MOLO:
A Microwave-Optical Local Oscillator for STE-QUEST

The ATC-MOLO consortium:

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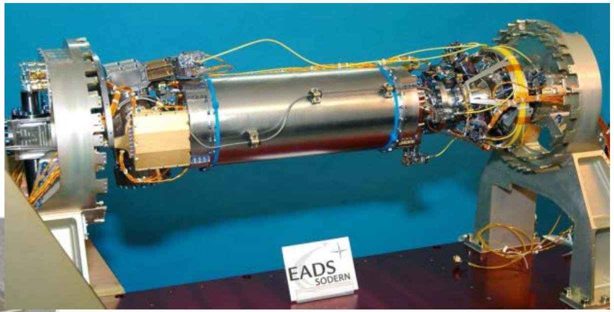
Introduction

STE-QUEST Atomic Clock Instrument

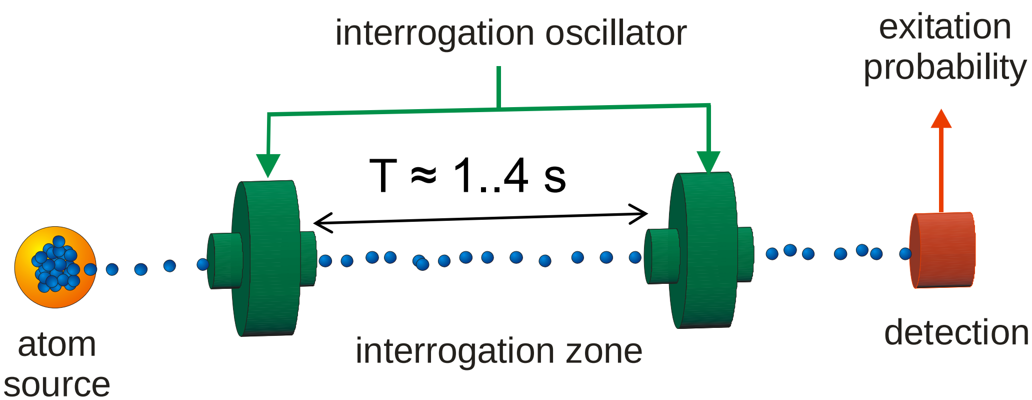
- PHARAO tube based Cs clock
- Microwave synthesis with minor modifications
- Improved microwave source: MOLO

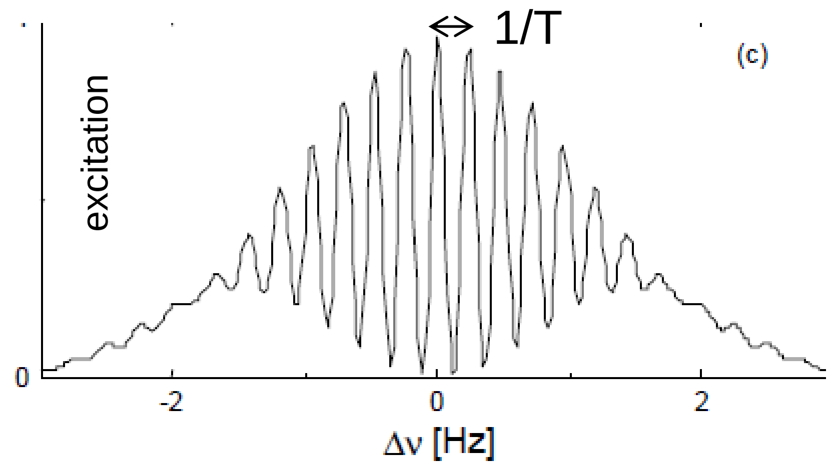


- **ACES approach**:
  - Stability from ultra-stable microwave oscillator from multiplied quartz
  - On board accuracy evaluation through comparison with space hydrogen maser acting as flywheel

- **STE-QUEST approach**:
  - Improved stability through low noise microwave source
  - Evaluation by comparison with the same stable microwave source
  - Provide optical frequency referenced to Cs for optional optical link

Atomic clock interrogation





Conversion of LO phase noise to noise of atomic error signal limits clock instability (Dick effect)

High stability over a few minutes for on-board evaluation of:

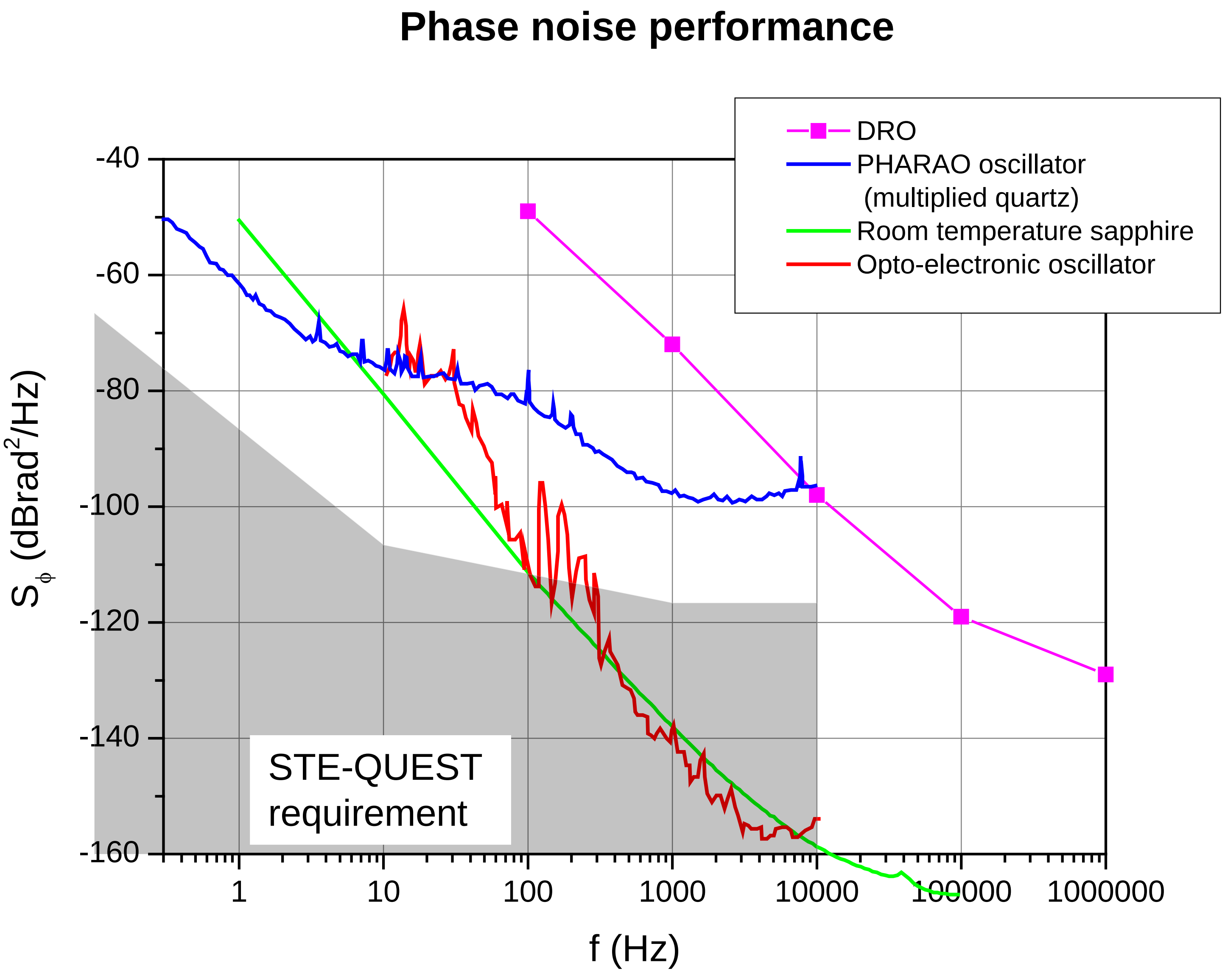
- collisions,
- velocity effects
- cavity phase shifts, ...

