Report from the BIPM Electricity Department

CCEM meeting

12-13 March 2015

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Activities of the Electricity Department

- **Voltage** metrology: international comparisons, calibrations, watt balance
- **Resistance** metrology: international comparisons, calibrations, watt balance
- **Capacitance** metrology: international comparisons, calibrations
- **Calculable capacitor:** capacitance metrology, measurement of R_K for *mise en pratique* of the electrical units
- **Coordination** (CCEM, CCPR, RMO-TCs, CIE, CPEM Exec. Com.)

BIPM.EM-K10: on-site Josephson comparisons (1.018 V and 10 V)

Meas. Sci. Technol.
23 (2012), 124001

IOP Publishing — Measurement Science and Technology

Meas. Sci. Technol. 23 (2012) 124001 (10pp) — doi:10.1088/0957-0233/23/12/124001

BIPM direct on-site Josephson voltage standard comparisons: 20 years of results

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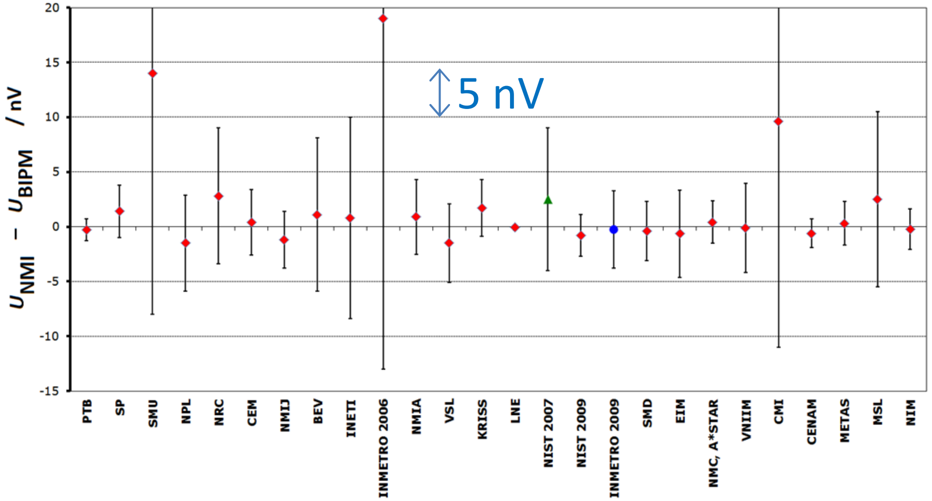
	Diff	Unc. /nV	
VNIIM (1)	1.1	2.9	Nov. 2010
VNIIM (2)	-0.1	2.0	Nov. 2010
CMI (1)	14.1	11.1	Feb. 2011
CMI (2)	9.6	10.3	Feb. 2011
CENAM (1)	2.5	1.3	Sep. 2011
CENAM (2)	-0.6	0.7	Sep. 2011
METAS	0.3	1.0	Jan. 2012
MSL (1)	-2.9	6.4	Apr. 2011
MSL (2)	2.5	4.0	Apr 2011
NIM (1)	0.9	3.3	Nov. 2013
NIM (2)	-0.2	0.9	Nov. 2013
INM (Ro)	Draft B		Jun. 2014
PTB	to be	published	Oct. 2014

10 V Josephson voltage, degrees of equivalence in nV (copied from the KCDB)



- On average 2 comparisons / year
- Technical expertise and improvements leading to better results for 85% of the comparisons
- Best relative results achieved: a few parts in 10^{11}
- 2 comparisons already scheduled for 2015 (DMDM, NIMT)

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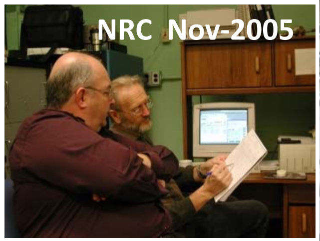
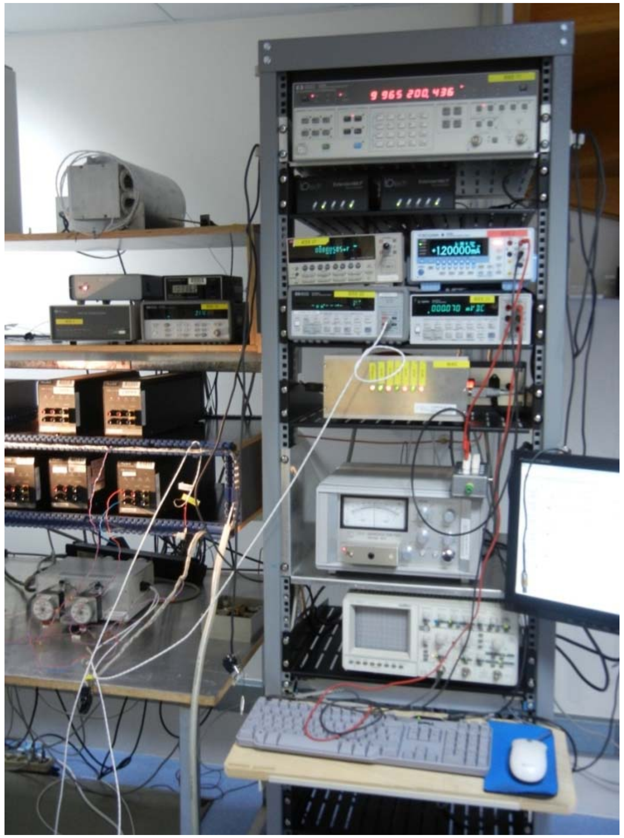


BIPM.EM-K11: bilateral Zener comparisons (1.018 V and 10 V)



Automated BIPM Zener measurement setup based on a PTB – programmable Josephson Voltage Standard

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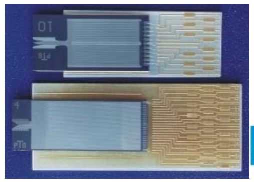
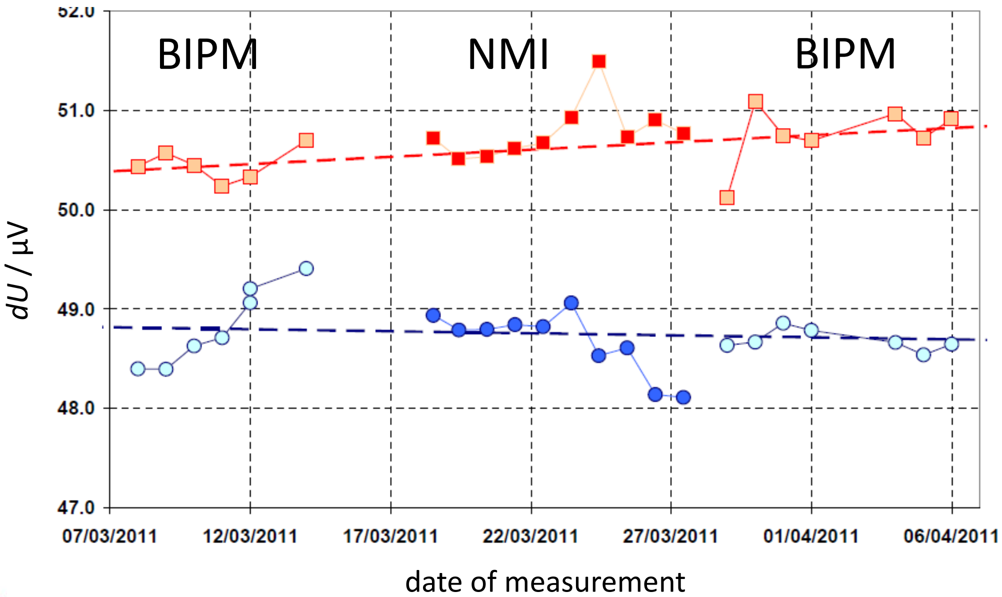


PTB

Significant increase of participation in 2014 (**Serbia, Egypt, Belgium, Ireland, Thailand**)

Reasons for this success:

- Preparation for an on-site comparison of JVSs
- As a final training exercise for new staff
- To support CMC claims and Quality Systems
- Results published within 6 months



Secondment of S. Solve at NIST (July 2012 – July 2013)

● Training on the use of the NIST 10 V PJVS: hardware and software
(July 2012 – Sep. 2012)

● DC applications: Investigations on possible voltage errors produced at the output of 10 V PJVS ultimately checked by a direct comparison between two PJVS systems
(Oct. 2012 – March 2013) -> *Metrologia* **50** (2013) 441

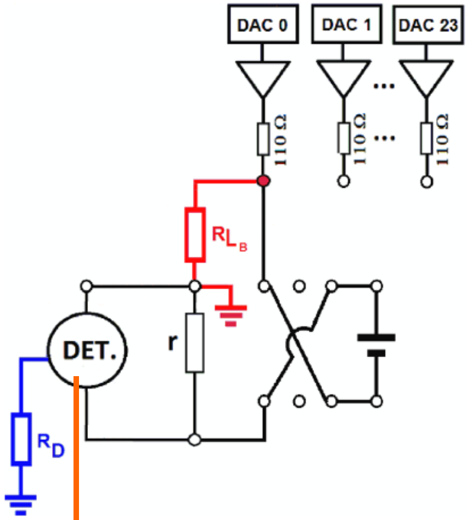
- systematic error sources investigated (biased at non-zero currents)
- agreement of 2.6 parts in 10^{11} (u_r=3.4 parts in 10^{11})
- dominant error source: leakage resistance to ground (up to 2 nV at 10 V)

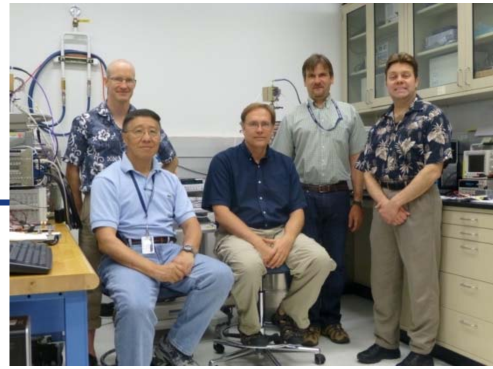
● AC applications: calibrator gain and linearity investigations using the differential sampling method for voltages up to 7 V rms and frequencies below 400 Hz.
(April 2013 – May 2013)

● Assembly and tests of the 10 V NIST PJVS dedicated to BIPM for future comparison of ac JVS **(June 2013 – July 2013)**

- further work planned with a secondee from an NMI

Investigations of LRG

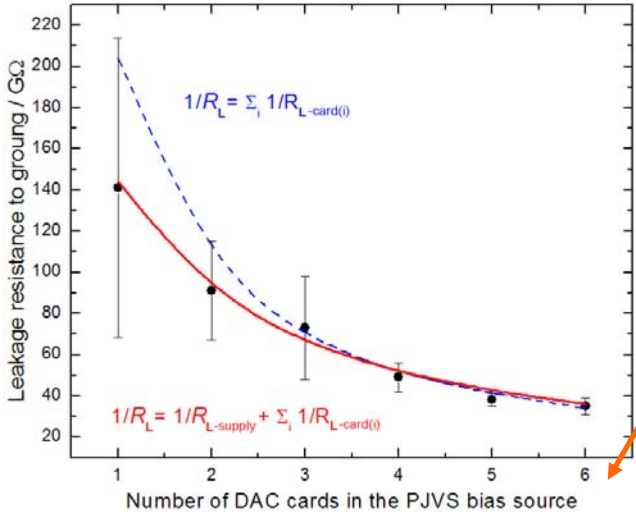




Collaborative work between

BIPM and NIST

- The total LRG is the contribution of the LR of each card in parallel to the others
- The total LRG is the contribution of the LR of each card in parallel to the others AND to the LRG of the power supply
- *Metrologia* 50 (2013) 441



