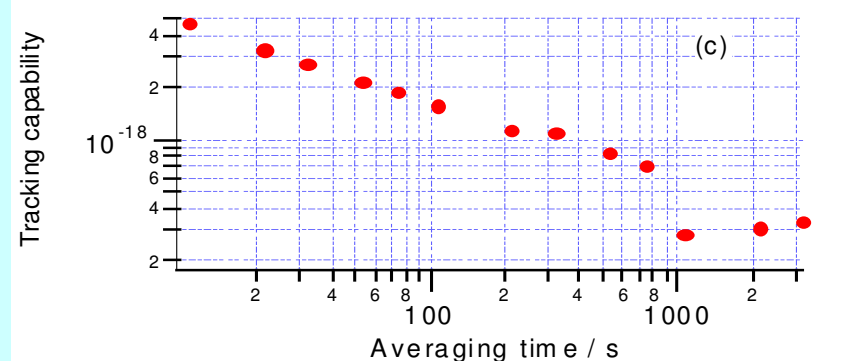
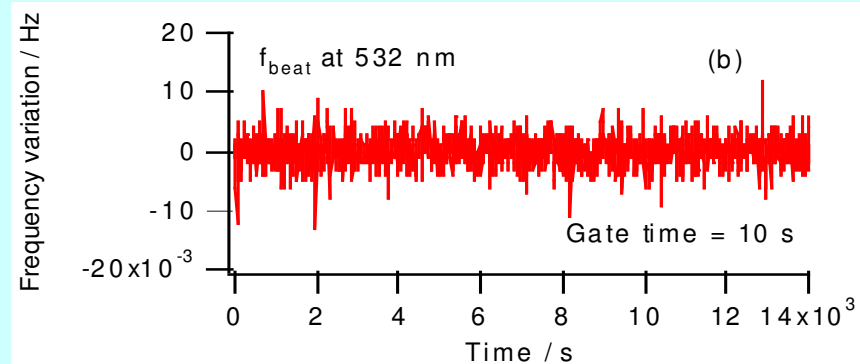
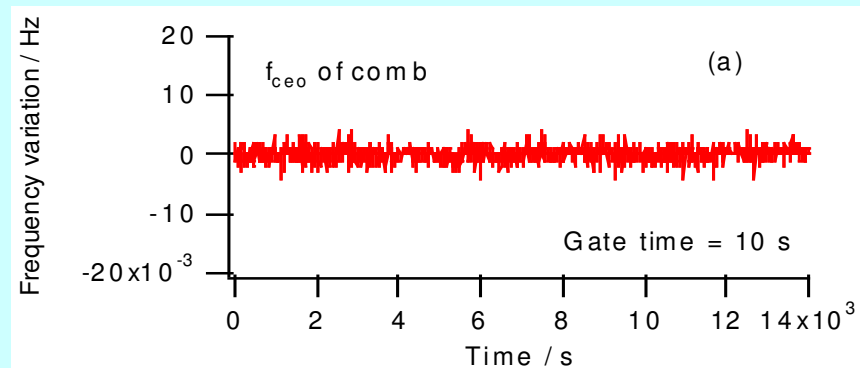
Optical frequency measurement using optical clock configuration at the BIPM



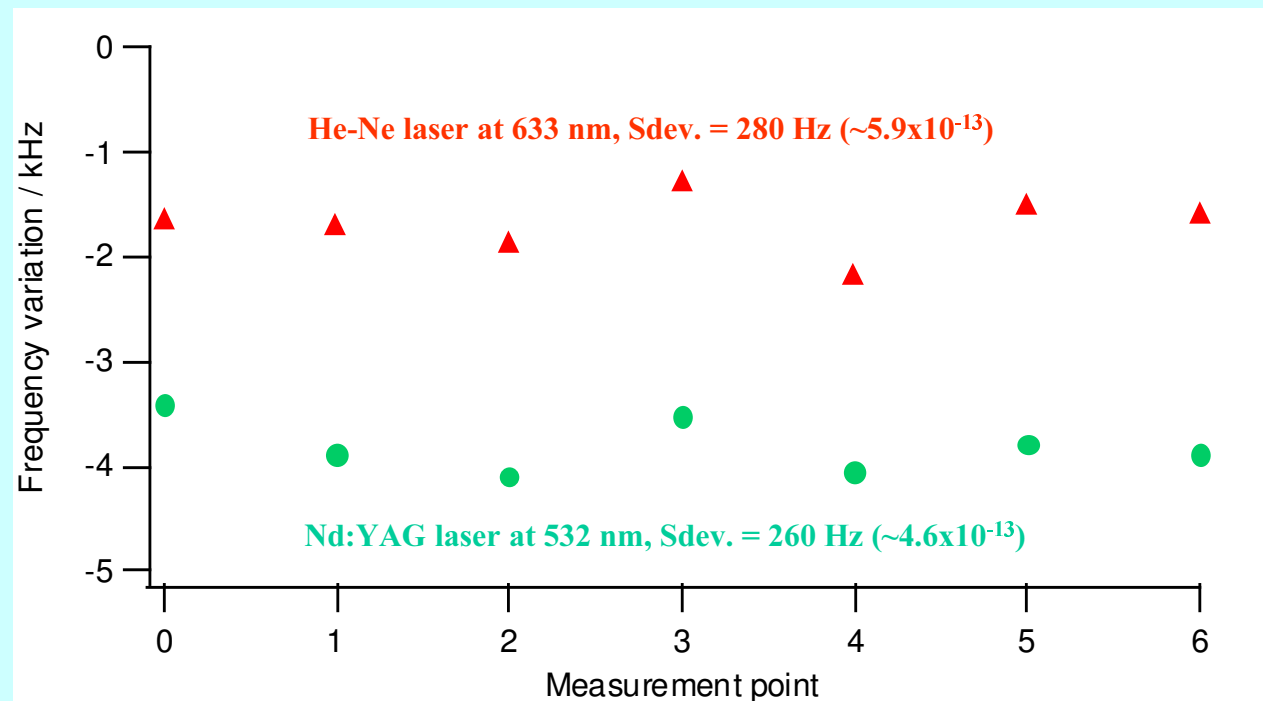
Signals for the servo of offset frequency and repetition rate



