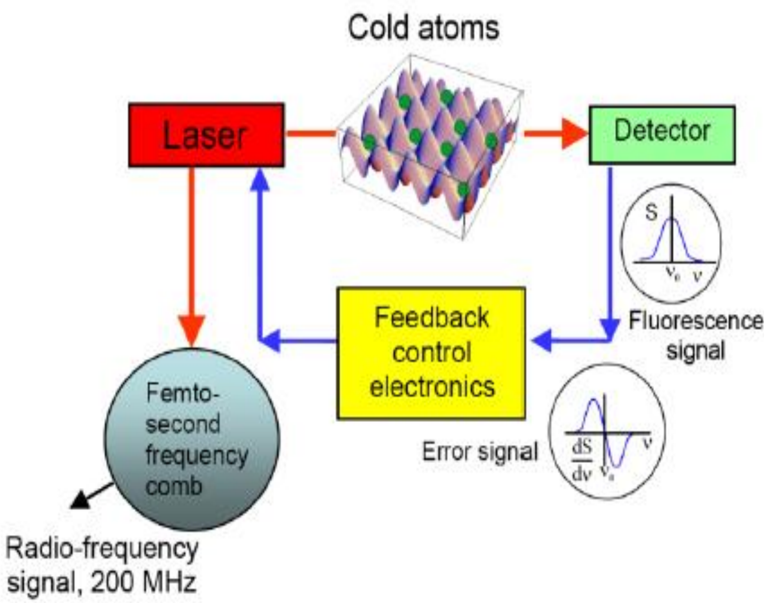
The Space Optical Clocks Project (SOC):

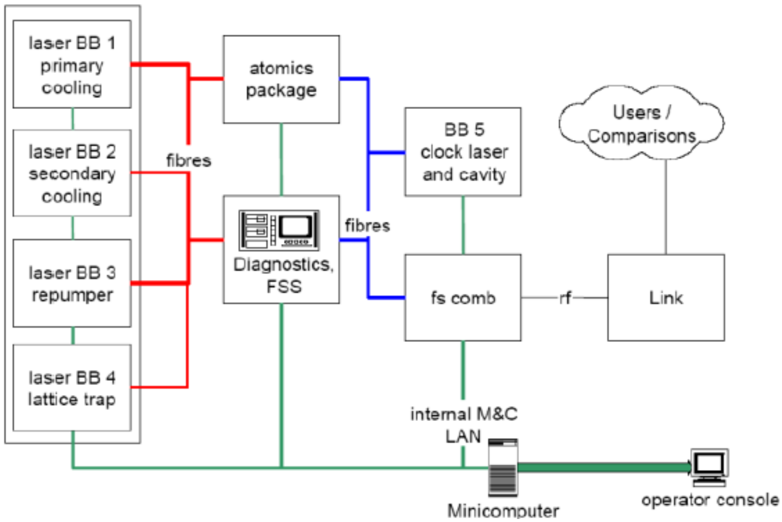
Development of high-performance transportable and breadboard optical clocks and advanced subsystems

Yb & Sr Systems

Physics with Clock in Space:

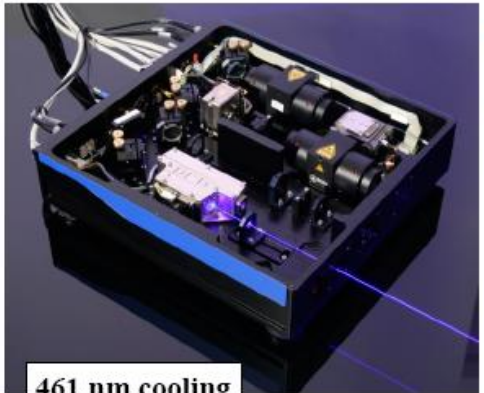
1) Tests of Einstein's theory of general Relativity.
2) Time and frequency metrology by means of the comparison of distant terrestrial clocks.
3) Geophysics: Mapping of the gravitational potential of Earth.
4) Astronomy: providing local oscillators for radio ranging and interferometry in space.