10 V NIST PJVS

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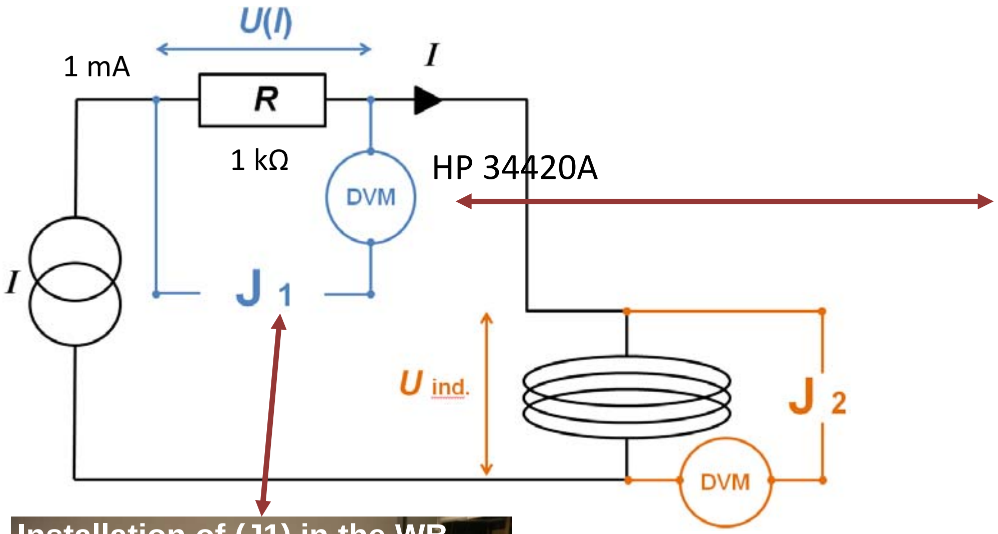
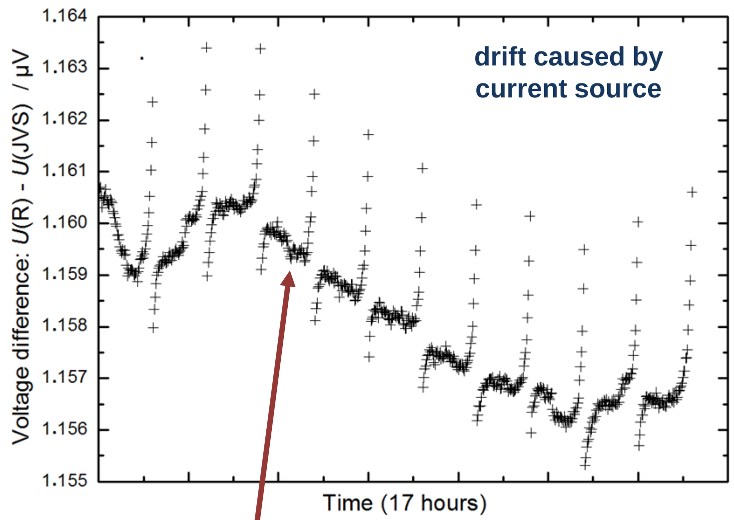
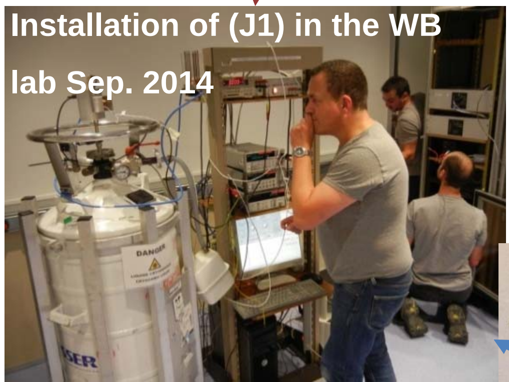
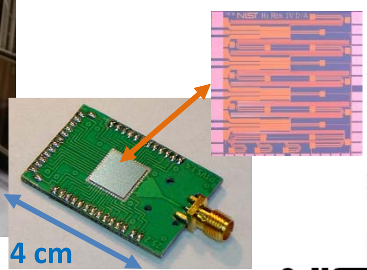
Measuring the current in the coil of the watt balance: implementation of a Josephson Voltage Standard

The simultaneous measurement mode of the BIPM Watt Balance (Force and velocity) requires 2 different Josephson Voltage Standards: one to measure the current in the coil **(J1)** and one to measure the induced voltage across the coil **(J2)**



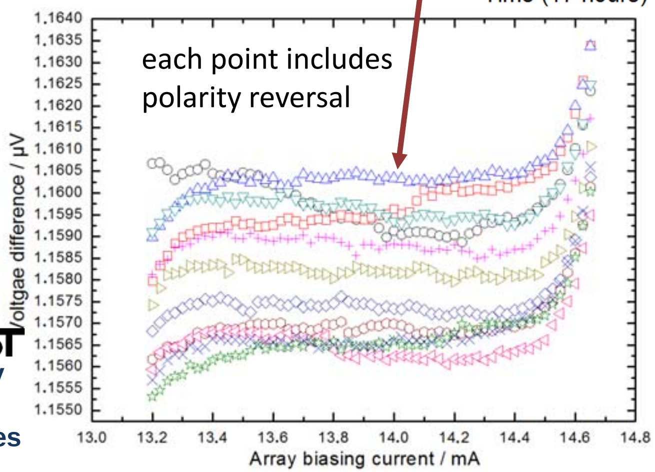






NIST

Josephson array - NIST technology
18.5 GHz,
1 bias source for 3 segments in series



voltage of JVS remains quantized on the Shapiro step in the complex electrical environment of the watt balance

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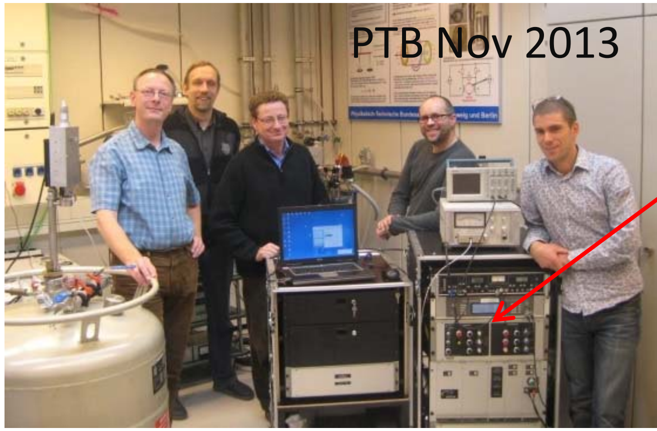
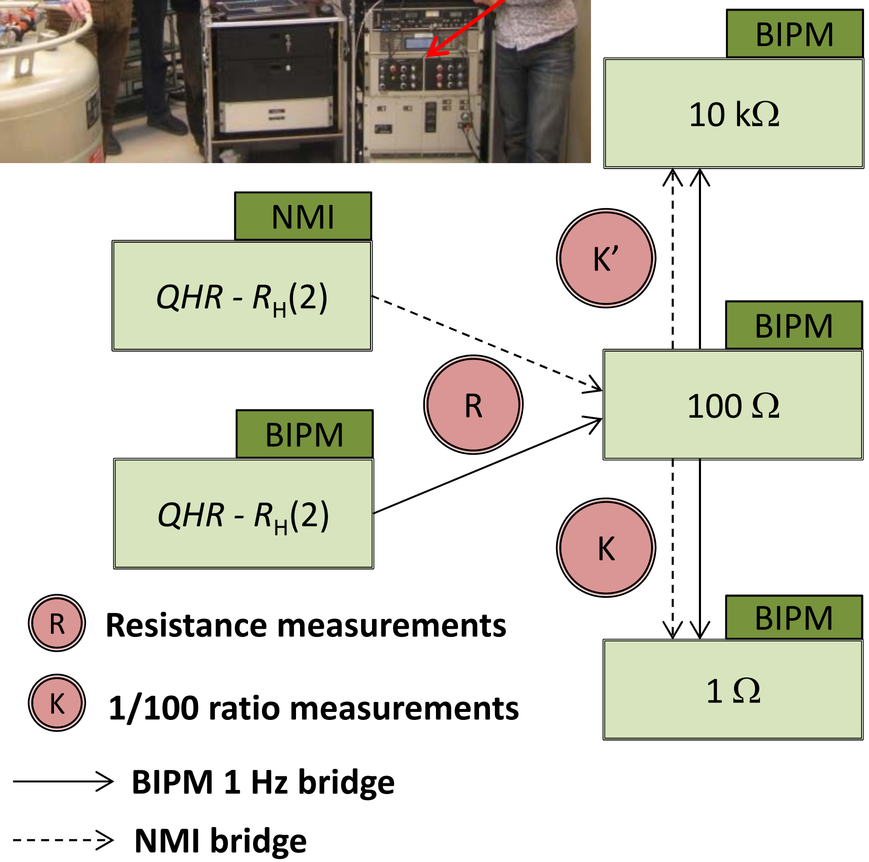
On-site quantum Hall resistance key comparisons (BIPM.EM-K12)

- To verify international coherence of primary resistance standards by comparing quantum Hall effect based standards of the NMIs with that of the BIPM
- Five such comparisons have already been carried out in the period 1993 to 1999. This comparison has been resumed in 2013 at the request of the CCEM
- A first comparison has been carried out with the PTB in Nov 2013
- 15 new comparisons are expected for the coming years (2015: VSL, INMETRO)



BIPM RT 1 Hz bridge



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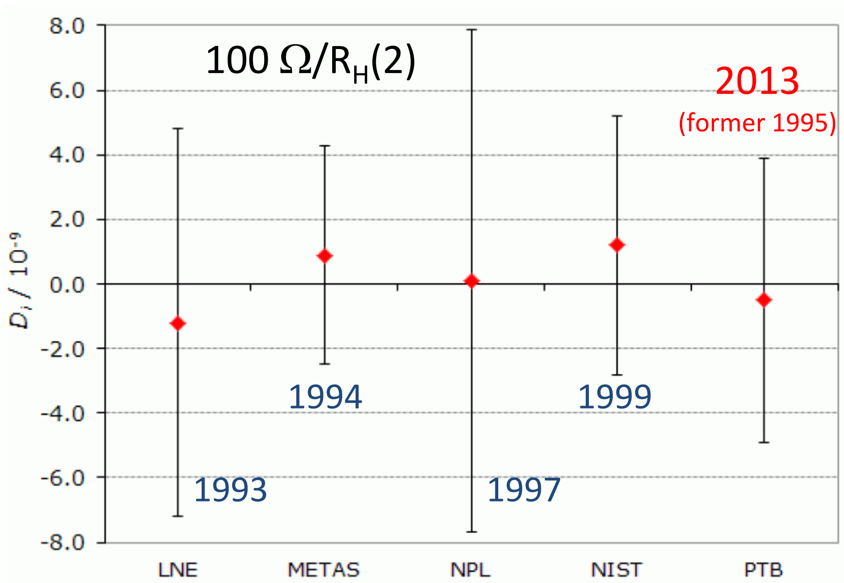
On-site quantum Hall resistance key comparison (BIPM.EM-K12)

$D_i \equiv$ Relative difference between the result of measurement of NMI *i* and that of the BIPM

Graph of equivalence (KCDB)