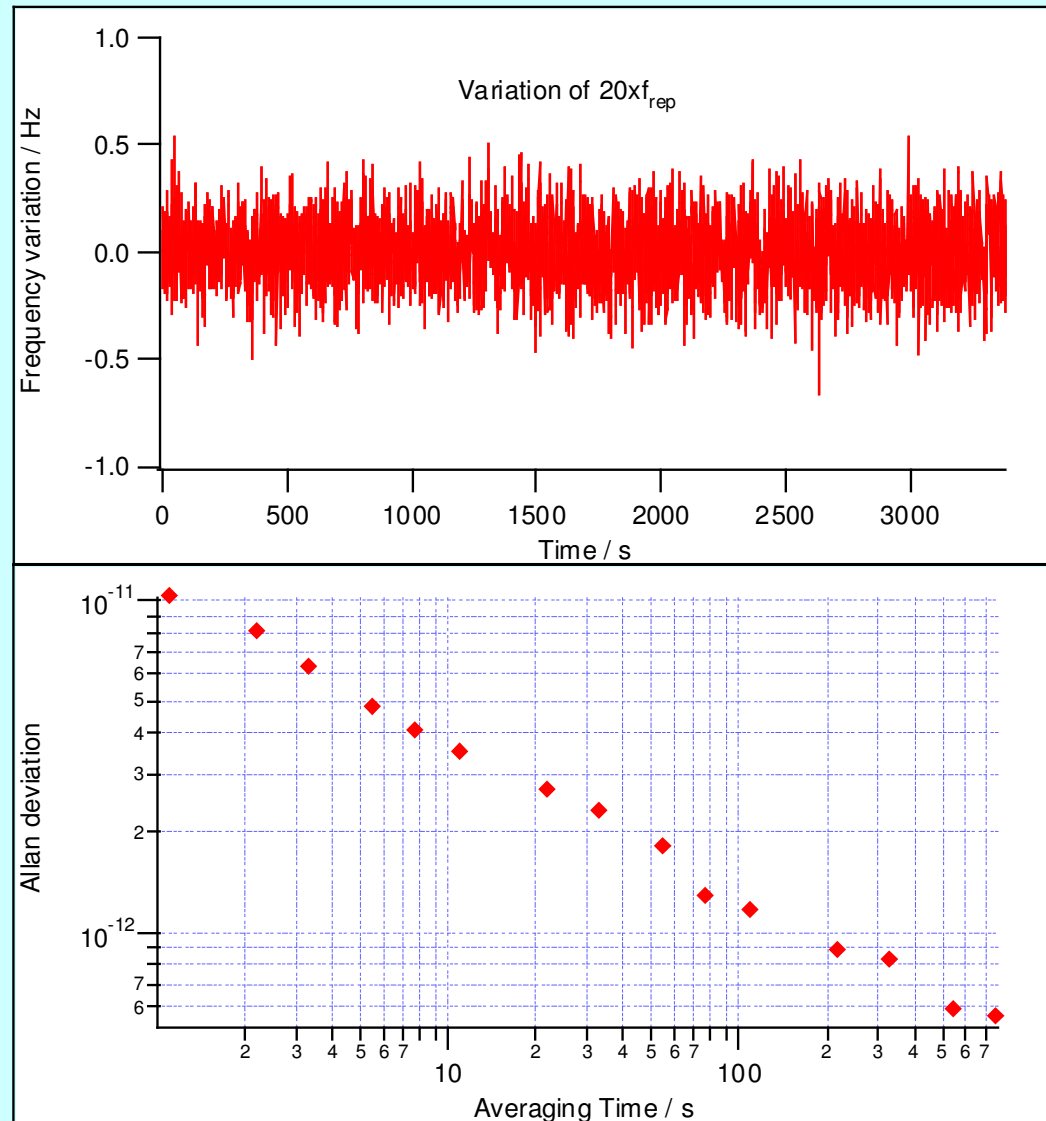
Tracking capability between fs-laser comb and I₂-stabilized Nd:YAG laser