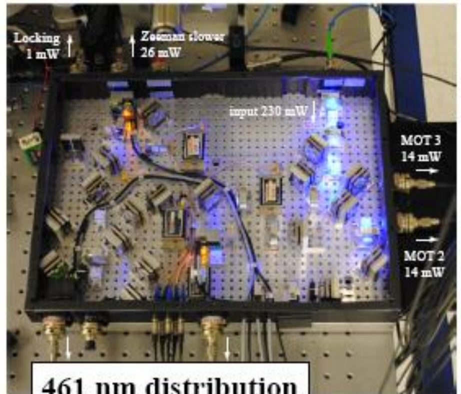


Towards Neutral-atom Space Optical Clocks
(FP7-SPACE-2010-1 Project 263500) www.soc2.eu

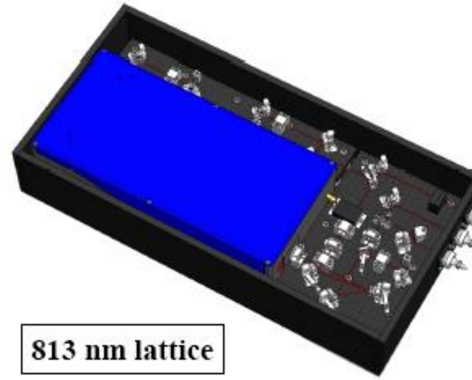
The modular laser system for Sr



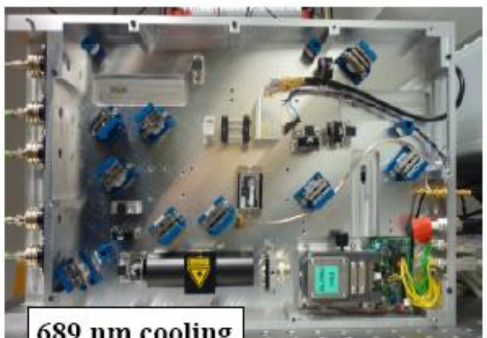
461 nm cooling



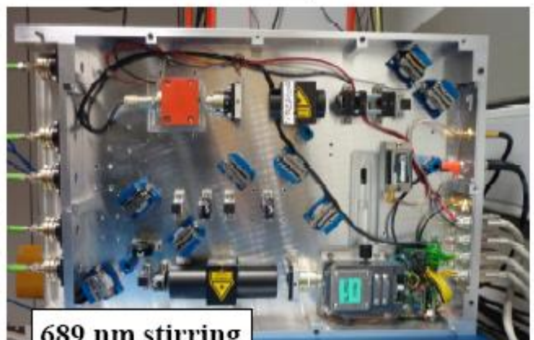
461 nm distribution



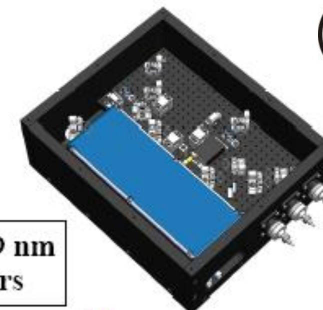
813 nm lattice



689 nm cooling