LO Stability and Drift:

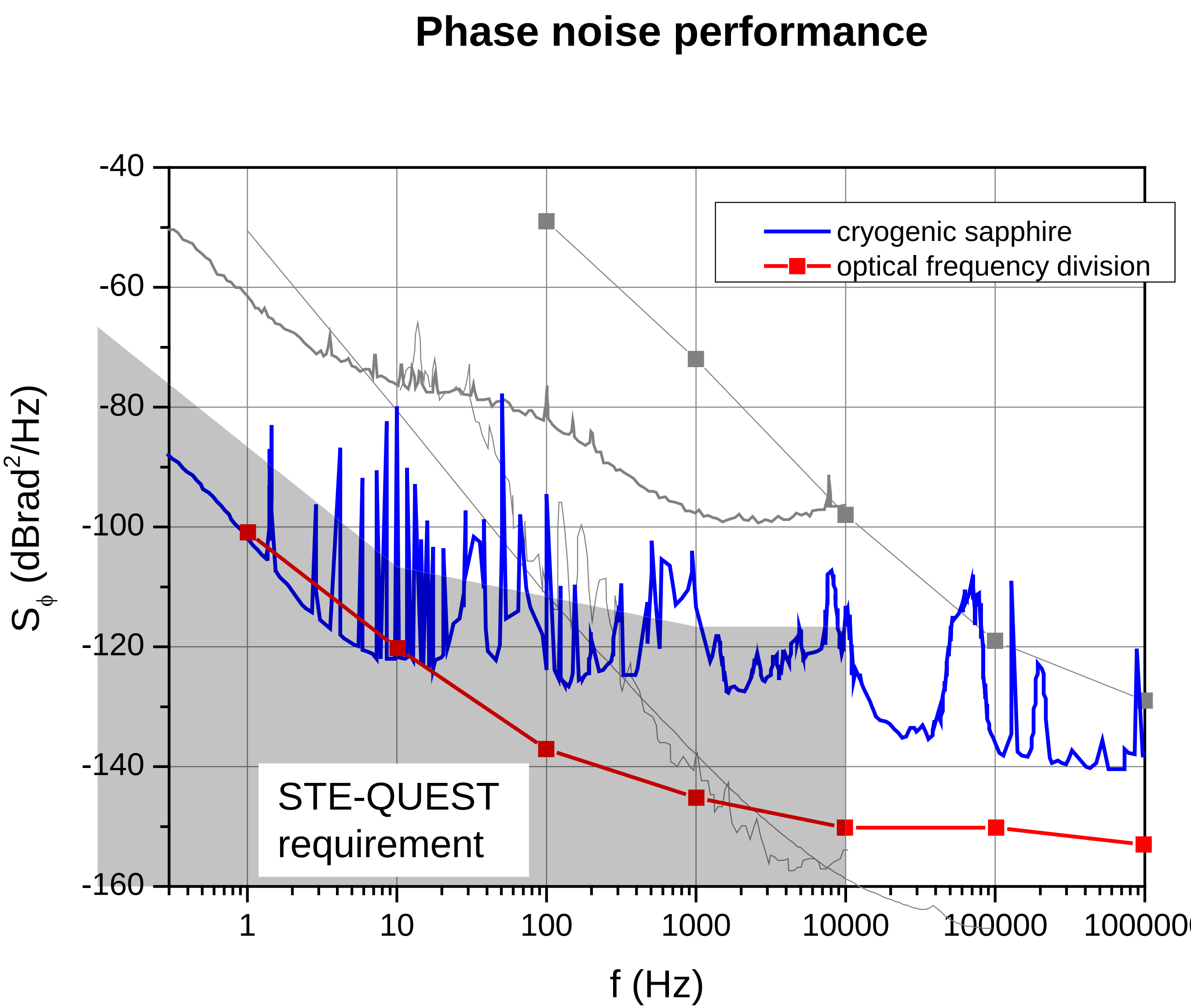
- $\sigma_y(\tau) < 3.5 \cdot 10^{-15}$ for τ = 1 s to 100 s
- drift uncertainty $< 2 \cdot 10^{-16}$ /s over 1000 s

PHARO synthesis document,
STE-QUST Science Requirement Doc.