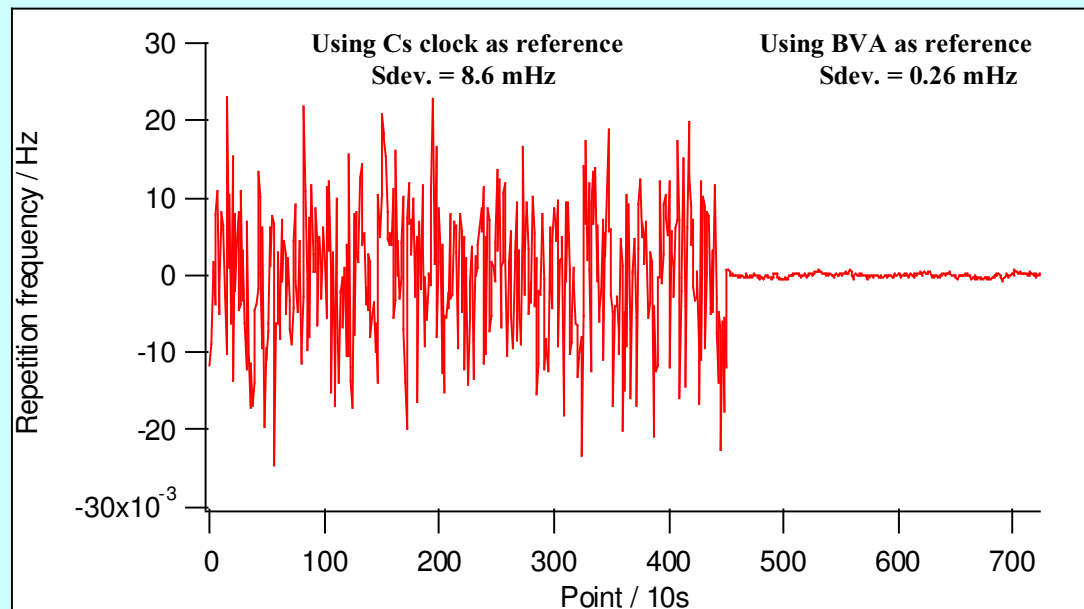
Optical frequency measurements of I₂ stabilized Nd:YAG laser at 532 nm and He-Ne laser at 633 nm simultaneously