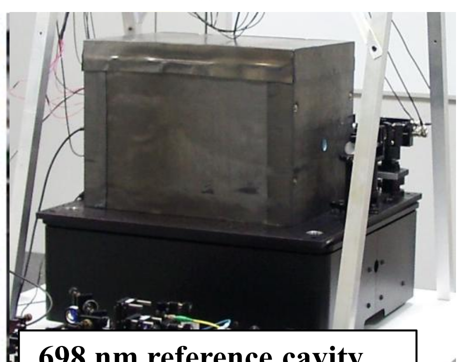


689 nm stirring

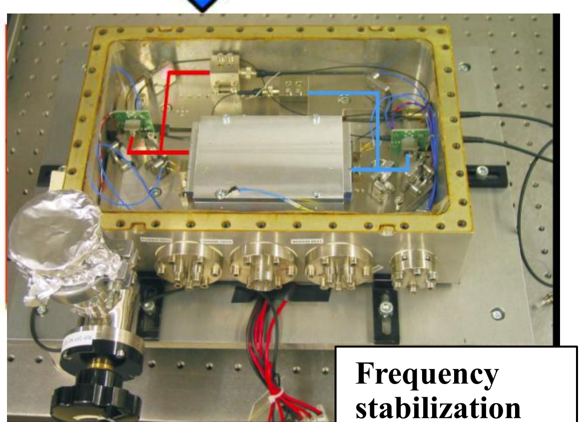


707 and 679 nm repumpers

698 nm clock



698 nm reference cavity

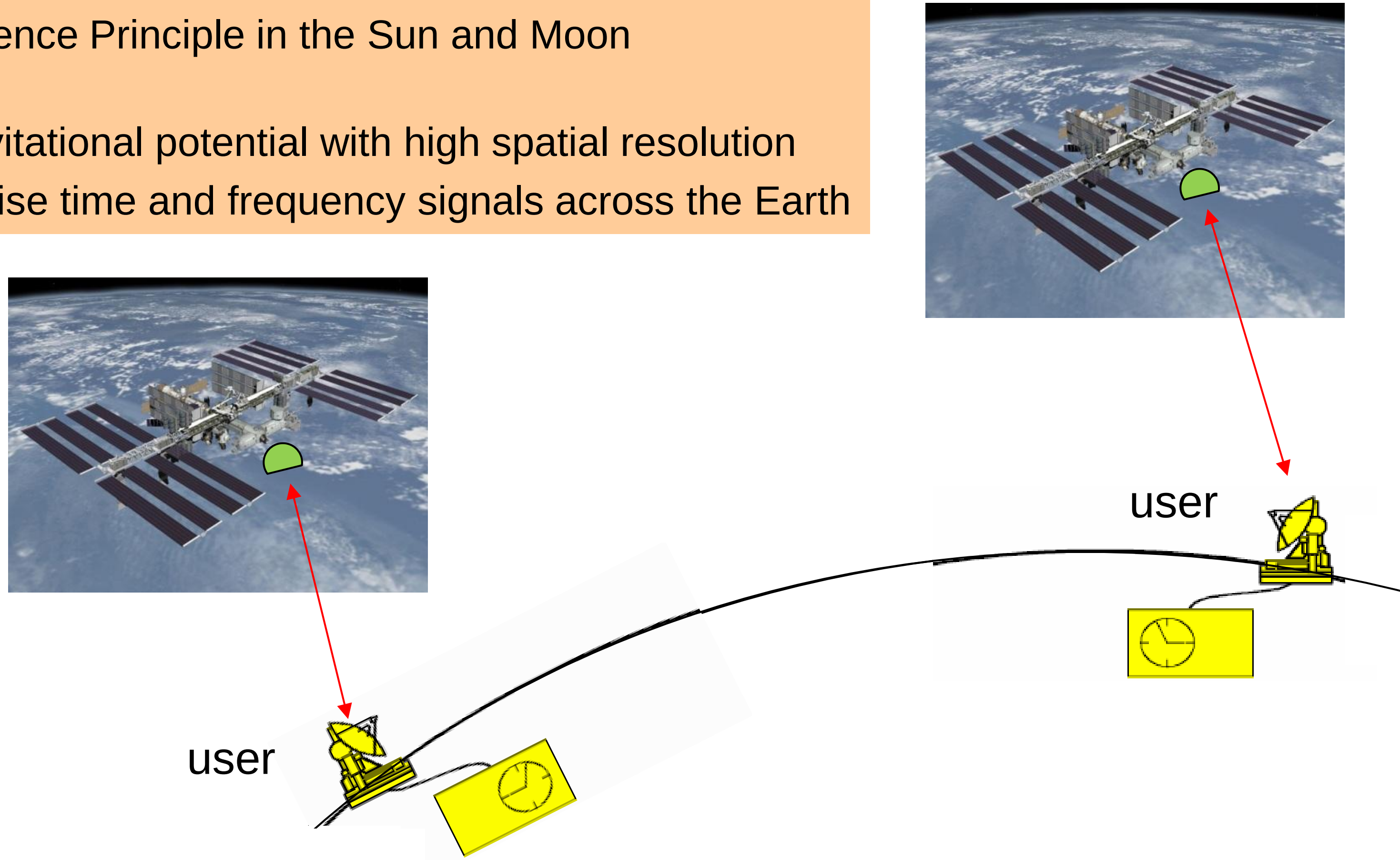


Frequency stabilization system

- Relies on robust, mostly COTS, laser technology
- Developed in cooperation with laser industry (TOPTICA)
- Integrated into the Sr breadboard clock apparatus