10 kΩ/100 Ω

NMI	D_i (10^{-9})	U_i (10^{-9})
LNE	2.2	6.6
METAS	0.1	3.6
NPL	3.3	6.4
NIST	5.9	11.0
PTB 2013	0.7	3.8

100 Ω/1 Ω

NMI	D_i (10^{-9})	U_i (10^{-9})
LNE	-3.2	8.8
METAS	0.8	5.4
NPL	2.8	9.6
NIST	3.8	6.2
PTB 2013	-0.8	8.0

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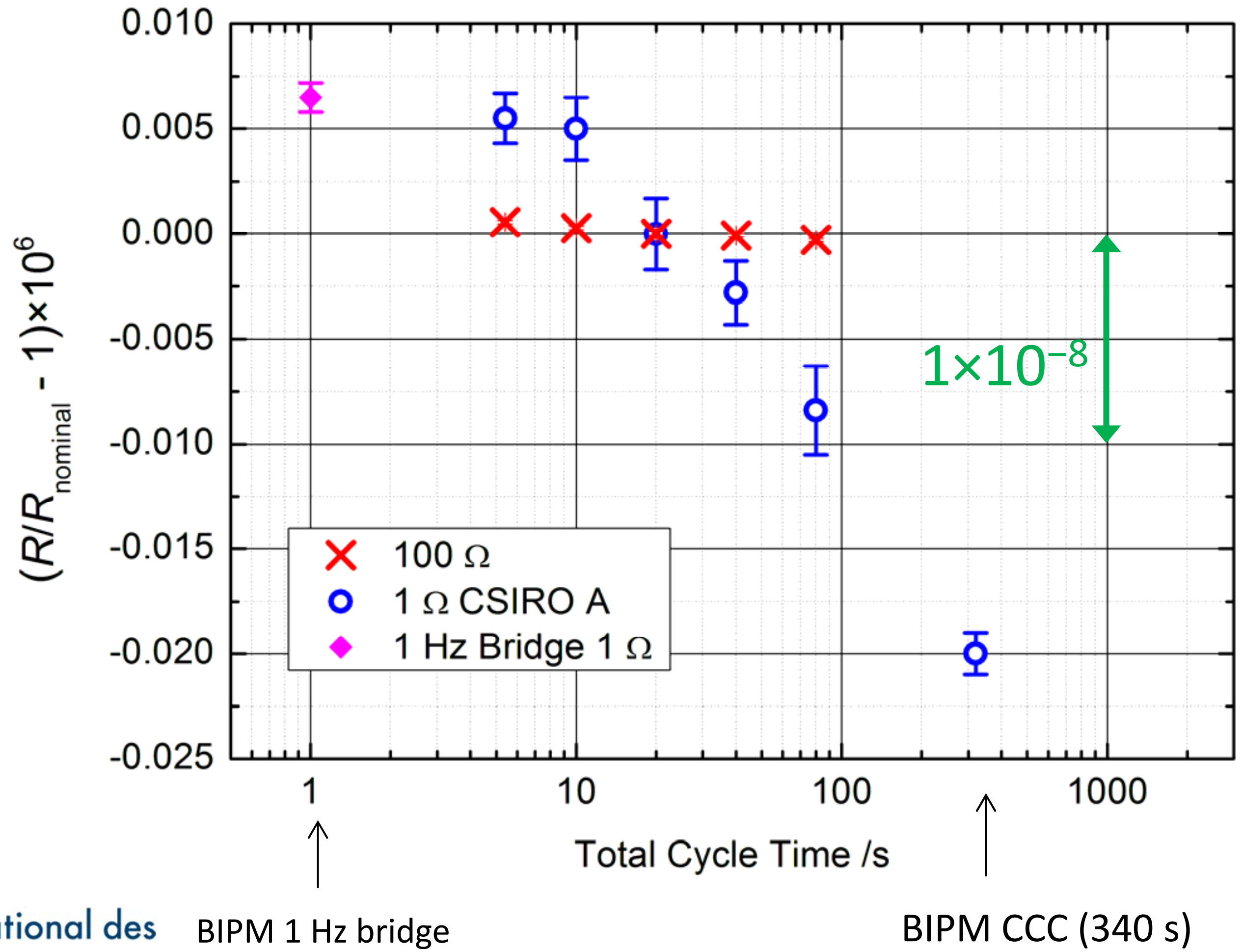
Additional investigations around BIPM.EM-K12

- Typical frequency dependence for 1 Ω and 100 Ω standard resistors



No well defined true dc value !

PTB-BIPM comp. at 1 Ω done for short cycle times (not "dc")

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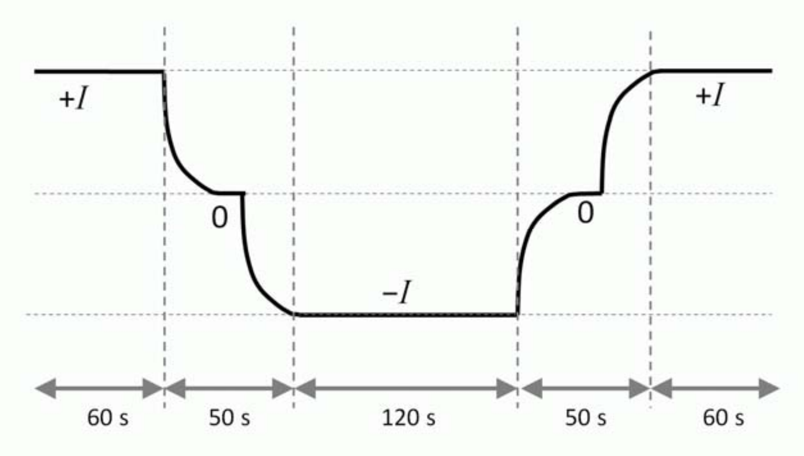
Additional investigations around BIPM.EM-K12

- Comparison with PTB has offered the opportunity to investigate differences between currently accepted “dc” measurements and very low frequency measurements



Typical “dc” measurement cycle
(BIPM CCC bridge)

Total cycle time = 340 s (3 mHz)

PTB bridge uses nearly rectangular signals

- It has been shown that this effect may be particularly important especially for low resistance values such as 1 Ω resistors which may show **unexpected frequency dependence** between 1 Hz and few mHz depending on their fabrication technology

- This demonstrate the importance of the choice of the 1 Ω standard resistor for such key comparisons and of the way the “dc” resistance value is defined

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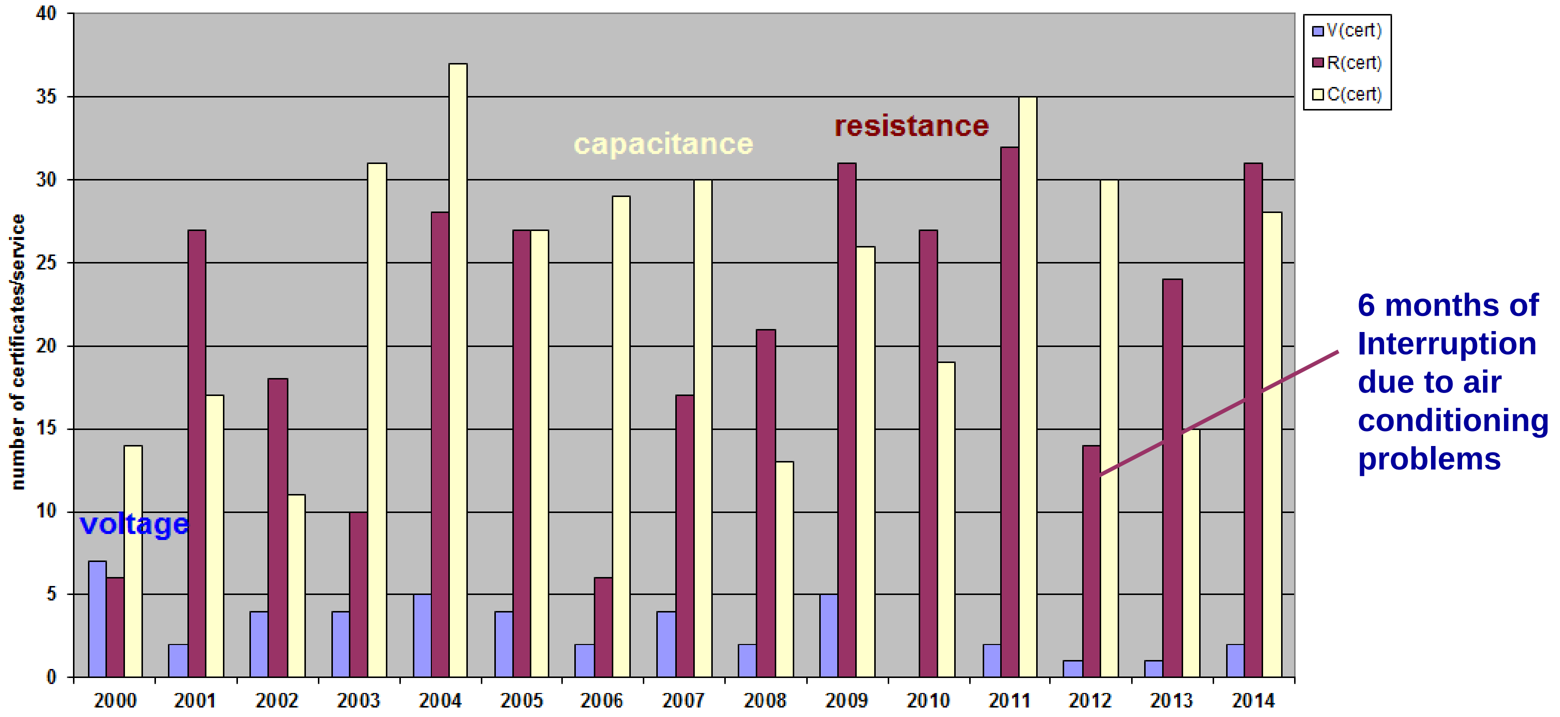
Comparisons in capacitance: EURAMET-S31, CCEM-K4.201X

- EURAMET EM-S31 comparison of 10 pF and 100 pF standards for measurements traceable to a quantum Hall effect resistance standard – piloted by PTB, participation of LNE, METAS, VSL and BIPM. Circulation of standards 2010-11.
- Original aim was to support capacitor charging single electron transport experiments – but has highlighted a wider lack of consistency in capacitance traceability.
- A supplementary circulation of ac-dc resistors in 2013 gave excellent results and eliminated one suspected cause of errors. Other internal investigations in each lab have so far not resolved the discrepancies.
- A new circulation of standards has started end 2014, this time to include calculable capacitor traceability from NMIA. The new BIPM calculable capacitor will also contribute useful information in this period.
- The 2016-19 work programme proposes a Key Comparison in capacitance piloted by the BIPM. The present situation indicates that this will be a valuable exercise to reaffirm confidence in capacitance traceability.

Calibrations

voltage: Zeners at 1.018 V, 10 V	2 per year
resistance: 1 Ω, 100 Ω, 10 k Ω	25-30 per year
capacitance: 1 pF, 10 pF, 100 pF	25-30 per year

Number of Calibration Certificates per year



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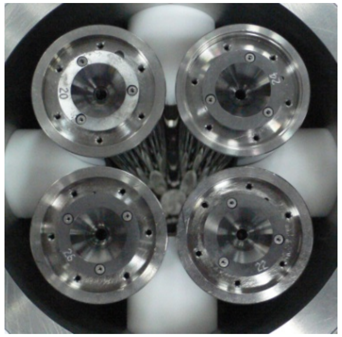
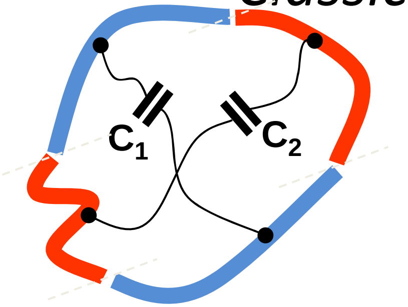
Determining R_K with a calculable capacitor

f ≈ 1 kHz

Capacitance ⟷ Quadrature bridge ⟷ Resistance

Classical





Calculable capacitor

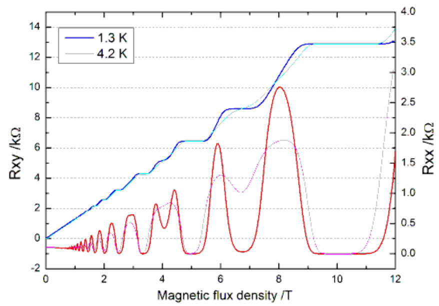
$$\Delta C = \frac{\varepsilon_0 \log_e 2}{\pi} \Delta l$$

For $\Delta l \approx 0.2$ m, $\Delta C \approx 0.4$ pF

To compare *C* to *R*, we also have to chose a frequency, *f*

(in our case, *f* ≈ 1 kHz)