Comparison between molecular optical clock and Cs clock

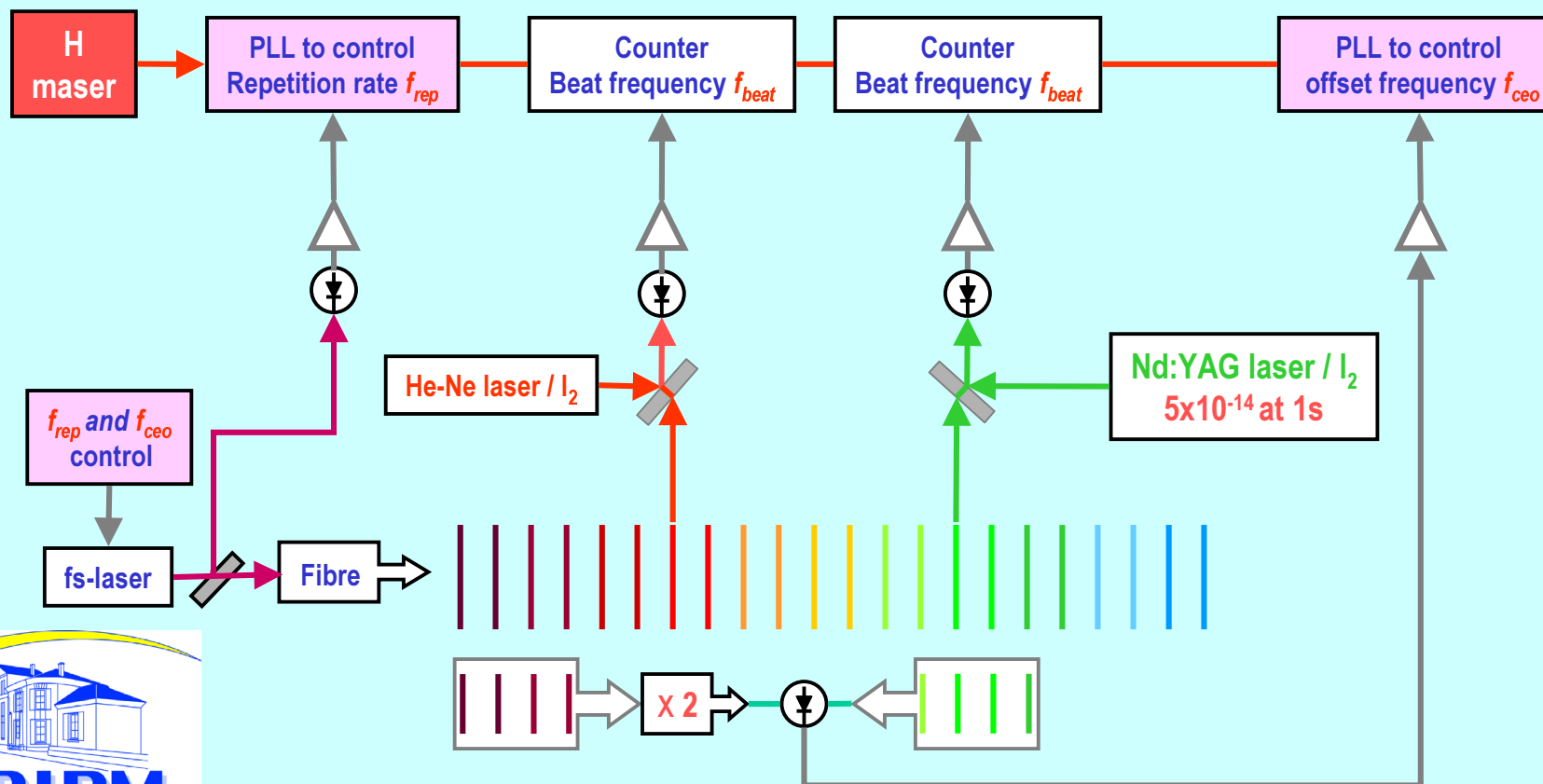


Comparison between microwave and optical standards

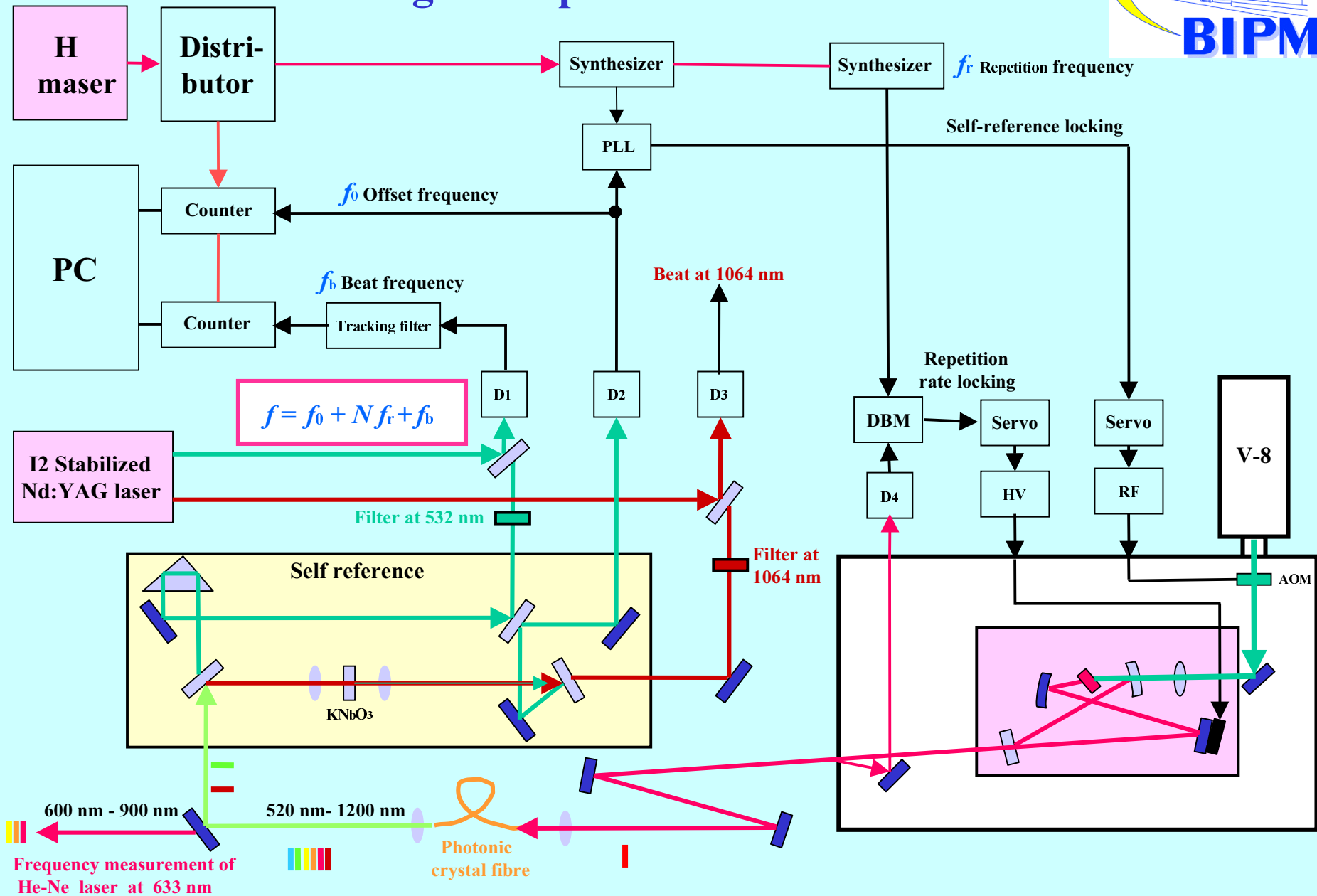


Optical frequency measurements at 633 nm and 532 nm based on RF frequency standard-H maser