The SOC Mission - Goals

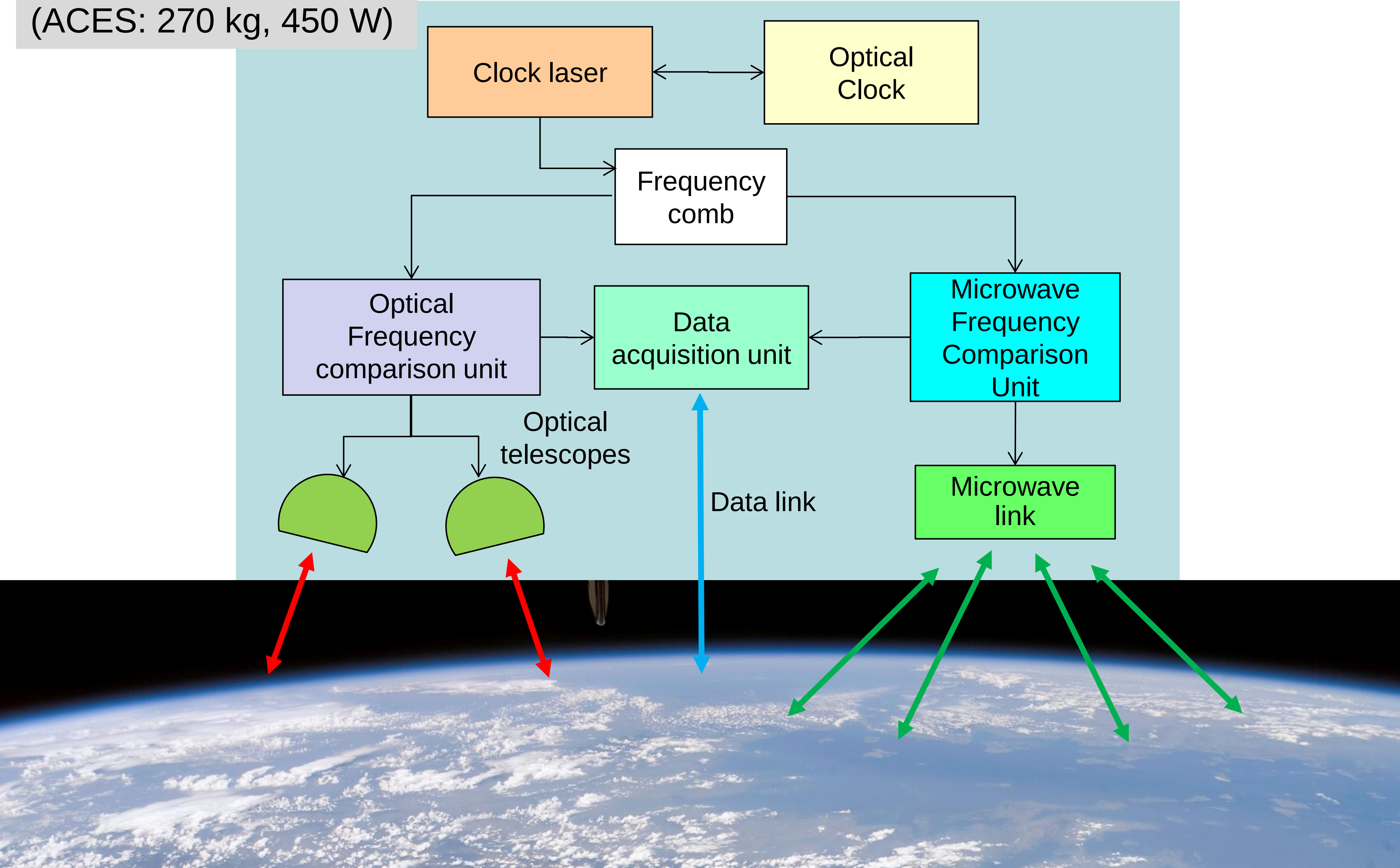
- Precision measurement of the Earth gravitational redshift
- Test of the Equivalence Principle in the Sun and Moon gravitational fields
- Map the Earth gravitational potential with high spatial resolution
- Distribution of precise time and frequency signals across the Earth



- ISS clock performance goal: with 1×10^{-17} inaccuracy
- Ground clocks with $<1\times10^{-17}$ inaccuracy certainly available
- Two-way link: optical and/or microwave
- Natural follow-up mission to ACES, targeted at the year 2020