Quantum



Quantum Hall effect

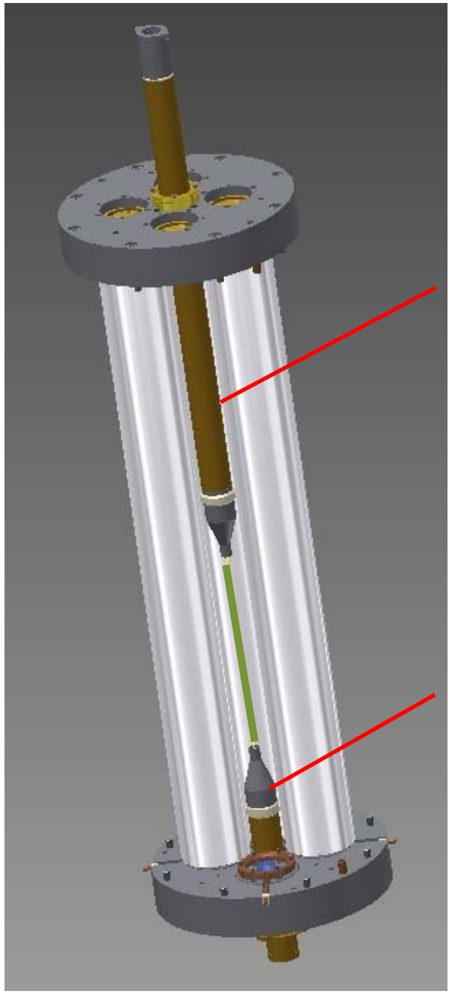
(2-d electron gas, *B* ≈ 10 tesla, *T* < 1 K)

$R_{hall} = R_K / i \quad (i = 1,2,4\ldots)$

$R_K = h / e^2 \approx 25.8$ kΩ

for *i* = 2 plateau: *R* ≈ 13 kΩ

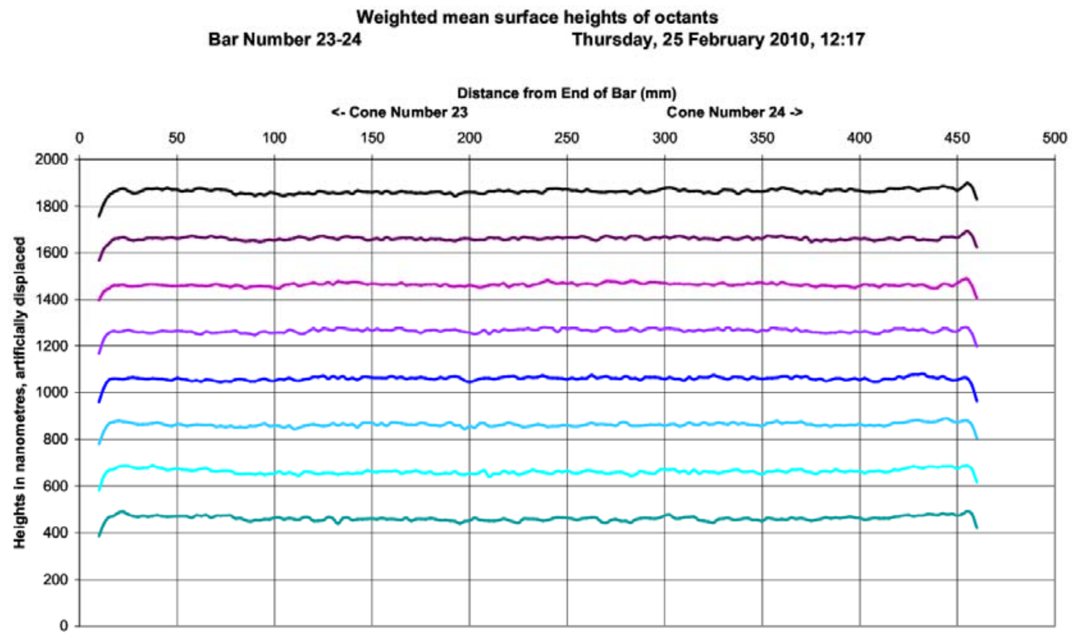
The new NMIA capacitor design



mov. guard electrode

4 main electrodes

fixed guard electrode



This instrument exists thanks to many years of dedicated work by Greig Small and John Fiander, well beyond their 'retirement'.

'A Calculable Standard of Capacitance', Clothier, *Thesis* **1963**

'Design of a Calculable Cross-Capacitor', Small and Fiander, *CPEM Digest* **2004**

'Fabrication and Measurement of the Main Electrodes of the NMIA-BIPM Calculable Cross Capacitors', Small and Fiander, *IEEE Trans. Instr. Meas.* **2011**

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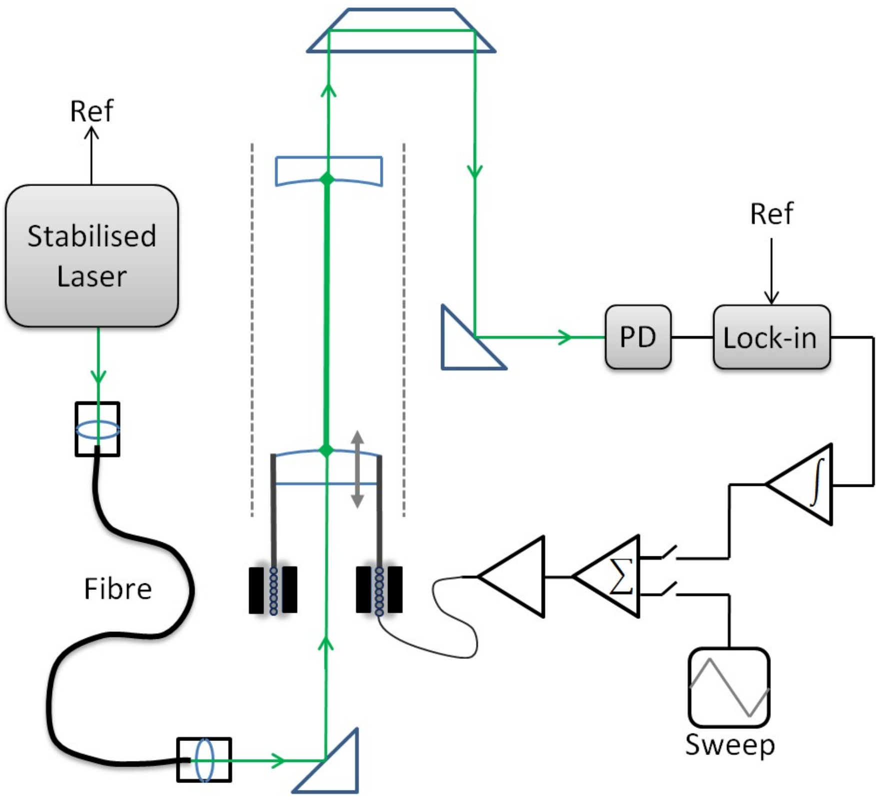
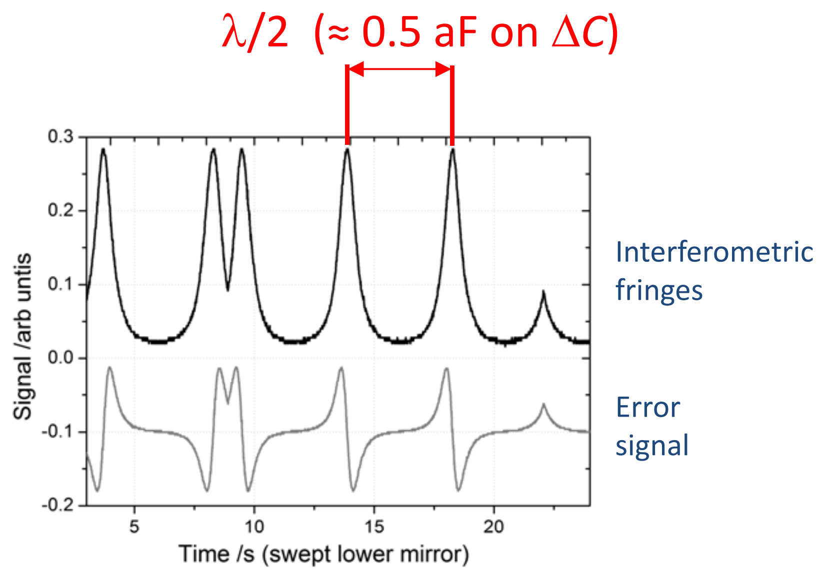
Servo-control of the distance between guard electrodes

Laser source stabilized on molecular $^{127}I_2$ transition : a_{10} component, f=563 260 223 513 kHz

$\lambda \approx$ 532,245 nm





0.2 m (0.4 pF) ≈ 770 000 fringes

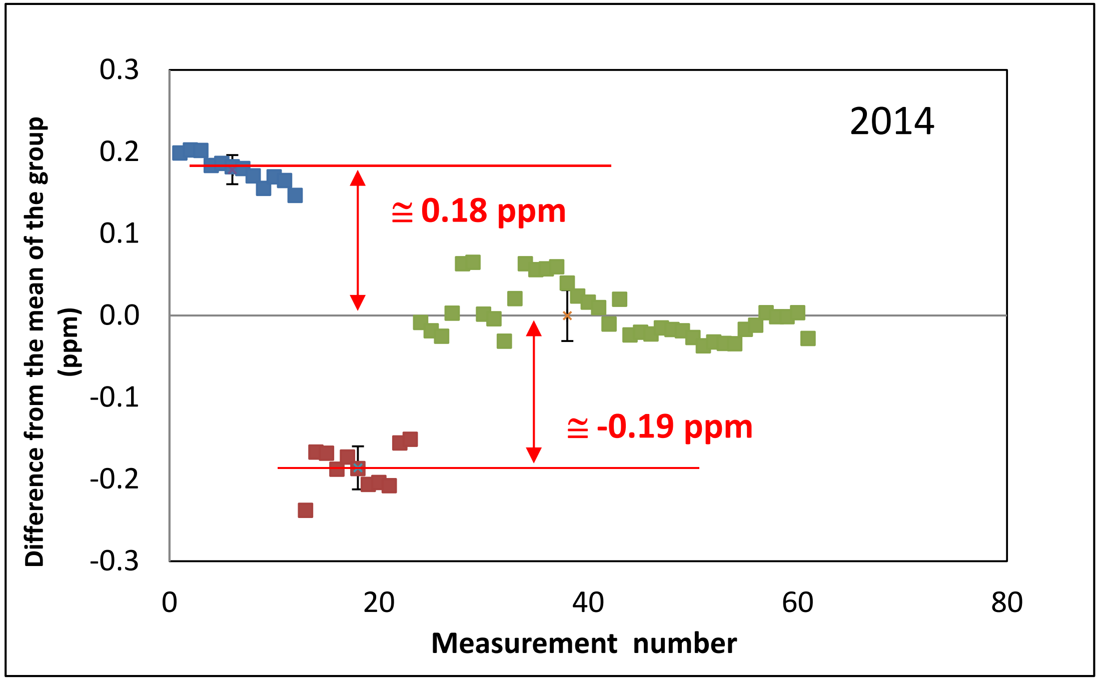
1 part in 10^9 of ΔL=0,2 m in terms of interferometric fringes = 0.77 mfr

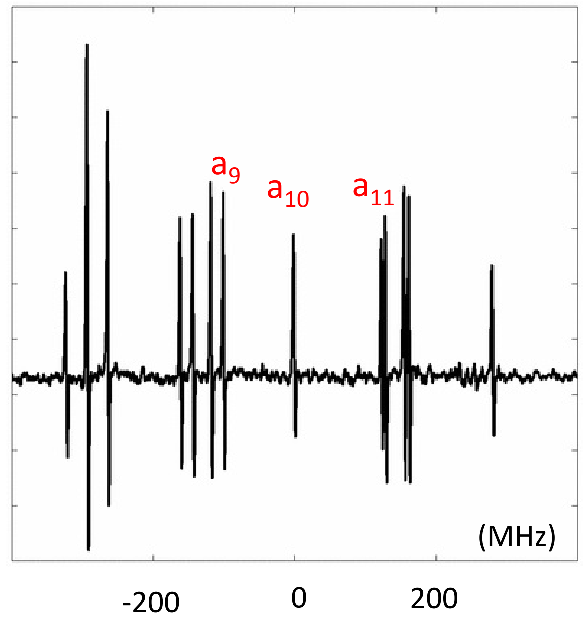
First set of measurements (2014)