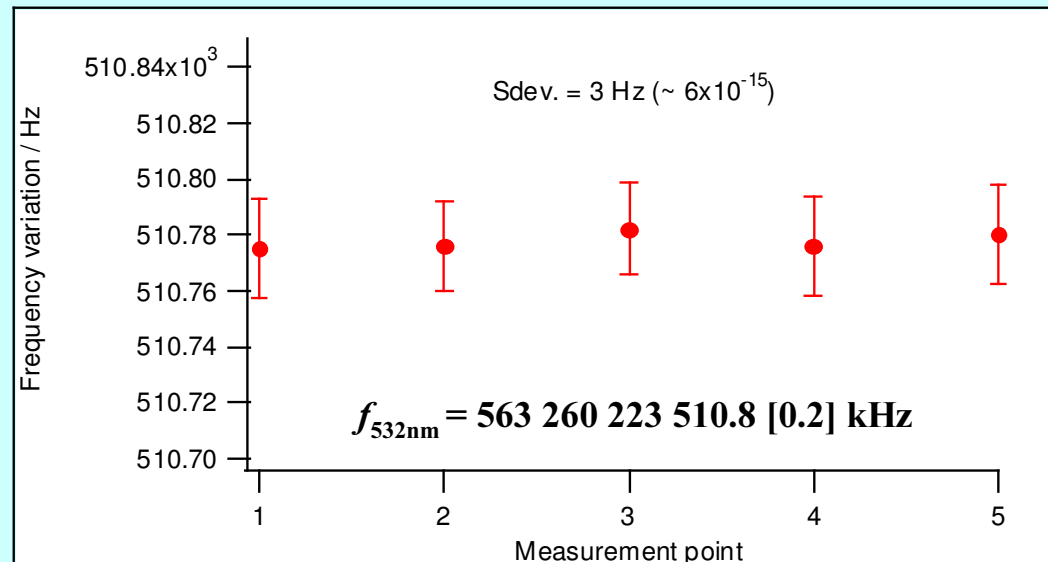
$$f = f_{ceo} + N \times f_{rep} + f_{beat}$$



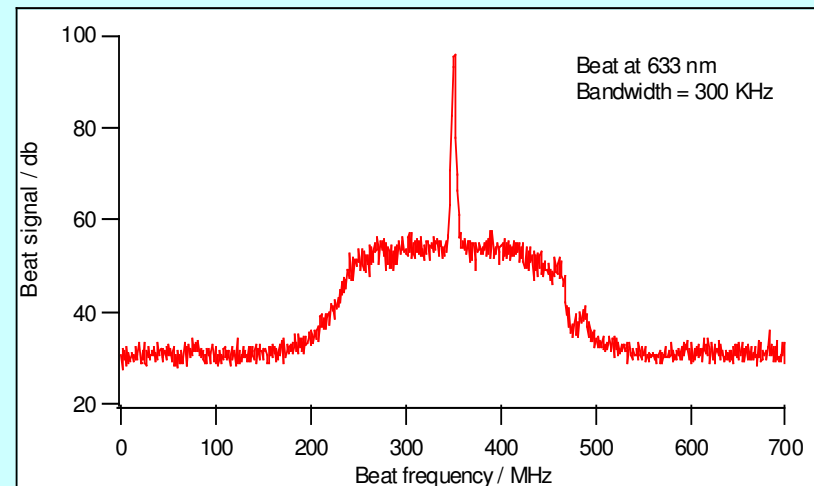
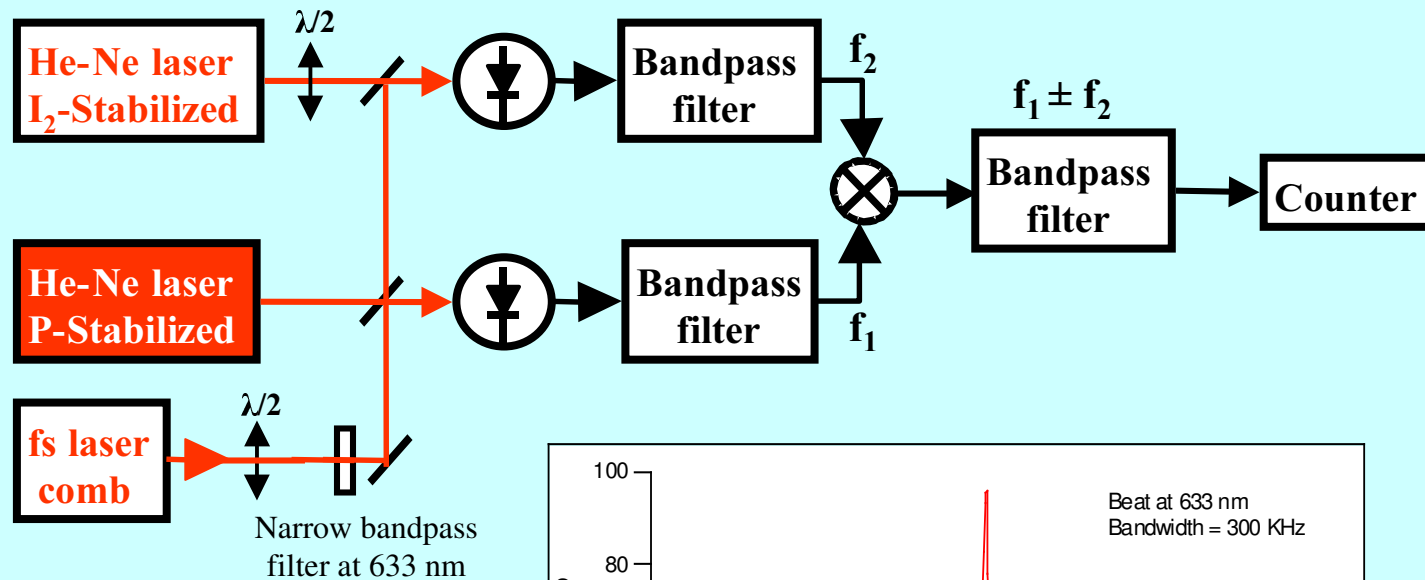
Optical frequency measurement by locking the repetition rate on H-maser