Payload overview

Est. total mass 295 kg
Est. total power 300 W
(ACES: 270 kg, 450 W)



Activities in SOC (2011-14)

2 transportable lattice clock systems (Yb & Sr), Technology readiness level 4 by 2014; Instability $< 1\times10^{-15}/\tau^{1/2}$, inaccuracy $< 5\times10^{-17}$

Three Categories:

1) Demostrators for Sr and Yb

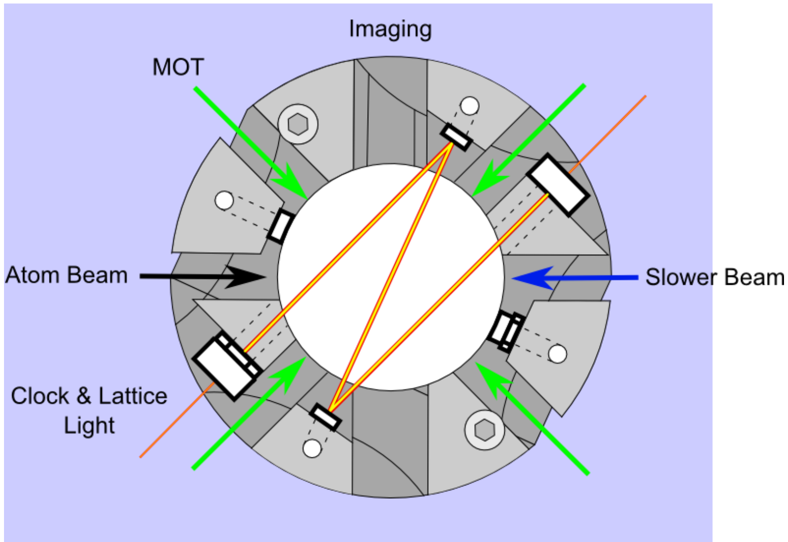
2) Advanced Systems

3) Lasers and Frequency Combs

Demo: Düsseldorf transportable Yb clock

$^1S_0 \rightarrow {}^3P_0$ clock transition in ^{171}Yb

clock laser: H. Luckmann, A. Nevsky, S. Schiller
atoms: C. Abou Jaoudeh, G. Mura, T. Franzen, A. Görlitz

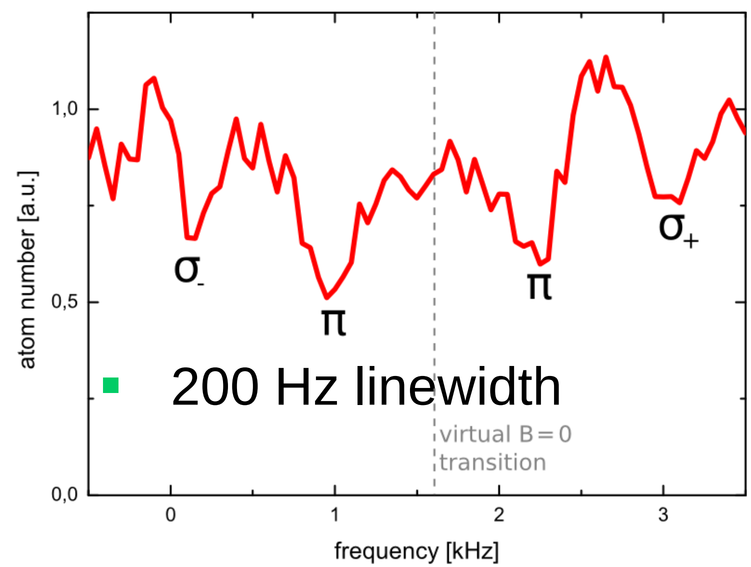


Trapping in 1d optical lattice

Lattice Trapping:

- loading efficiency from green MOT into lattice: ~ 5 - 25%
- Ca. 10^5 atoms in lattice
- lifetime ~ 70 ms

- Zeeman splitting of carrier
- $m_F = \pm½$ mixture
  → 4 Zeeman components
- saturation limited linewidth (200 Hz observed)