Lack of stability of the first set of measurements obtained; but the cloud of data may be split in 3 different parts

($a_{10} - a_9$) frequency error ≅ +0.22 ppm

($a_{11} - a_{10}$) frequency error ≅ -0.21 ppm





→ Laser frequency 'a priori' locked on the hyperfine component a_{10} in the transition of iodine

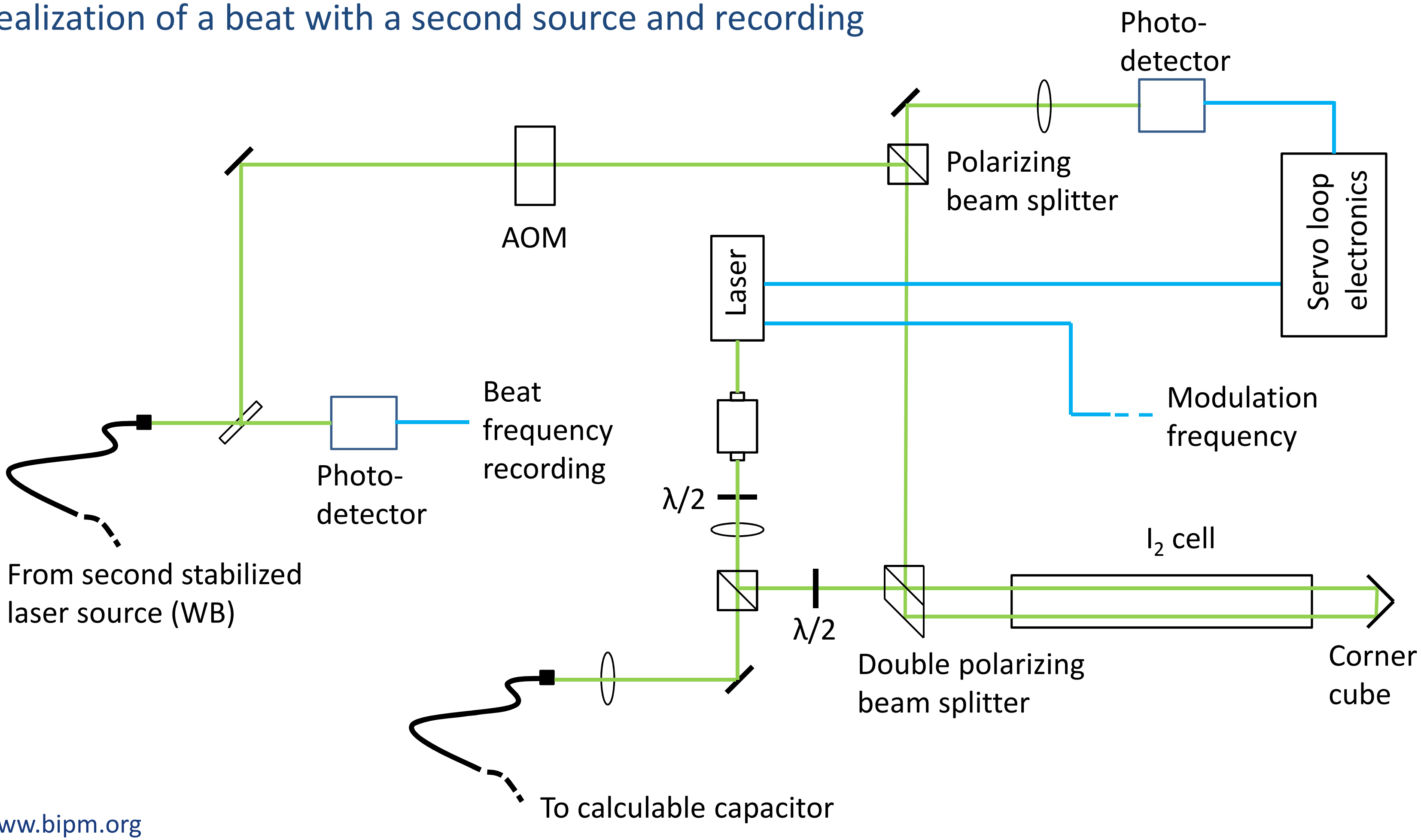
→ Jumps between a_{10} line and its two adjacent lines a_9 and a_{11} could explain instabilities of measurements

New frequency stabilized laser source

→ Previous compact laser source doesn't offer access to all possible tuning

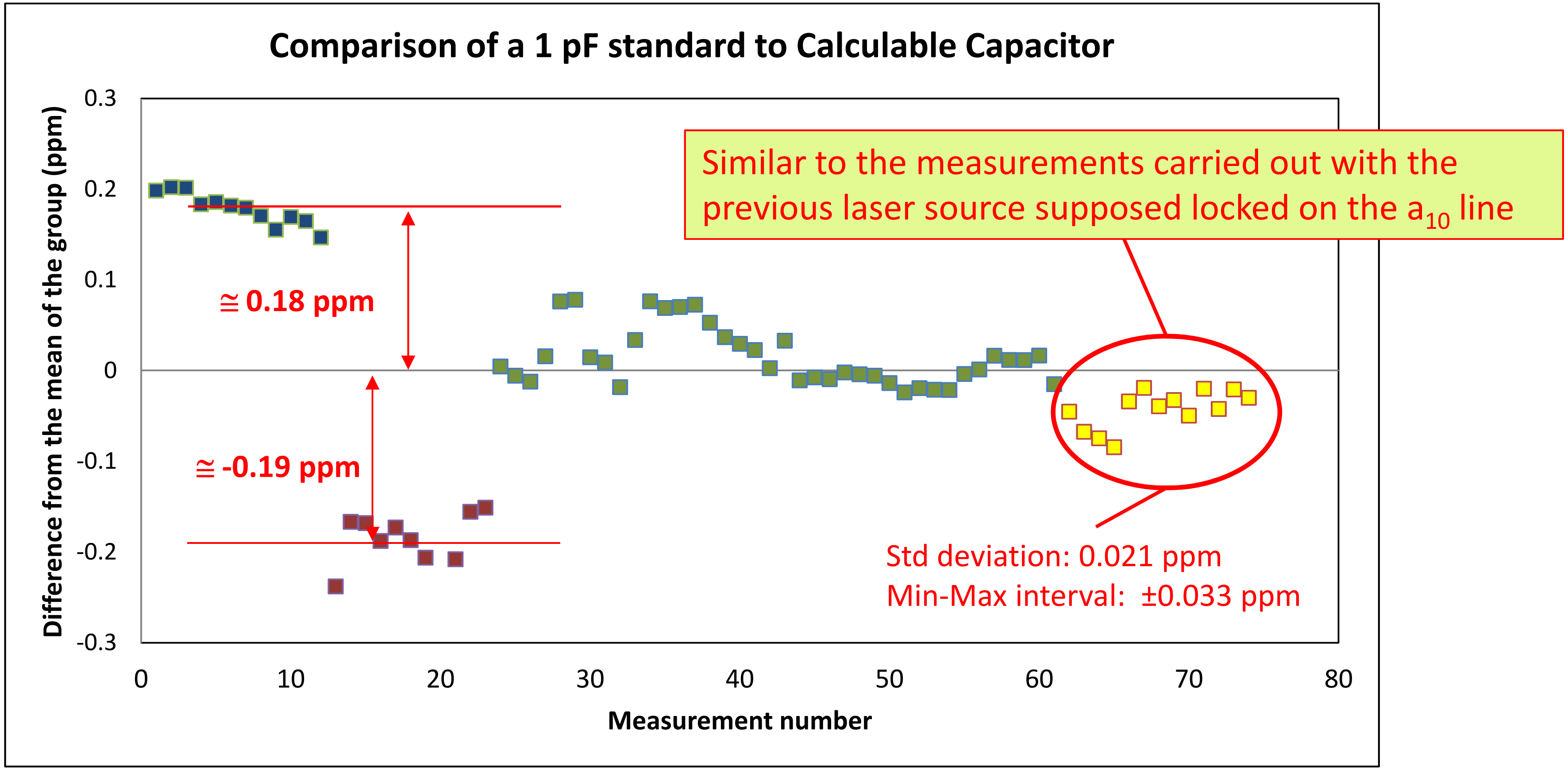
→ Change for home made stabilized source

→ Realization of a beat with a second source and recording



New data with the new frequency stabilized laser source

New stabilized laser source is operational since few weeks only ⇒ start a new set of measurements



⇒ Remains some instabilities within ± few parts in 10^8

Preliminary uncertainty budget – part 1: bridge

Bridge uncertainty budget for 1541 Hz, 250 V (100 V on 1 pF)
Estimated relative standard uncertainties in parts in 10^9

Divider calibration

Component	u /10^{-9}
In-phase balance injection	0.1
Phase error of quadrature injection	0.2
Detector noise and offset	0.1
Effectiveness of current equalisers	0.1
Value of guard potential	0.3
Voltage drift during calibration	0.2
Voltage dependence of IVD	0.1
Type A (repeatability)	0.1
	0.5

Bridge to 1 pF

Component	u /10^{-9}
Bridge divider ratio	0.5
Loading of divider	0.1
In-phase balance injection	1.5
Phase error of quadrature injection	2
Detector noise and offset	1
Effectiveness of current equalisers	0.5
Cable corrections	0.1
Type A (repeatability)	2
	3.4

Uncertainty budget part 2: calculable capacitor

	Component	Relative uncertainty $/10^{-8}$
Mechanical imperfections in capacitor geometry	Cylindricity defect	0.2
	Skew defect	1
	Asymmetry defect	0.2
	Dielectric films on electrodes	0.1
	Alignment errors	5
Length of displacement of moveable guard electrode	Laser wavelength	0.05
	Gouy shift	1
	Air index (residual pressure)	0.1
	Laser beam alignment	0.2
	Servo lock to fringe peaks	2
	Gap (leakage) capacitances	0.1
	Definition of lower electrode position	0.5
	Close approach error	0.1
	Frequency dependence (uncertainty on correction)	3.1
	Voltage dependence	<5
		8.1

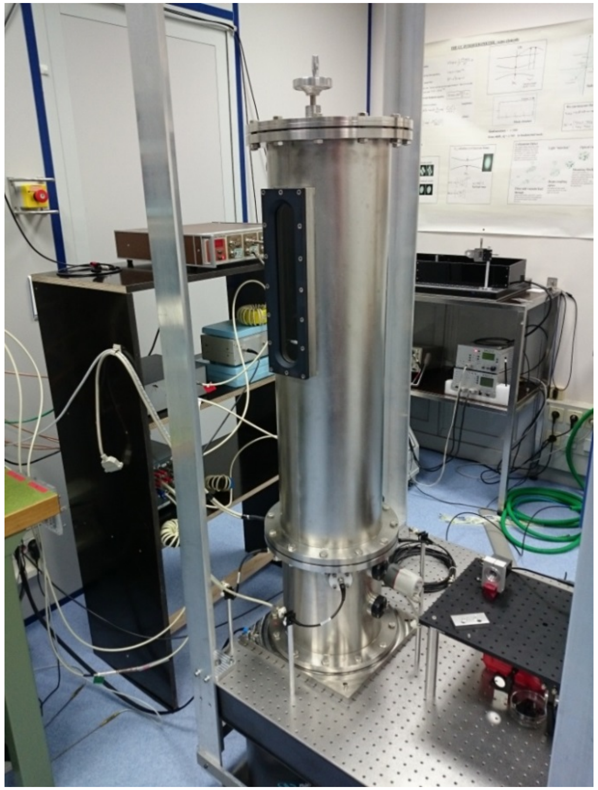
NB: 10^{-8} here, not 10^{-9}

Towards R_K at 1×10^{-8}

- Now that our problem of laser stability has been fixed, we need to finish some characterization measurements (voltage stability, linearity, …) to be confident in an preliminary measurement of R_K within 1×10^{-7} or slightly better (expected before end of 2015)