10 GHz microwave oscillators



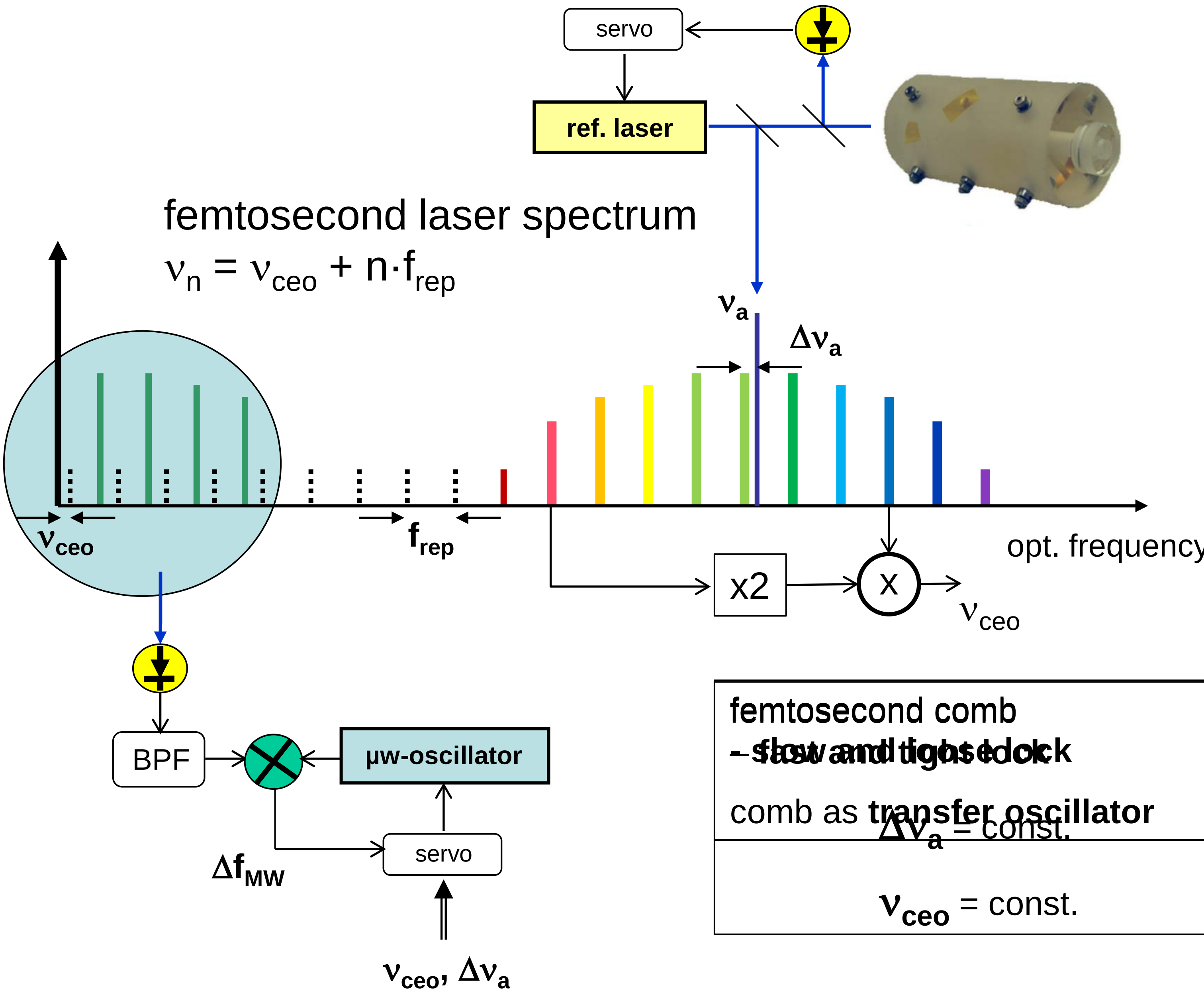
10 GHz microwave oscillators



Cryogenic sapphire: J. G. Hartnett, N. R. Nand, and C. Lu, Appl. Phys. Lett. **100**, 183501 (2012)

Frequency divider: T. M. Fortier et al, Nature Photonics **5**, 425 (2011)

Optical Frequency Divider



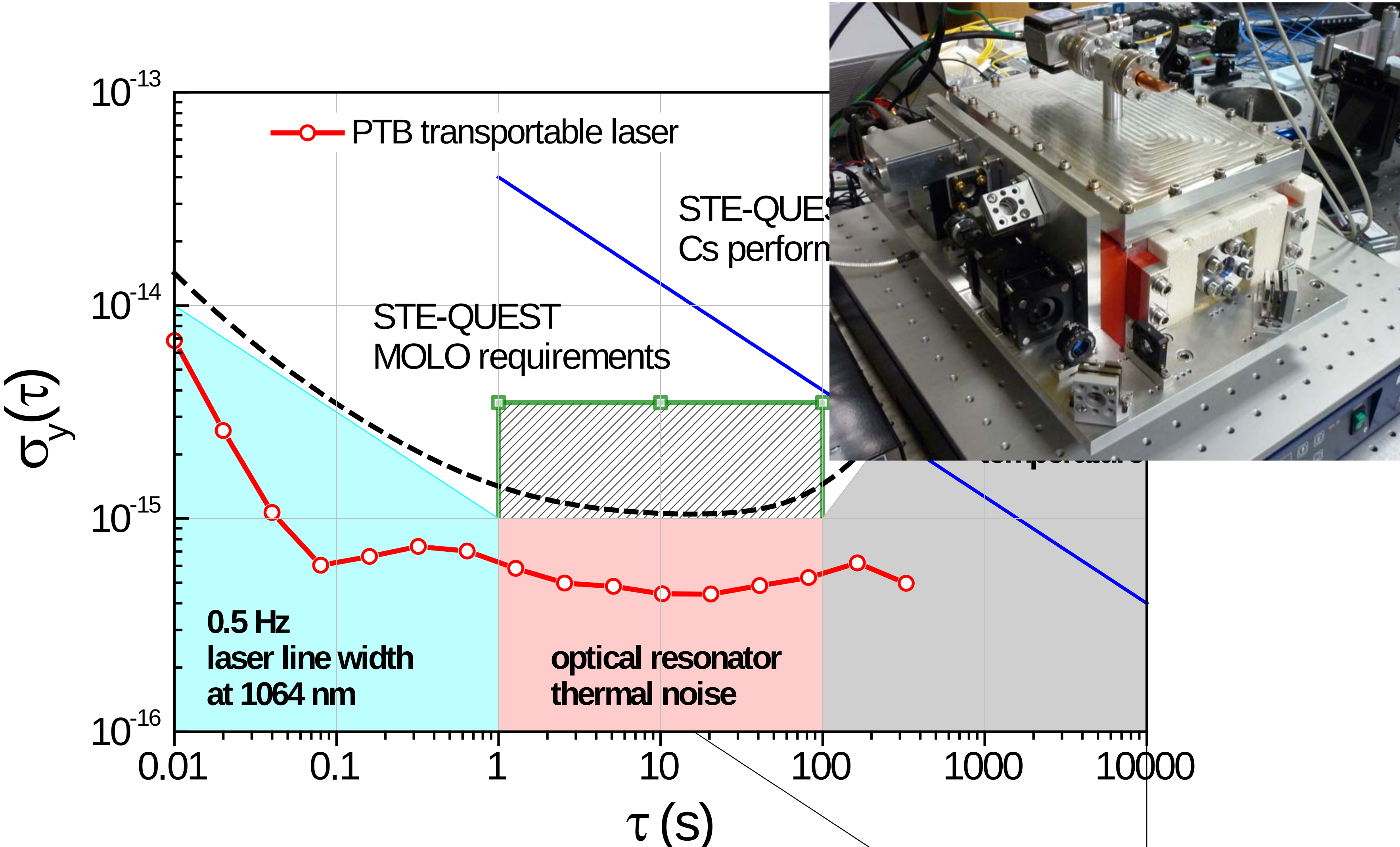
femtosecond comb
– slow and tight lock
– fast and tight lock

comb as **transfer oscillator**

$\Delta\nu_a$ = const.