Optical frequency measurements of I₂ stabilized Nd:YAG laser at 532 nm



Frequency measurement of He-Ne laser at 633 nm



analysis **configure**

date & time

12/03/03 15:20

LASER SERIAL NUMBER:
BIPM 4, f component
M = 6.0 MHz
Pf = 74.1 mW

SAVE RESULTS?
(file names: "120303_1520.txt" and "120303_1520.html"
in directory C:\633 meas

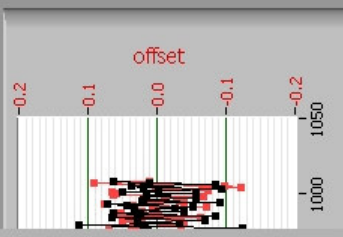
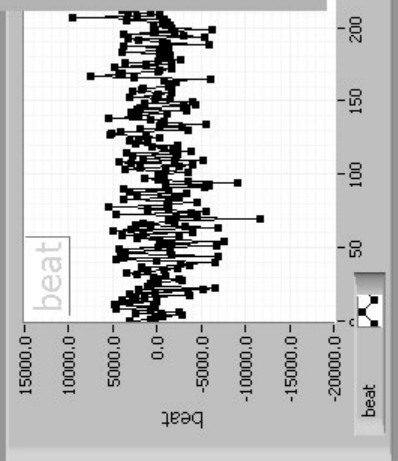
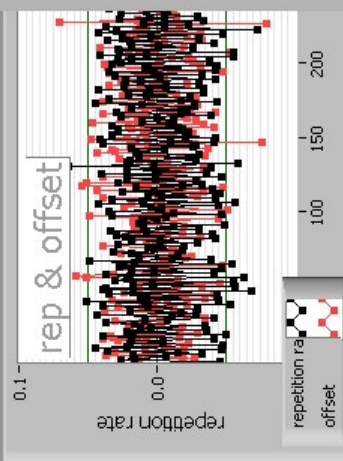
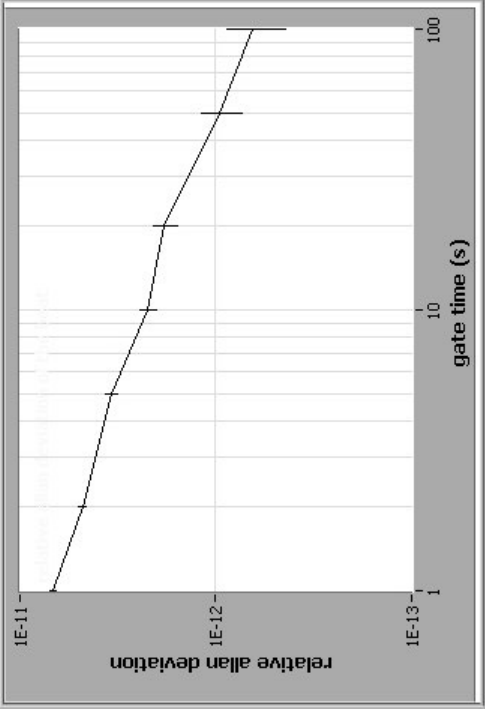
OK Cancel

Repetition Rate (rounded) (Hz)	739076380	±	0.029
Offset (rounded) (Hz)	498944000	±	0.046
Beat (Hz)	595128173	±	3268
Expected frequency (Hz)	473612353604000		
Number of Data	1009		
Initial number of Data	1015		

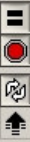
0.029
0.046
3267.865

	N ROUGH	N ROUNDED	f estimated (Hz)	diff expected (Hz)
+ fo	+fbeat	640815.04	640815.00	473612324521872.85 -29082127.15
- fo	+fbeat	640816.39	640816.00	473612065710252.85 -287893747.15
+ fo	-fbeat	640816.65	640817.00	473612612418287.15 258814287.15
- fo	-fbeat	640818.00	640818.00	473612353606667.15 2667.15