- The capacitor will then be partly disassembled to re-align bars and guard electrode displacement: a new more sensitive probe will be used for this alignment; this should significantly reduce alignment errors

- A measurement of R_K approaching the target relative uncertainty of 1×10^{-8} should be possible in course of year 2016



Work Programme 2016-2019

E-A1 International reference standard for voltage

- E-A1.1 On-site comparisons of dc Josephson voltage standards (JVS)
- E-A1.2 On-site comparisons of ac Josephson voltage standards
- E-A1.3 Bilateral voltage comparisons using Zener diode transfer standards
- E-A1.4 Calibrations of Zener diode secondary standards

E-A2 International reference standard for resistance

- E-A2.1 On-site comparisons of quantum Hall resistance (QHR) standards
- E-A2.2 Bilateral resistance comparisons using resistance transfer standards
- E-A2.3 Calibrations of resistance secondary standards

E-A3 International reference standard for capacitance

- E-A3.1 Bilateral capacitance comparisons using capacitance transfer standards
- E-A3.2 CCEM key comparison of capacitance
- E-A3.3 Calibrations of capacitance secondary standards
- E-A3.4 ac quantum Hall effect

E-A4 Coordination

- E-A4.1 Coordination of CCEM (Electricity and Magnetism)
- E-A4.2 Coordination of CCPR (Photometry and Radiometry)
- E-A4.3 Liaison activities (RMO TCs, CIE etc…)

Update from the BIPM Watt Balance

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BIPM watt balance

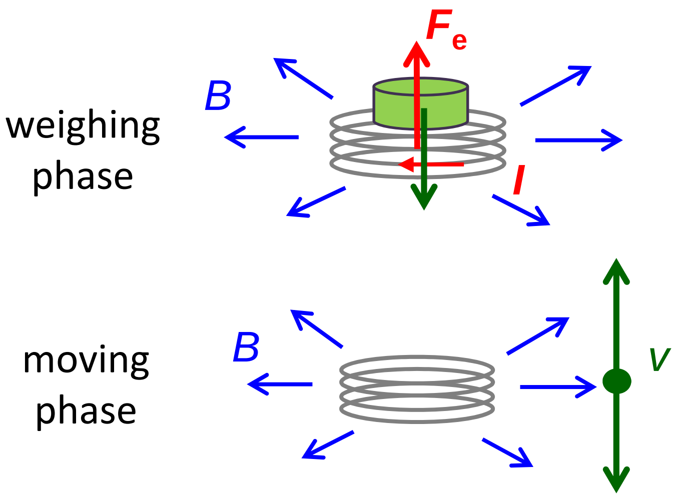
- Motivation

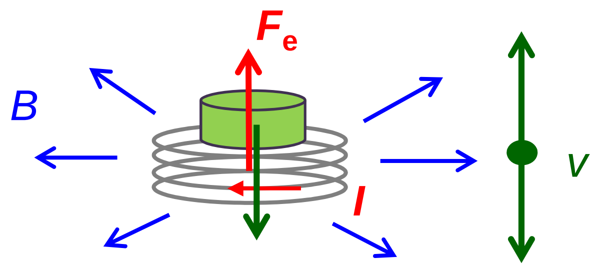
  provide long-term sustainable operation for a primary realization of the kilogram on a cost-shared basis

- Main feature

  capability of implementing a "one-phase" measurement scheme

  in addition to conventional "two-phase" scheme





simultaneous (weighing & moving)

Brief overview over project history

2005: start of construction

2009: operational in air

2010: first *h* determination

2011: improved repeatability

move to the new lab.

Early 2013: new laboratory

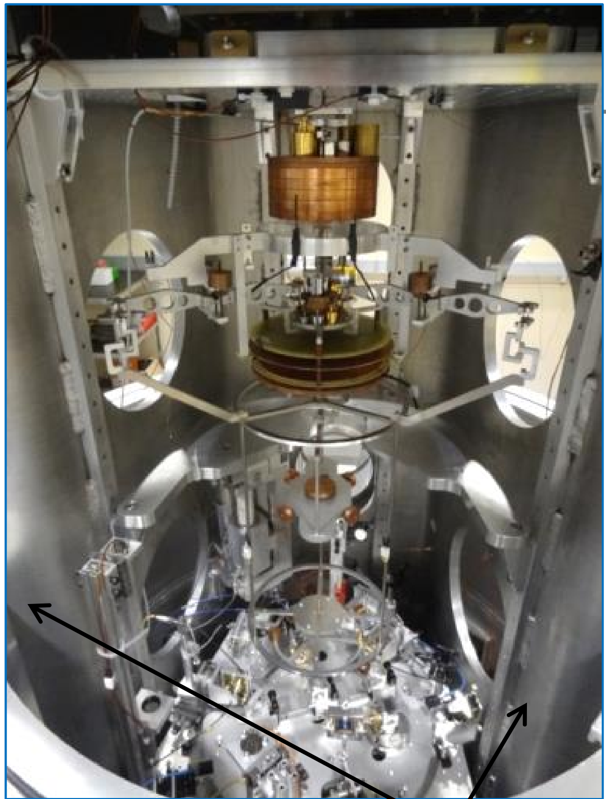
(improved thermal and vibrational environment)

Planck constant determination

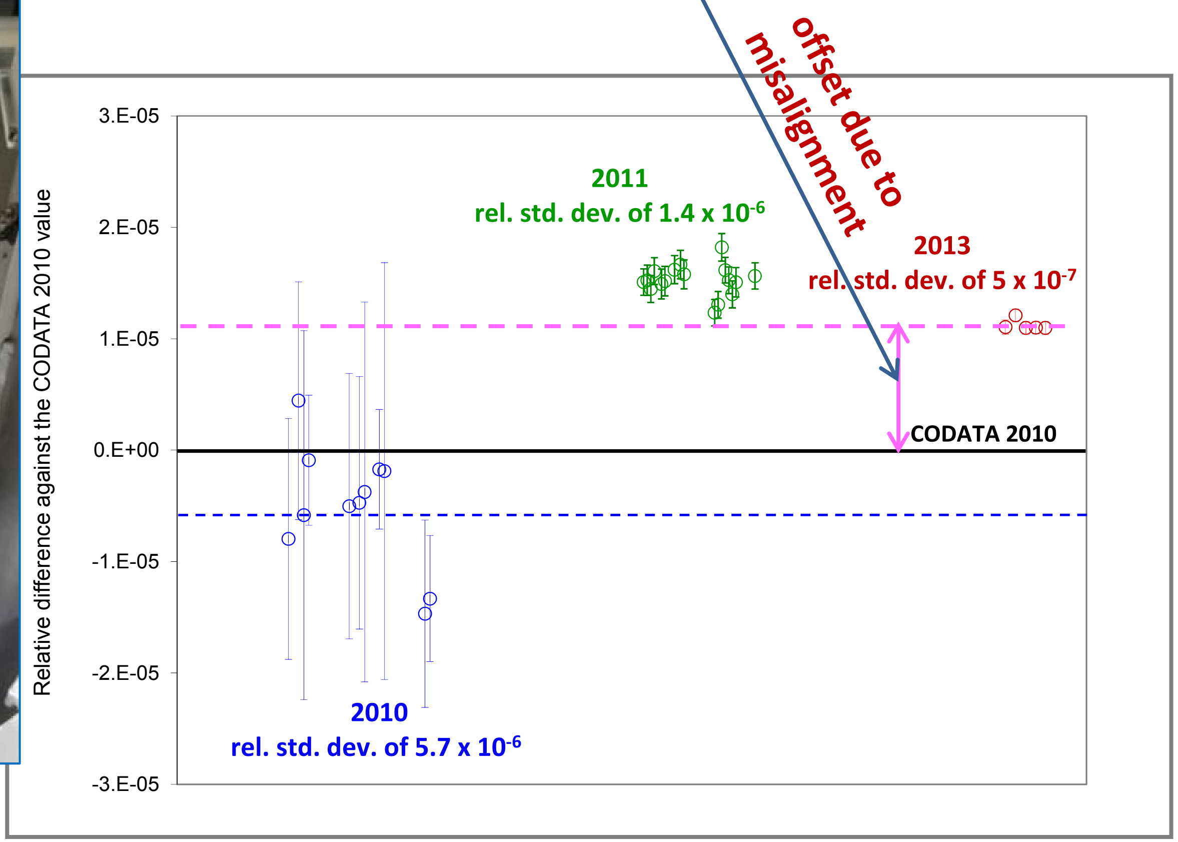
Determination of the Planck constant *h*