ν_{ceo} = const.

Cavity Stability



PTB's shoebox sized 698 nm cavity setup from transportable Sr clock reaches specs, was basis for the current STE-QUEST design.

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Optical Reference Cavity

Required performance:

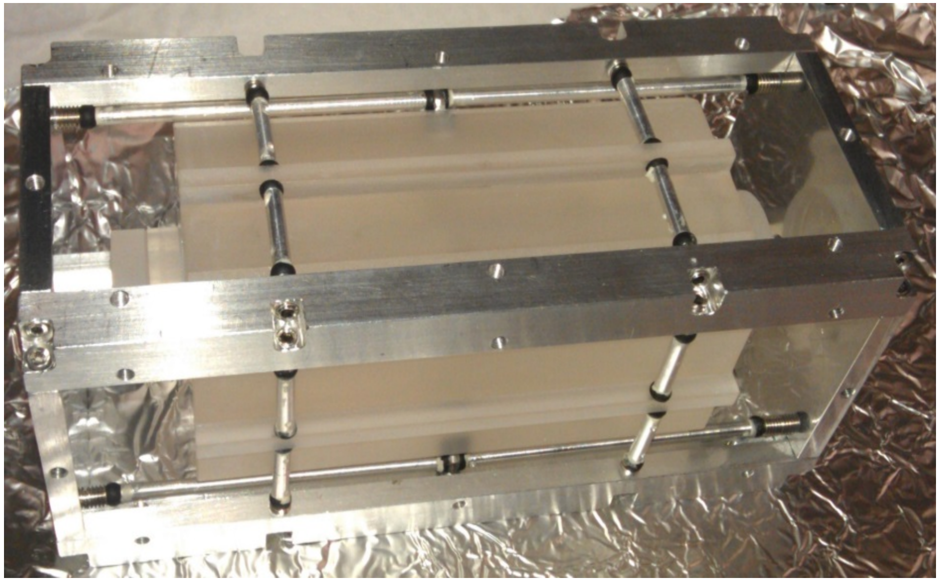
- $\sigma_y(\tau) < 3 \cdot 10^{-15}$
  for τ = 1 s to 100 s
- drift uncertainty < $2 \cdot 10^{-16}$ /s over 1000 s

Design drivers:

- thermal noise requires length ≥ 5 cm
- even ultralow expansion glass (ULE) requires temperature control to $\Delta T < 1$ mK
- vibrations in space at the µg level:
  mounting structure and support designed to achieve sensitivity $\delta\nu/\nu < 3 \times 10^{-10}$ /g
- launch conditions
  - keep optical alignment under
    >20 g random vibrations
    shock

HHUD Cavity mounting

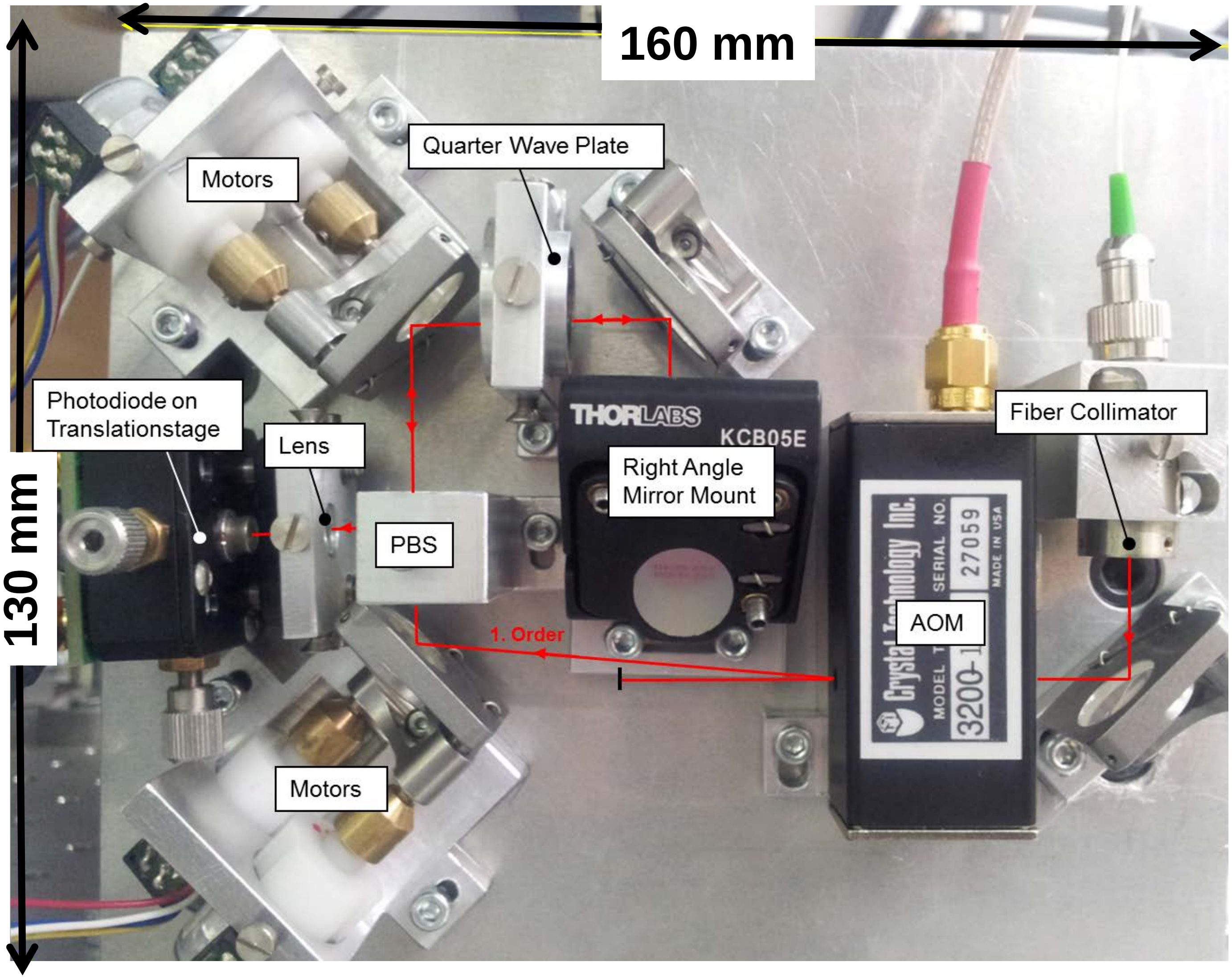
Cavity with stubs glued.



Cavity fixed to the frame.