Tau (s)	sigma(tau)	unc(tau)
1.0	6.78E-12	2.14E-13
2.0	4.79E-12	2.14E-13
5.0	3.42E-12	2.42E-13
10.0	2.22E-12	2.23E-13
20.0	1.82E-12	2.60E-13
50.0	9.61E-13	2.20E-13
100.0	6.55E-13	2.18E-13



Time



analysis **configure**

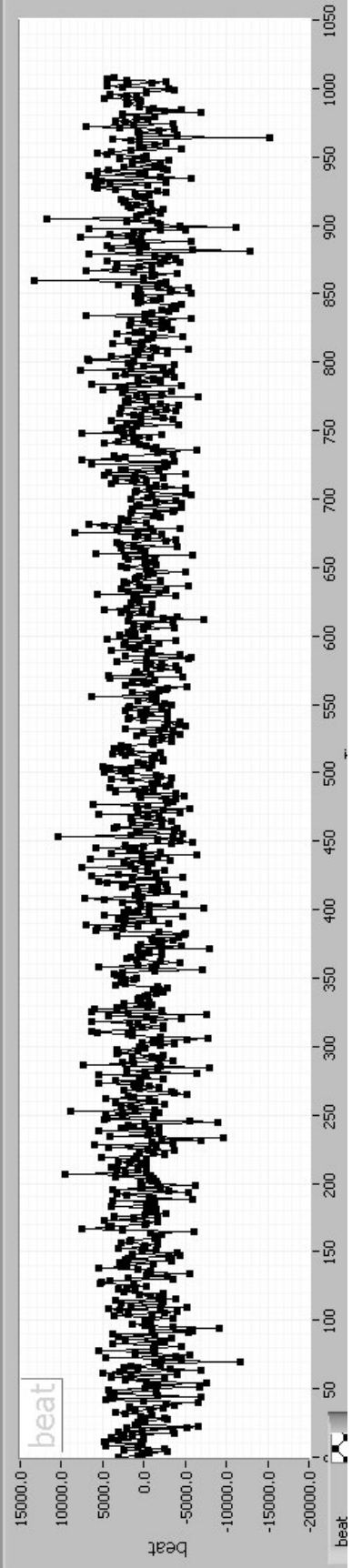
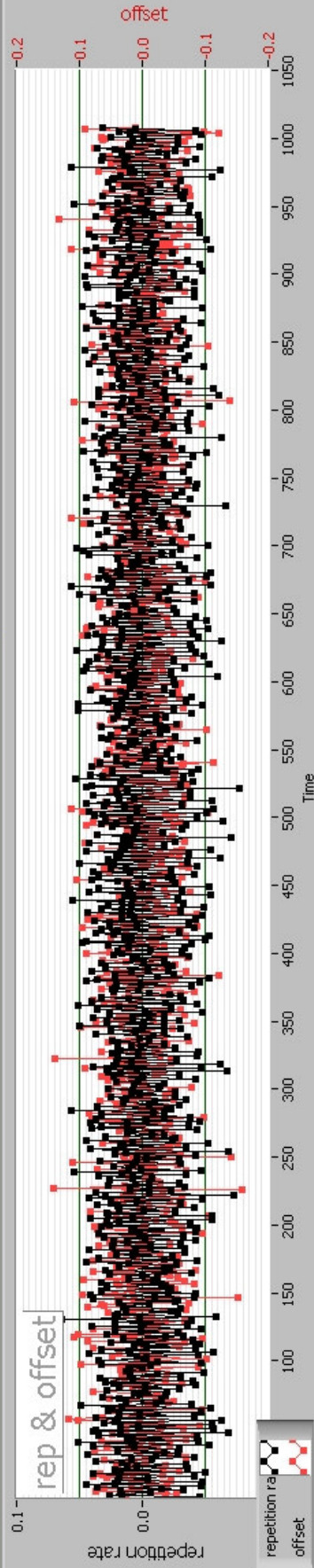


- f1 - Acquisition
- f2 - Filter
- f3 - Data Statistics
- f4 - Test
- f9 - Stop**

date & time

12/03/03 15:18

Repetition Rate (Hz)	739076380	±	0.029
Offset (Hz)	498944000	±	0.046
Beat (Hz)	595128173	±	3267.865
Number of Data	1009		
Initial number of Data	1015		
Time interval (s)	1.0		



Determine the absolute mode number of a mode-locked fs-laser comb for absolute frequency measurements

- **Previously measured data**
- **Atlas of molecular and atomic transitions**
- **Measured by precision wavemeter**
- **Self determination using fs-laser comb**