Type A: ~ 5 x 10^{-7}

Type B: ~ 5 x 10^{-5}

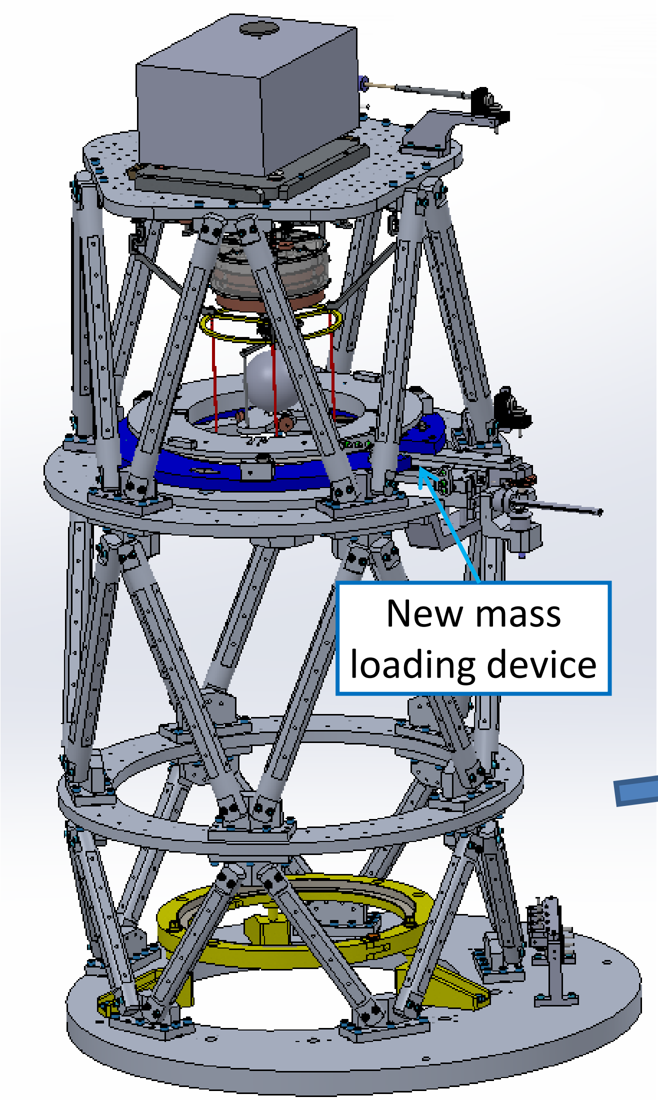


massive "closed" support structure

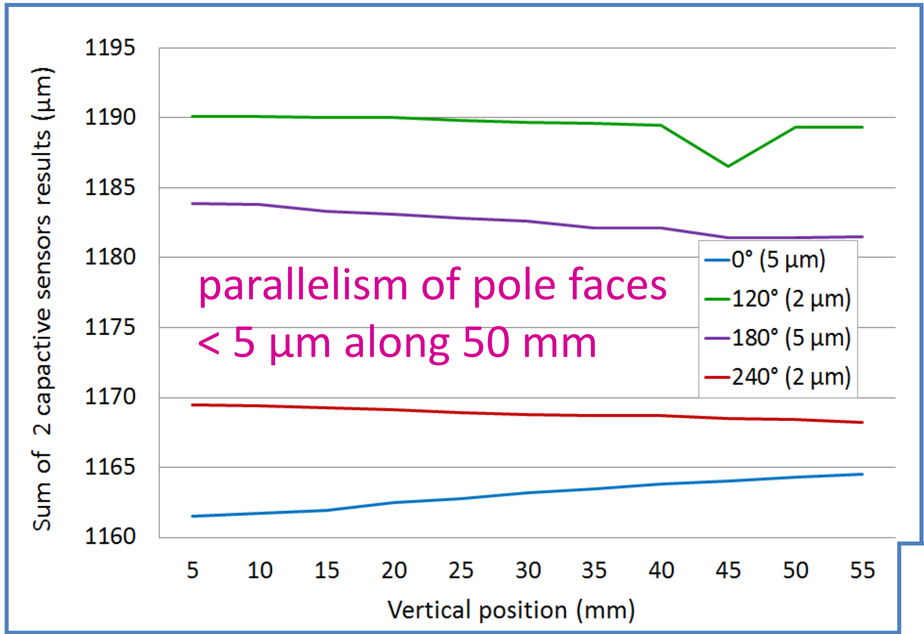


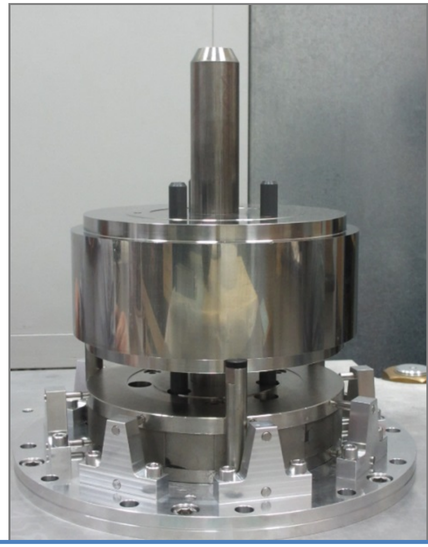
New support structure & new mass loading device

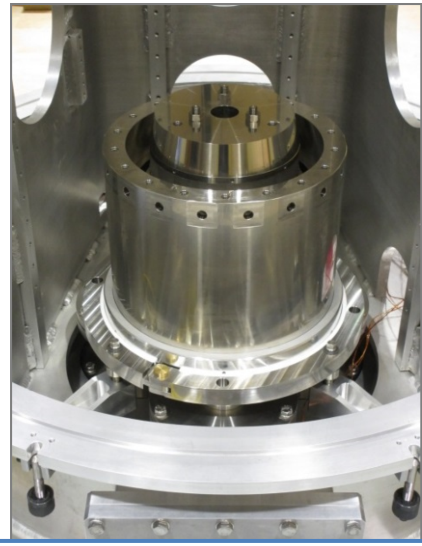
- Pentapod structure
  - ✓ open access
  - ✓ rigid & stable
- Finite elements analysis → no resonance frequencies in vertical direction below 200 Hz

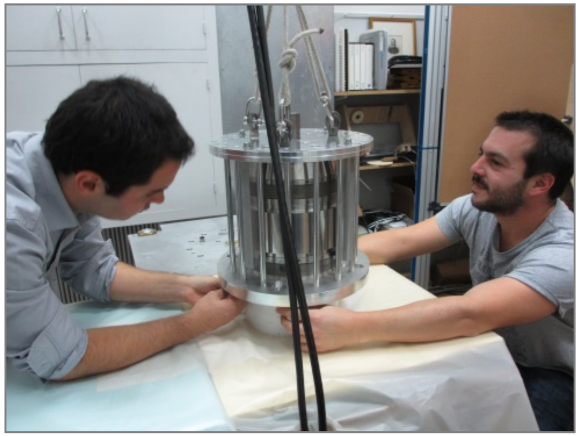


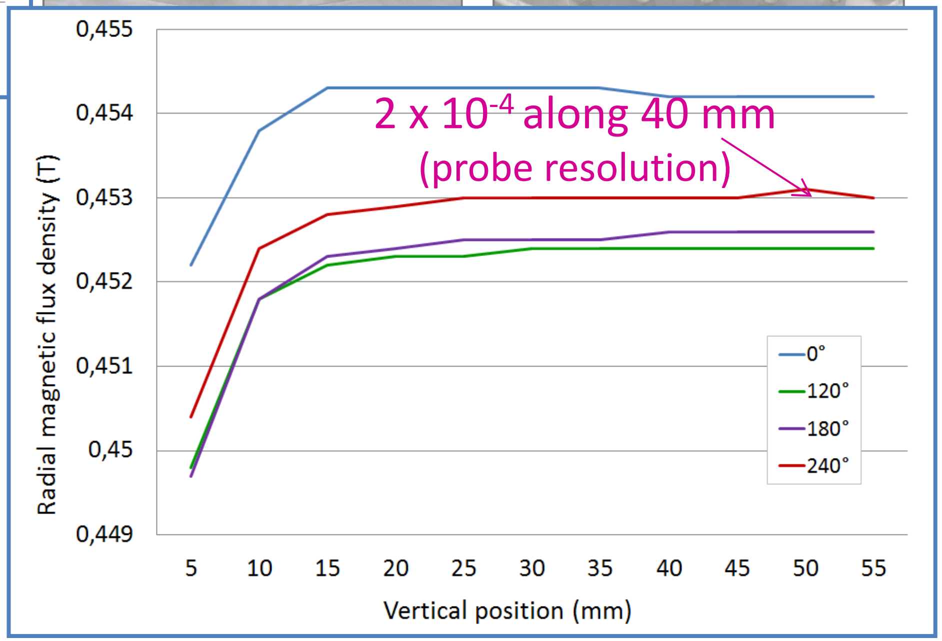
New magnet


1195
1190
1185
1180
1175
1170
1165
1160
Sum of 2 capactive sensors results (µm)
5 10 15 20 25 30 35 40 45 50 55
Vertical position (mm)
parallelism of pole faces
< 5 µm along 50 mm
0° (5 µm)
120° (2 µm)
180° (5 µm)
240° (2 µm)

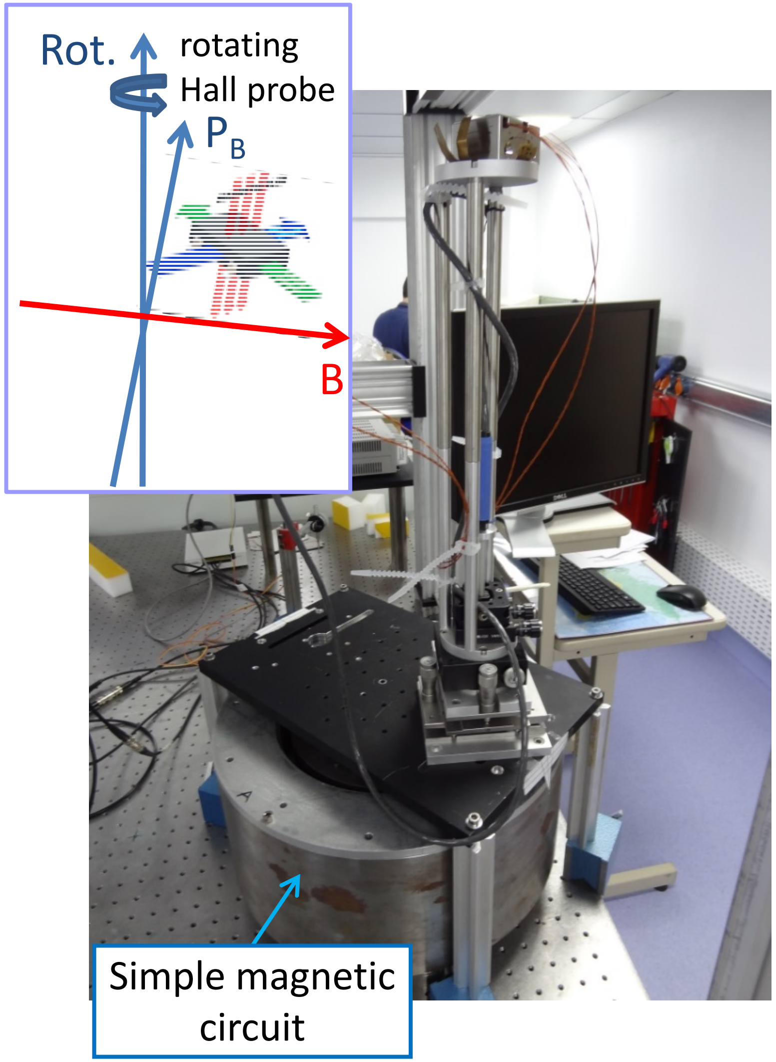




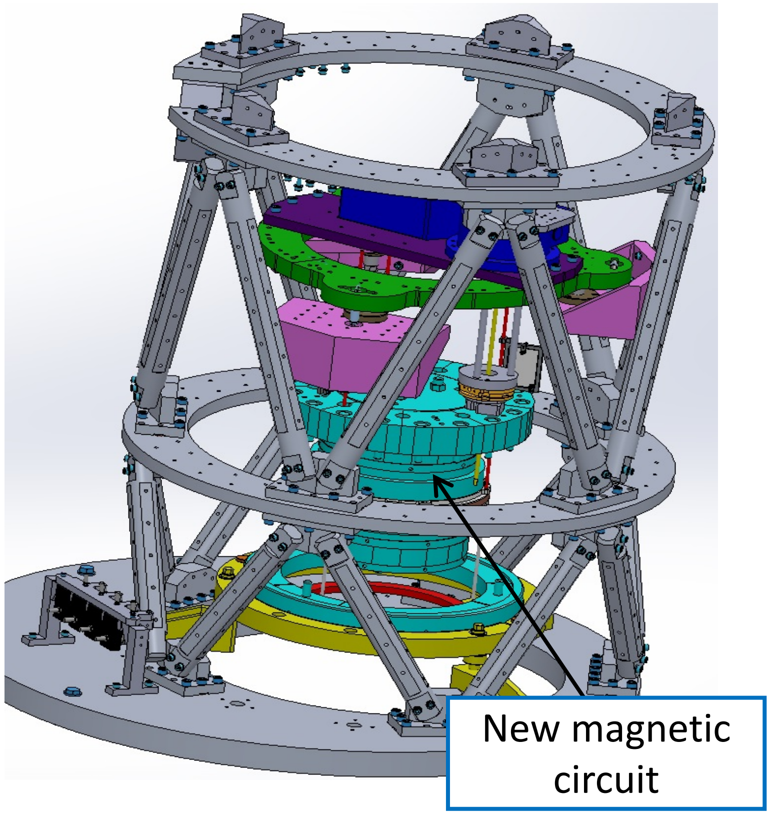



0,455
0,454
0,453
0,452
0,451
0,45
0,449
Radial magnetic flux density (T)
5 10 15 20 25 30 35 40 45 50 55
Vertical position (mm)
2 x 10-4 along 40 mm
(probe resolution)
0°
120°
180°
240°

New method for magnet alignment



- Horizontal alignment of the magnetic field of a test magnet using a Hall probe with uncertainty of 50 µrad
- Alignment of the new magnet next month

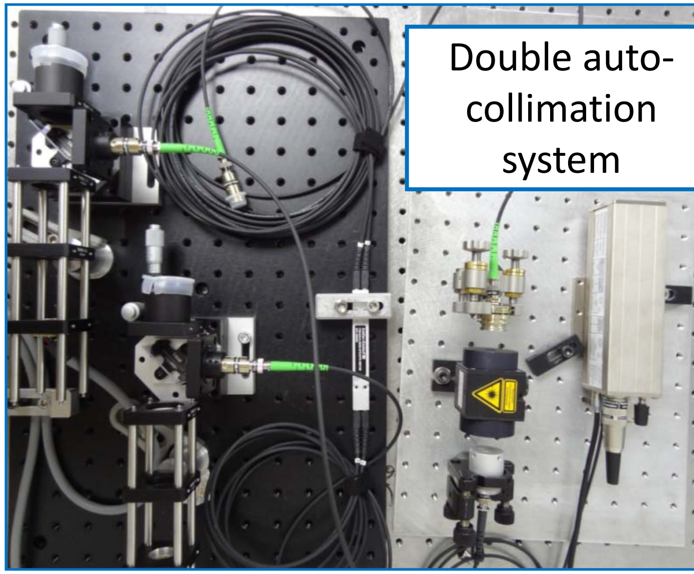


Coil alignment

Long solenoid (long term loan from NIST)