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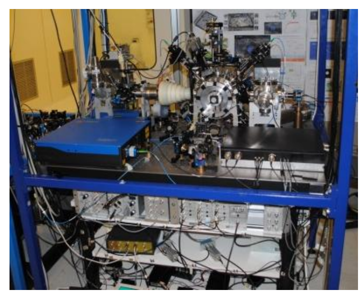
SEVENTH FRAMEWORK PROGRAMME

Demo: Integration of the compact laser-cooling strontium source (UNIFI) with the transportable clock laser (PTB)

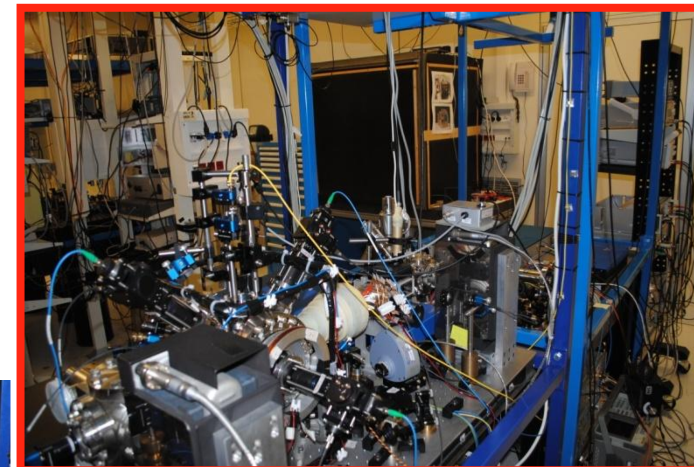
PTB
HEINRICH HEINE UNIVERSITÄT DÜSSELDORF
Leibniz Universität Hannover
l'Observatoire de Paris — SYRTE
Systèmes de Référence Temps-Espace
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA
UNIVERSITY OF BIRMINGHAM
NPL National Physical Laboratory
TOPTICA PHOTONICS
KAYSER-THREDE Ein Unternehmen der OHB Technology AG
EADS astrium
MenloSystems GmbH
KAYSER ITALIA
EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
LTF Université de Neuchâtel unine
csem centre suisse d'électronique et de microtechnique

~1300 km transportation PTB -> UNIFI

Transportable clock laser *(PTB)*



Compact laser-cooling Sr source *(UNIFI)*



Compact laser-cooling Sr source *(UNIFI)*
+
Transportable clock laser *(PTB)*

Compact clock laser (698 nm) with ~ 1 Hz linewidth

Towards Neutral-atom Space Optical Clocks
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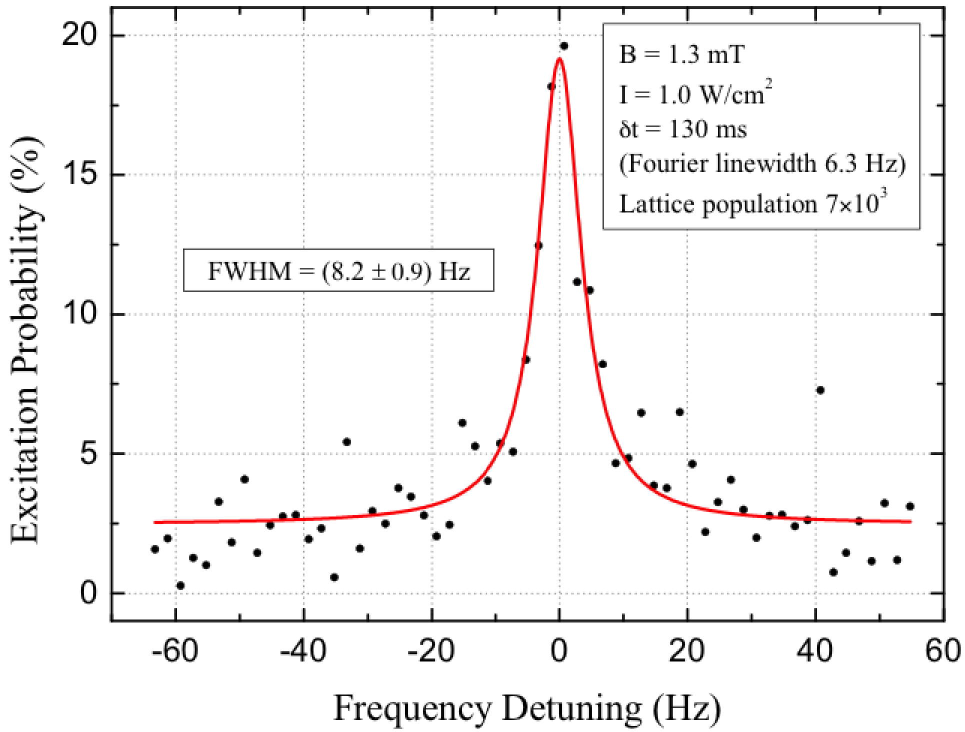
SEVENTH FRAMEWORK PROGRAMME