L = 100 mm ULE spacer
temperature-compensated fused silica mirrors
thermal noise $\sigma_y \approx 4 \times 10^{-16}$
vibration insensitive mounting at ridges
in multiple points

optical setup for the MOLO cavity

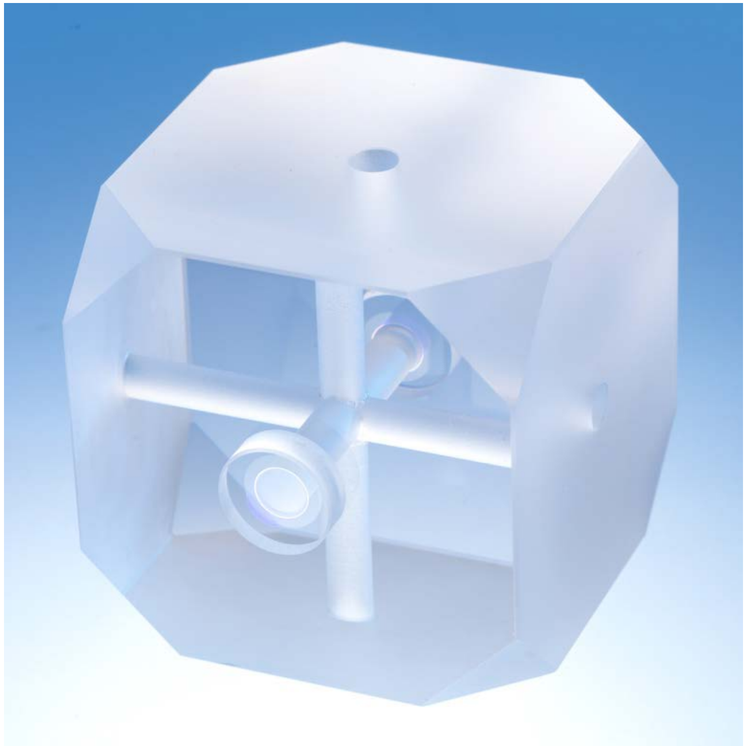


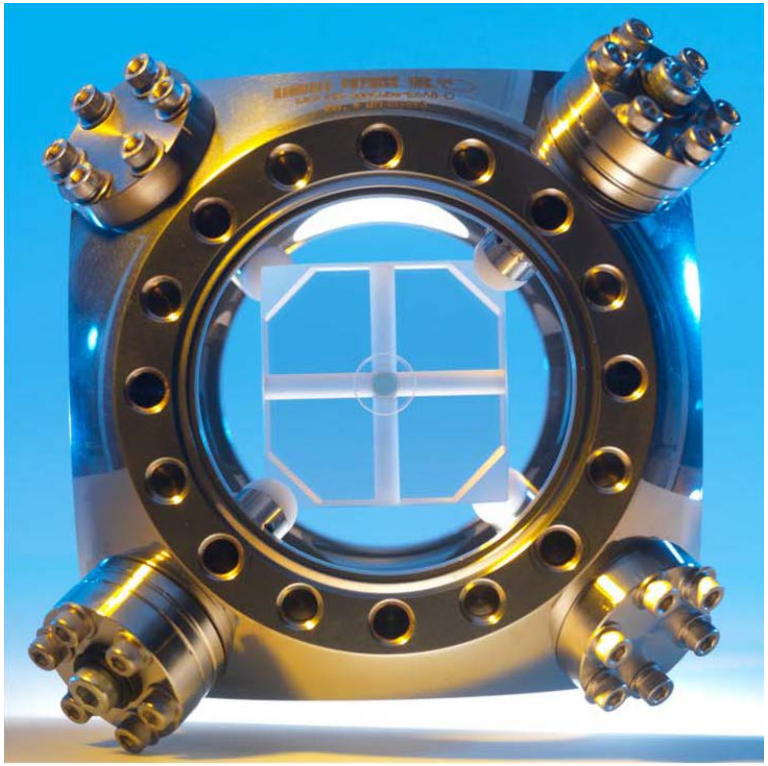
small optic board (130 mm × 160 mm) attached to cavity chamber

active alignment by two motorized mirror mounts

Optical Reference Cavity

National Physical Laboratory





NPL design: Squeezed cubical cavity

L = 5 cm

suppression of vibration sensitivity due to high symmetry

$\delta\nu/\nu < 2.5 \times 10^{-11}$ / g

S. Webster and P. Gill, *Force-insensitive optical cavity,* Opt. Lett. **36**, 3572 (2011)

HEINRICH HEINE
UNIVERSITÄT DÜSSELDORF

Ultrastable Laser:

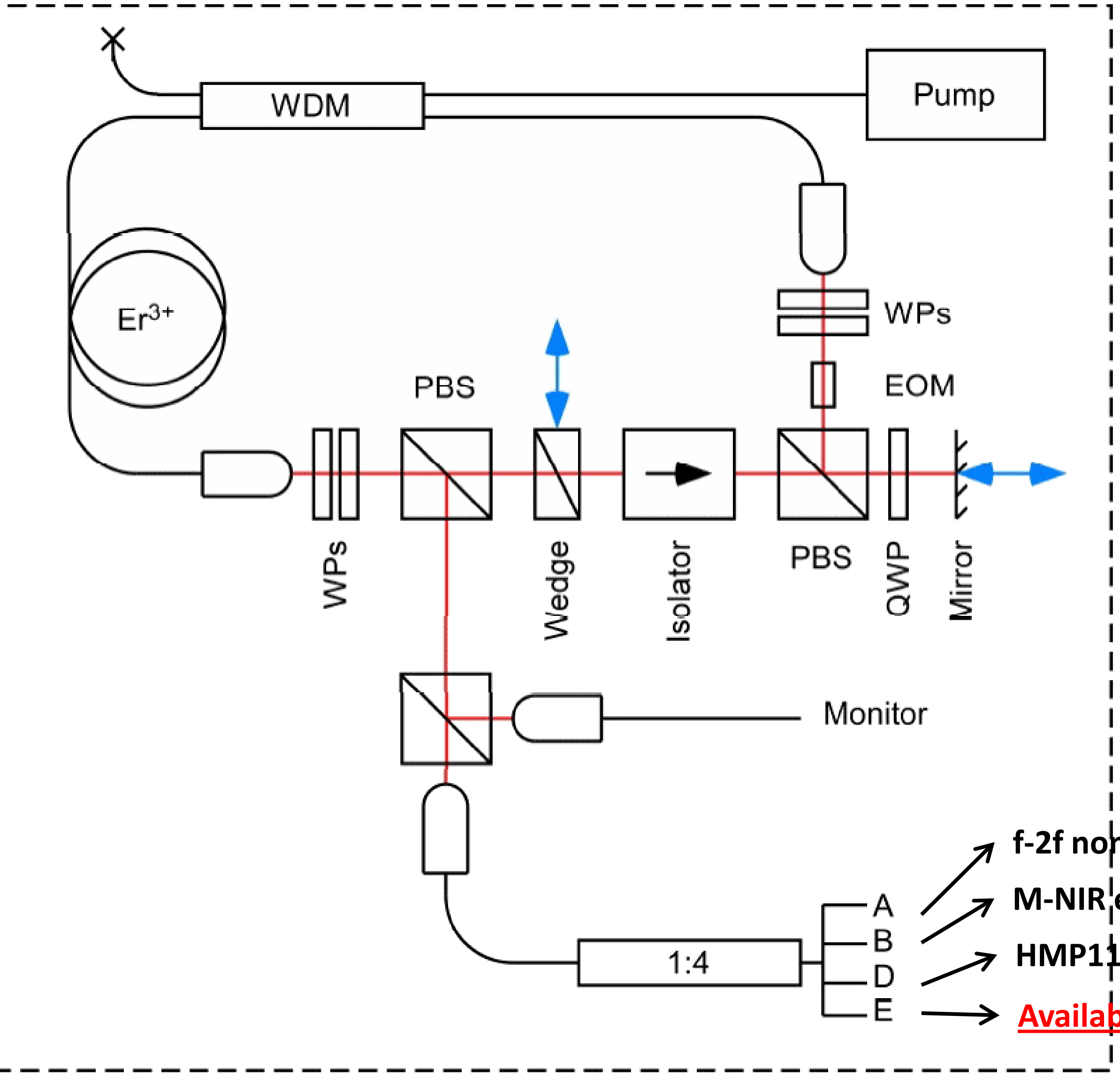
PTB

1064 nm Laser baseline:
TESAT Laser from
Laser Communication Terminals:
TRL 9

Ongoing Studies on Cavities:

- mounting of cavities
- vibration and shock tests of cavities
- radiation tests of optical cavities and coating
  (U Birmingham, HHUD)
  – very promising results – minor changes on finesse
- thermal testing of cavity setups

Frequency combs at HHUD and PTB



Menlo Systems Er:fiber comb for tests of microwave generation concepts

Controls:

repetition rate:
- cavity length
- EOM (at HHUD)

Carrier-envelope frequency
- dispersion control
- pump power

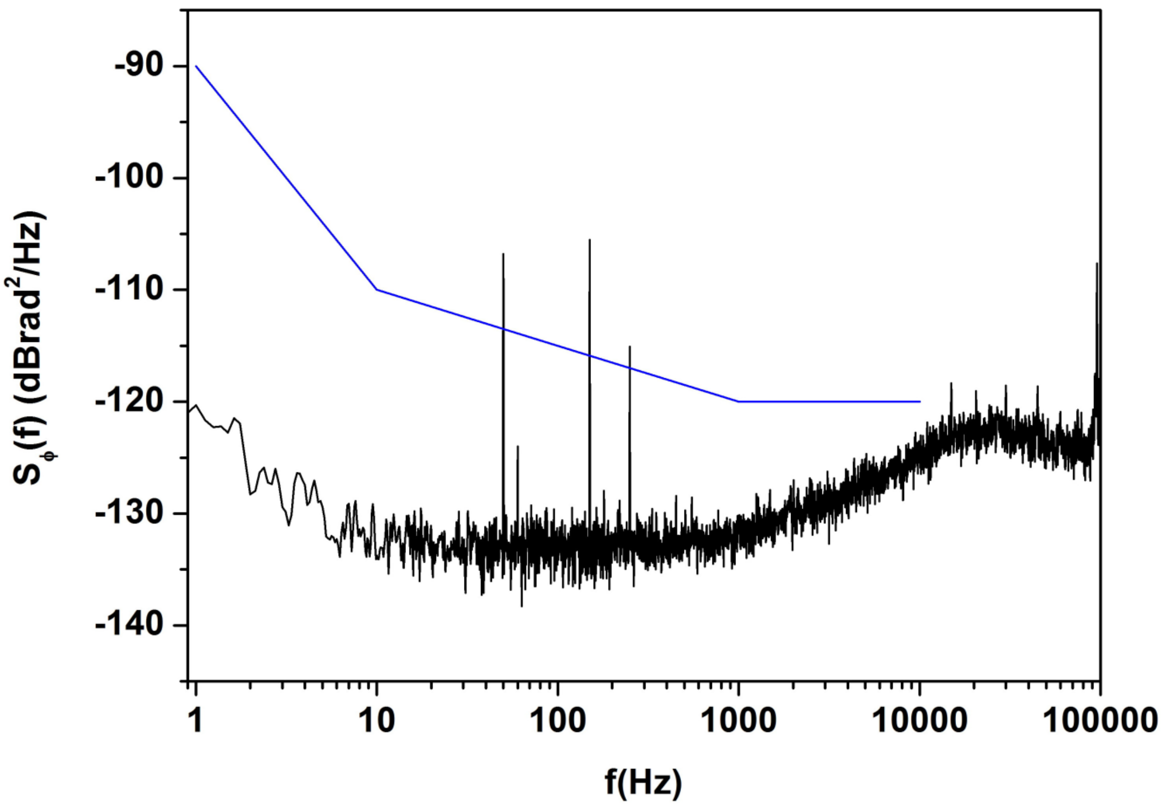
f-2f nonlinear interferometer (f_{CEO})

M-NIR extension to near IR spectral range EDFA

HMP1156 high power measuring port EDFA

Available for optical to rf-conversion (f_{rep})