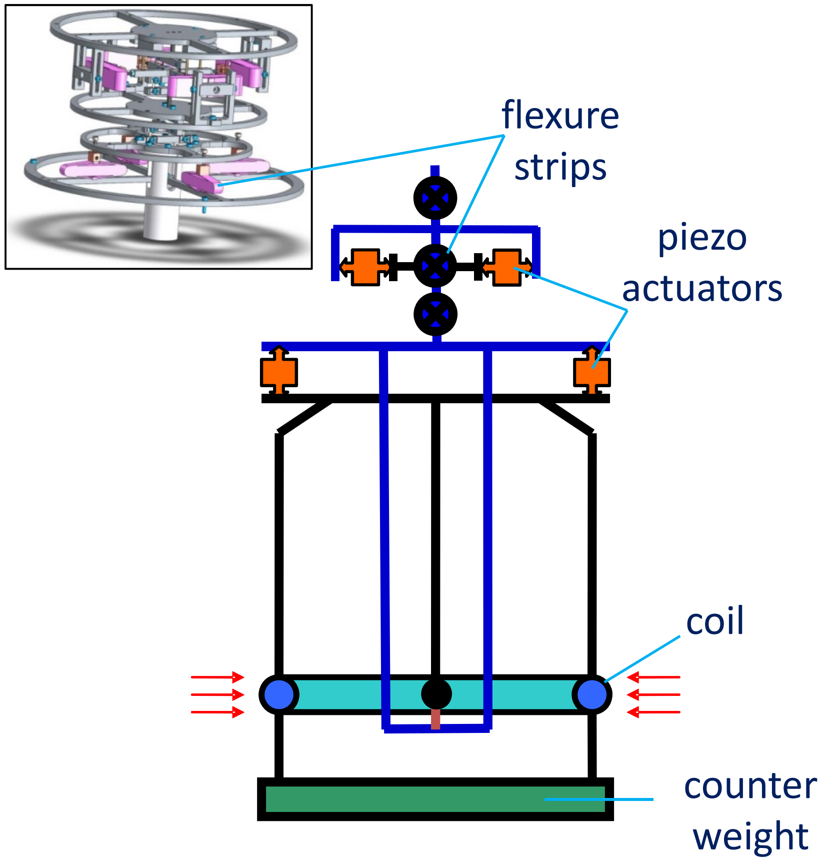
Watt balance coil inside the solenoid

- Alignment of the electric plane of a watt balance coil with an uncertainty of 150 µrad, presently improved
- Alignment to be transferred using several small mirrors fixed onto the coil
- To be compared with magnet alignment



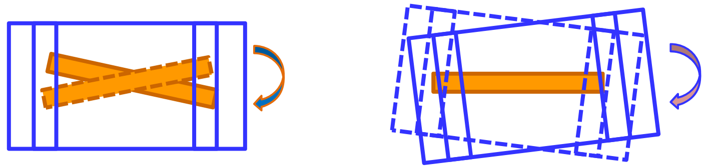
Double auto-collimation system

Dynamic coil alignment mechanism

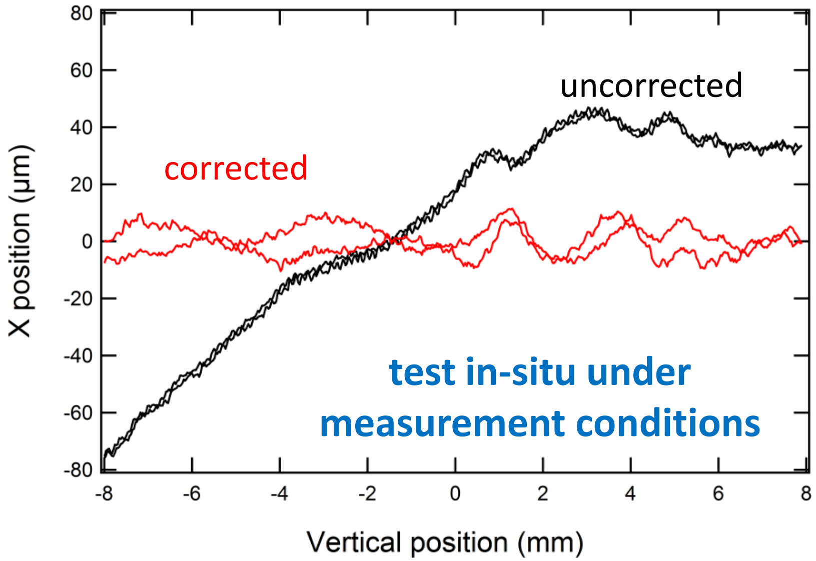


- Initial alignment of the apparatus

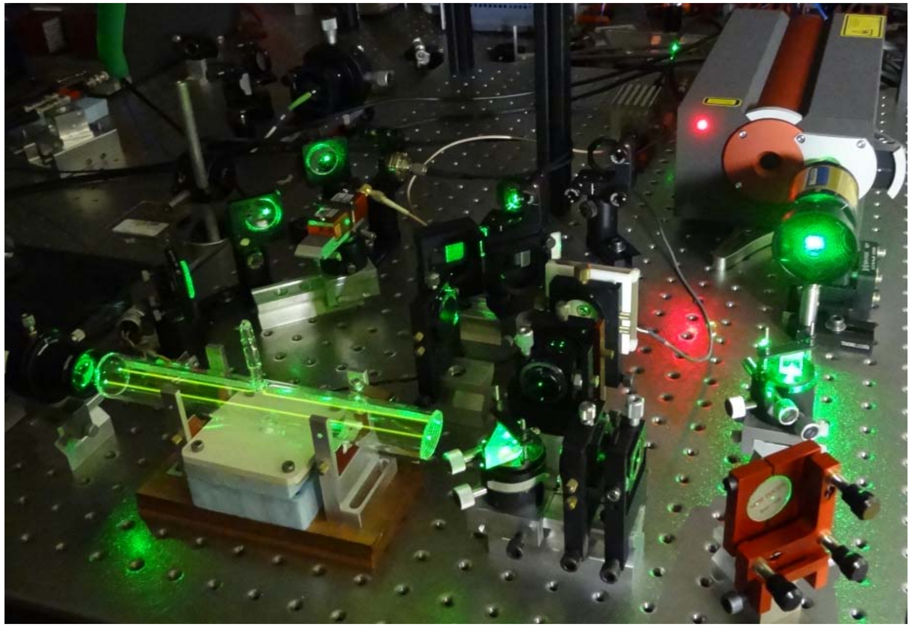
  magnet alignment ↔ coil alignment



- Dynamic correction of the coil trajectory in working mode

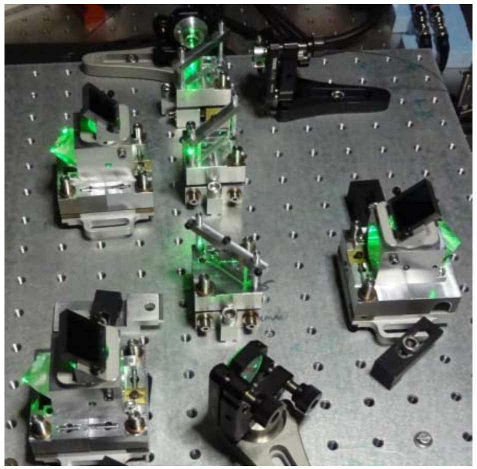


New interferometer



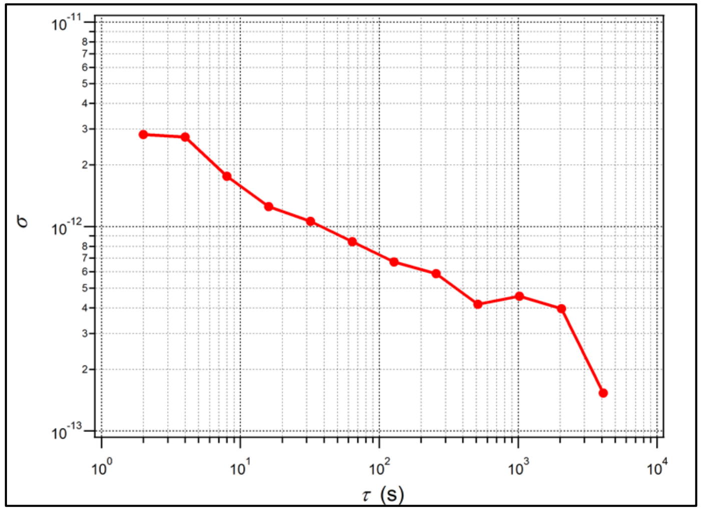
Frequency stabilized laser source

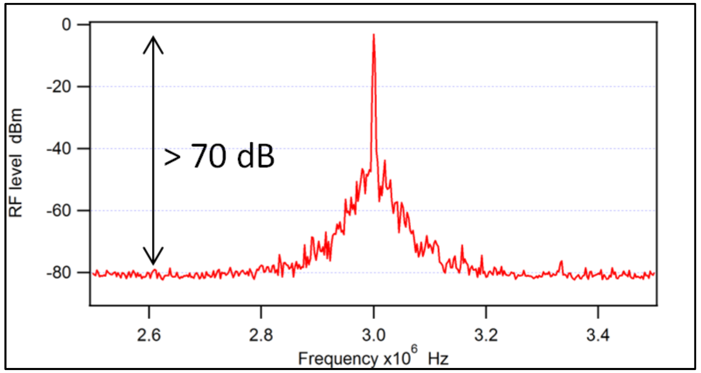
better frequency stability (<<10^{-8})
less non-linearity (< 1 nm)



3 heterodyne interferometers

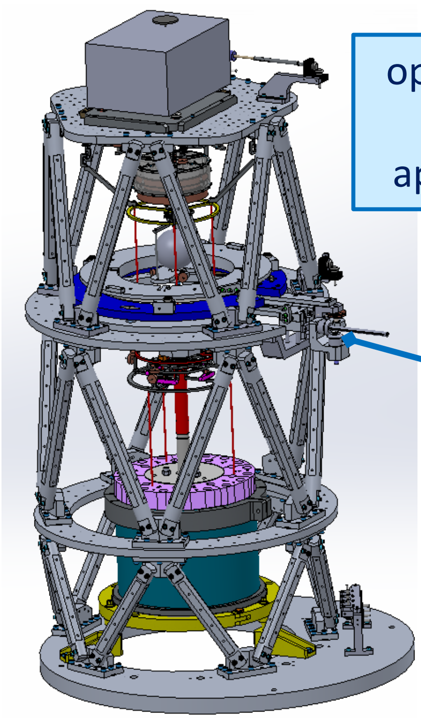
Beat between two frequency stabilized lasers





Interferometric signal

Expected progress



assembly of the improved apparatus in air

operation of the improved apparatus in air

early 2016
$u_{rA}(h) = 1 \times 10^{-7}$
$u_{rB}(h) = 5 \times 10^{-7}$

vacuum operation JVSs

early 2017
$u_{rA}(h) = 5 \times 10^{-8}$
$u_{rB}(h) = 1 \times 10^{-7}$

Deadline CODATA
1 July 2017

continuous improvement mass from 100 g to 1 kg

end 2018
$u_{rA}(h) = 1 \times 10^{-8}$
$u_{rB}(h) < 5 \times 10^{-8}$

Target
$\boldsymbol{u_r(h) = 2 \times 10^{-8}}$