Demo: Sr clock spectroscopy

Clock spectroscopy



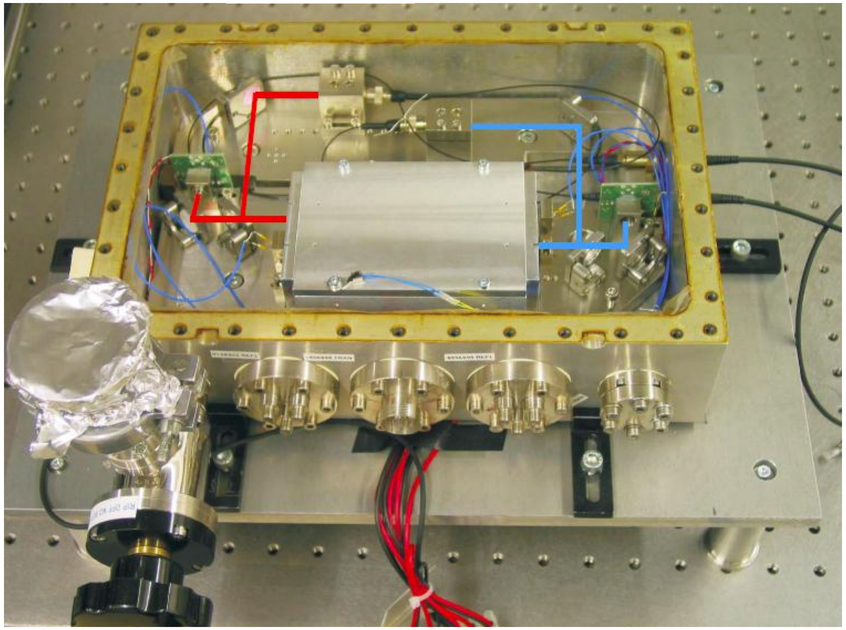
Clock transition linewidth

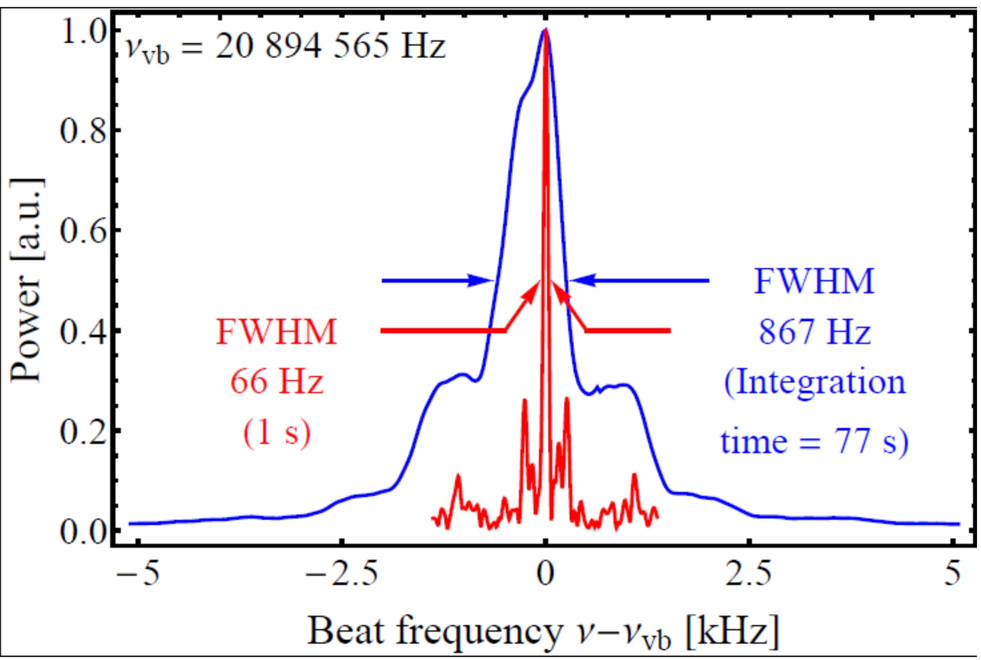
FWHM ~ 10 Hz

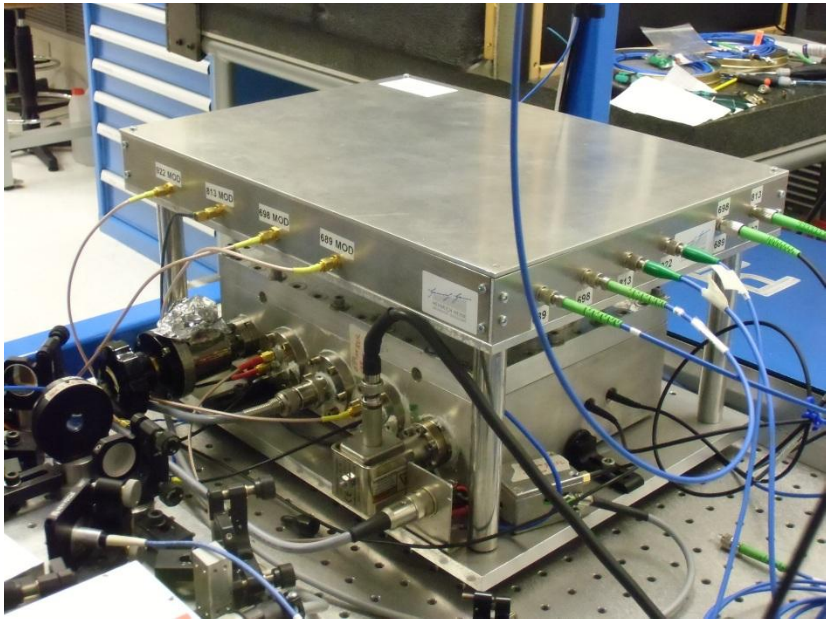
7th day joint measurment

Compact frequency-stabilization unit

- Stabilizes 922 nm, 813 nm, 689 nm lasers
- Single ULE block with 3 cavities
- Each laser has has microwave sidebands;
  one sideband is locked to cavity;