HHUD: First results



Tightly stabilized comb

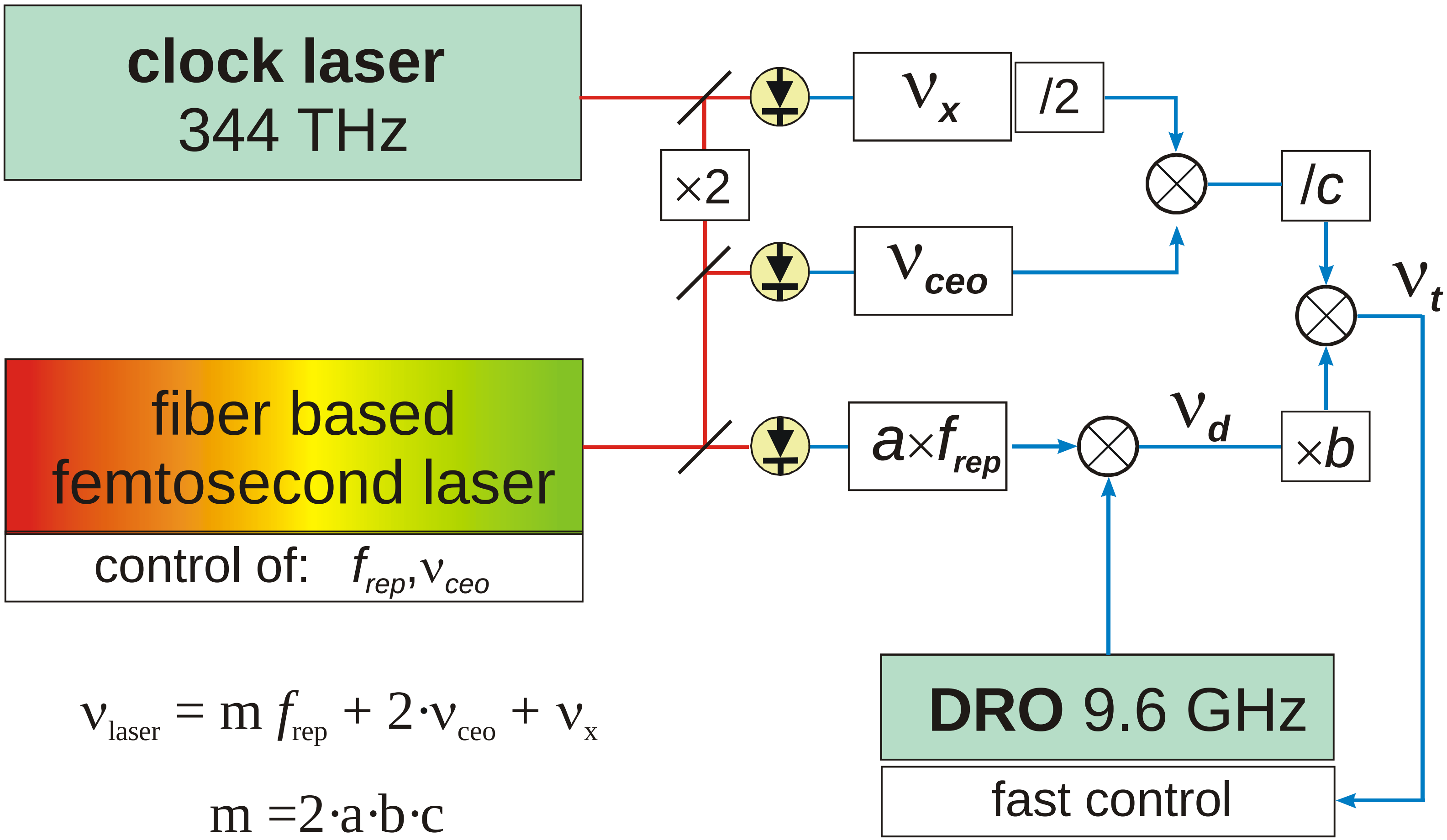
In-loop error of DRO:

Microwave Phase lock opeating with sufficient bandwidth

Next:
Comparisont to PTB system

MOLO test at PTB

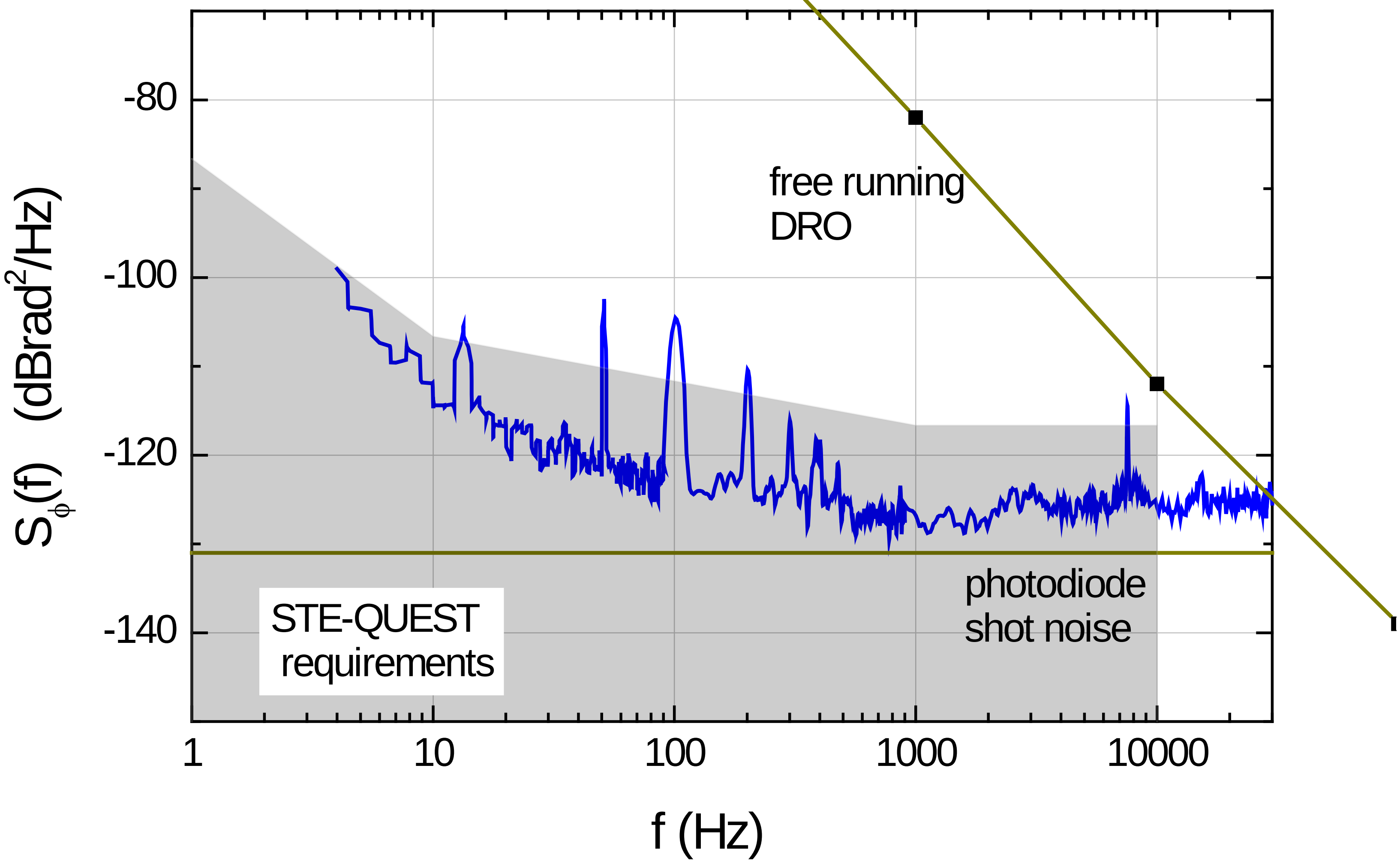
- femtosecond comb is used as loosely locked transfer oscillator
- corrections to microwave output are applied in real time
- currently employed with PTB's Cesium fountain clock