Self determination using fs-laser comb

$$f_x = \pm f_{\text{ceo}} + N \cdot f_{\text{rep}} \pm f_{\text{beat}}$$

$$f_x = \pm f'_{\text{ceo}} + (N+m) \cdot f'_{\text{rep}} \pm f'_{\text{beat}}$$

$$N = [\pm f'_{\text{ceo}} - (\pm f_{\text{ceo}}) + m \cdot f'_{\text{rep}} \pm f'_{\text{beat}} - (\pm f_{\text{beat}})] / [f_{\text{rep}} - f'_{\text{rep}}]$$

$$\delta = N_{\text{exp}} - N$$

			N_{exp}				
λ	f_{ceo}	m	case	$+f'_{\text{beat}} - (+f_{\text{beat}})$	$+f'_{\text{beat}} - (-f_{\text{beat}})$	$-f'_{\text{beat}} - (-f_{\text{beat}})$	$-f'_{\text{beat}} - (+f_{\text{beat}})$
633 nm	$f_{\text{ceo}} = f'_{\text{ceo}}$	-1	$\pm f'_{\text{ceo}} - (\pm f_{\text{ceo}})$	636572.9102	-9465.3696	640510.5630	1286548.8428
633 nm	$f_{\text{ceo}} = f'_{\text{ceo}}$	-2	$\pm f'_{\text{ceo}} - (\pm f_{\text{ceo}})$	642112.5681	317692.6513	640510.9861	964930.9029
633 nm	$f_{\text{ceo}} = f'_{\text{ceo}}$	-3	$\pm f'_{\text{ceo}} - (\pm f_{\text{ceo}})$	641373.3901	425218.4268	640510.9798	856665.9431
633 nm	$f_{\text{ceo}} = f'_{\text{ceo}}$	-4	$\pm f'_{\text{ceo}} - (\pm f_{\text{ceo}})$	640172.8194	478208.6869	640510.9511	802475.0836
633 nm	$f_{\text{ceo}} \neq f'_{\text{ceo}}$	-4	$+f'_{\text{ceo}} - (+f_{\text{ceo}})$	641838.4381	479941.4444	641898.4533	803795.4470
			$+f'_{\text{ceo}} - (-f_{\text{ceo}})$	454595.7761	292698.7824	454655.7912	616552.7850
			$-f'_{\text{ceo}} - (+f_{\text{ceo}})$	827693.7167	665796.7230	827753.7318	989650.7256
			$-f'_{\text{ceo}} - (-f_{\text{ceo}})$	640451.0546	478554.0609	640511.0698	802408.0635

$$f_x = \pm f_{\text{ceo}} + N \cdot f_{\text{rep}} \pm f_{\text{beat}} \quad (1)$$

$$f_x = \pm f'_{\text{ceo}} + (N+m) \cdot f'_{\text{rep}} \pm f'_{\text{beat}} \quad (2)$$

$$N = [\pm f'_{\text{ceo}} - (\pm f_{\text{ceo}}) + m \cdot f'_{\text{rep}} \pm f'_{\text{beat}} - (\pm f_{\text{beat}})] / [f'_{\text{rep}} - f_{\text{rep}}] \quad (3)$$

			N_{exp}				
λ	f_{ceo}	m	case	$+f_{\text{beat}} - (+f_{\text{beat}})$	$+f_{\text{beat}} - (-f_{\text{beat}})$	$-f_{\text{beat}} - (-f_{\text{beat}})$	$-f_{\text{beat}} - (+f_{\text{beat}})$
532 nm	$f_{\text{ceo}} \neq f'_{\text{ceo}}$	-1	$+f_{\text{ceo}} - (+f_{\text{ceo}})$	772407.5182	79967.6341	770232.5191	1462672.4033
			$+f_{\text{ceo}} - (-f_{\text{ceo}})$	-137534.3905	-829974.2747	-139709.3896	552730.4946
			$-f_{\text{ceo}} - (+f_{\text{ceo}})$	1672390.9207	979951.0365	1670215.9216	2362655.8058
			$-f_{\text{ceo}} - (-f_{\text{ceo}})$	762449.0120	70009.1278	760274.0129	1452713.8971
532 nm	$f_{\text{ceo}} \neq f'_{\text{ceo}}$	-7	$+f_{\text{ceo}} - (+f_{\text{ceo}})$	915241.8930	798970.8517	915275.7607	1031546.8020
			$+f_{\text{ceo}} - (-f_{\text{ceo}})$	762448.9998	646177.9585	762482.8675	878753.9088
			$-f_{\text{ceo}} - (+f_{\text{ceo}})$	1039050.2888	922779.2474	1039084.1565	1155355.1978
			$-f_{\text{ceo}} - (-f_{\text{ceo}})$	886257.3955	769986.3542	886291.2632	1002562.3046

$$f_x = \pm f_{\text{ceo}} + N \cdot f_{\text{rep}} \pm f_{\text{beat}} \quad (1)$$

$$f_x = \pm f'_{\text{ceo}} + (N+m) \cdot f_{\text{rep}} \pm f_{\text{beat}} \quad (2)$$

$$N = [\pm f'_{\text{ceo}} - (\pm f_{\text{ceo}}) + m \cdot f_{\text{rep}} \pm f_{\text{beat}} - (\pm f_{\text{beat}})] / [f_{\text{rep}} - f'_{\text{rep}}] \quad (3)$$