$$\nu_{laser} = m\, f_{rep} + 2 \cdot \nu_{ceo} + \nu_x$$

$$m = 2 \cdot a \cdot b \cdot c$$

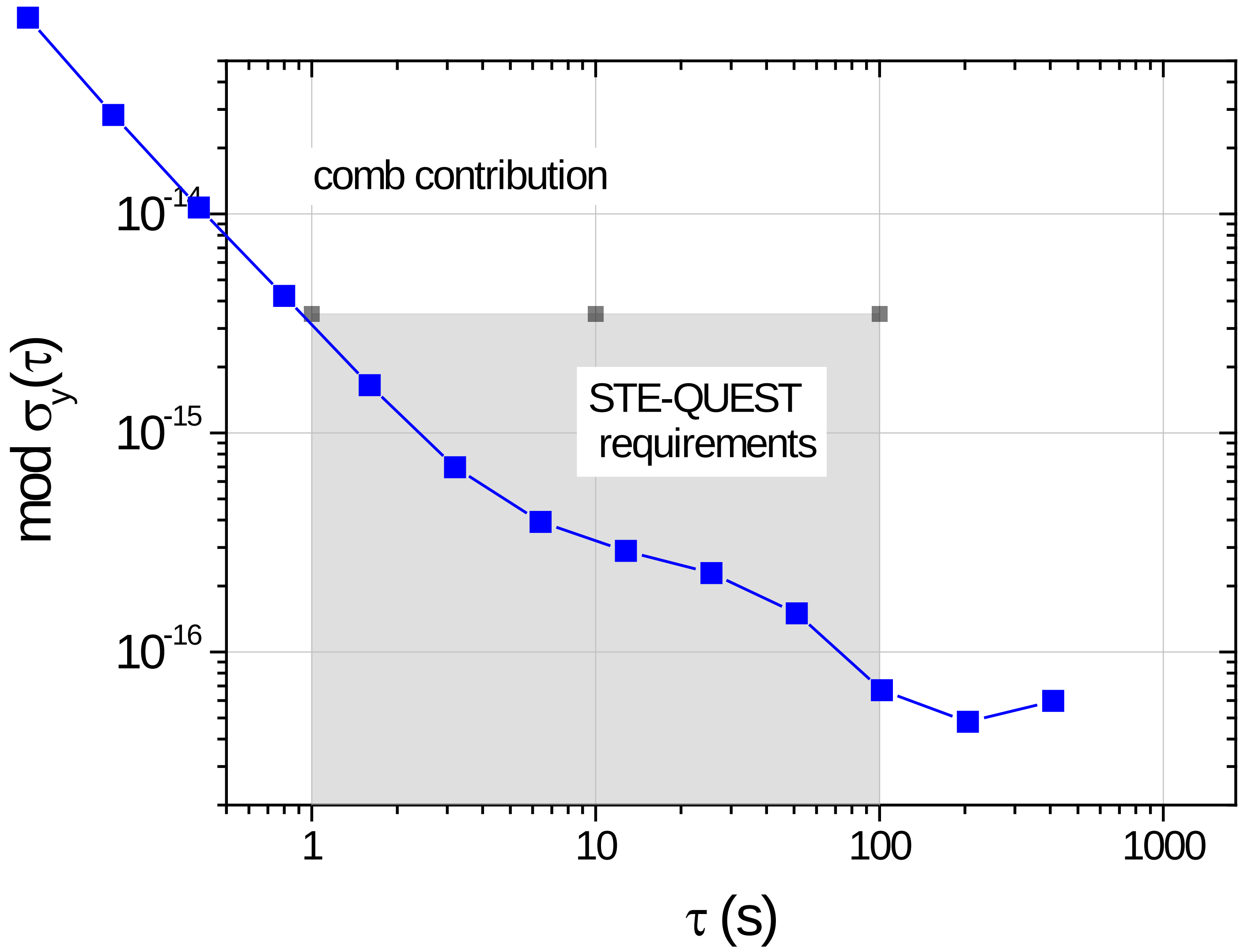
PTB transfer method



comparison of two systems with the same optical reference

B. Lipphardt et al. IEEE Trans. Instrum. Meas. **58**, 1258 (2009)

PTB transfer method



comparison of two systems with the same optical reference

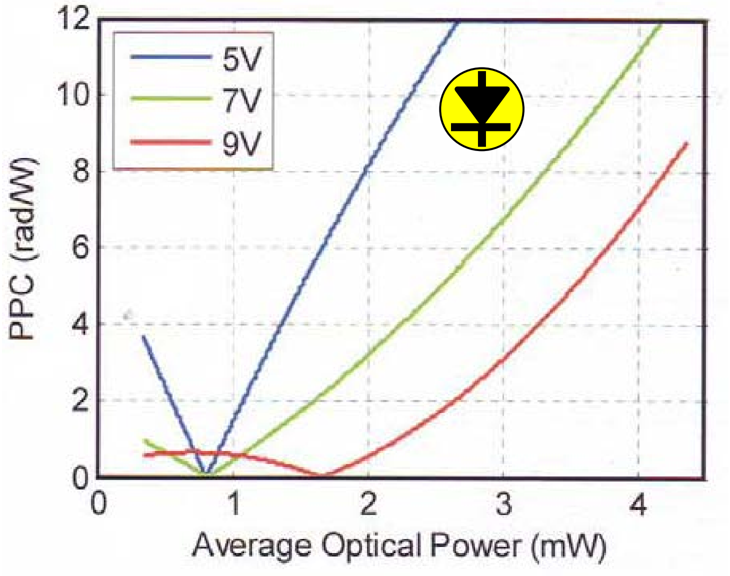
Parameter Sensitivity

Sensitivity to fs-comb properties:

Conversion factor $\Delta\phi$ per $\Delta P/P$ of an InGaAs PIN photo detector due to saturation and space charge:

Intensity noise of comb may limit phase noise.

Phase noise can be suppressed by using an optimized and stabilized power at the photodetector



PPC: power-to-phase conversion (Discovery Semiconductor diode)

W. Zhang, T. Li, M. Lours, S. Seidelin, G. Santarelli, and Y. Le Coq
Amplitude to phase conversion of InGaAs pin photo-diodes for femtosecond lasers microwave signal generation, Appl. Phys. B **106**, 301 (2012)

Conclusion

MOLO baseline design available

- requirements on phase noise and stability can be achieved

Cavity designs under test

- vibration and thermal test inpreparation

Microwave extraction

- comparison HHUD-PTB systems in near future
- determine parameter sensitivities
- estimate performance with MENLO Systems FOKUS comb

Demonstration of sufficient technological readiness by Sept. 2013