  the carrier is tuned to atomic transition
- 689 nm laser stabilized to 70 Hz linewdith
- Drift < 0.5 Hz/s for all lasers
- Optional: cavity drift can be read out by 698 nm clock laser and compensated
- Size: 30 cm × 20 cm × 15 cm





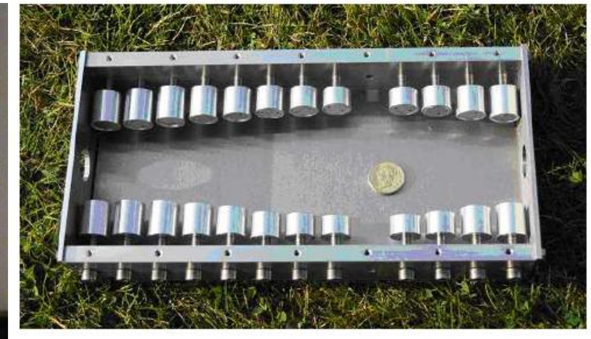


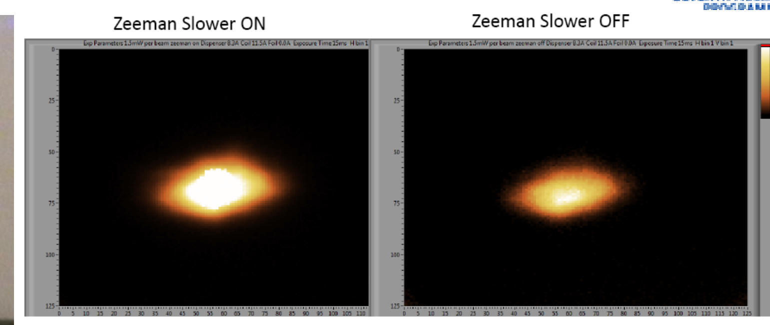
Advanced Systems

Development of 2nd generation subsystems:

- smaller, simpler, more robust -

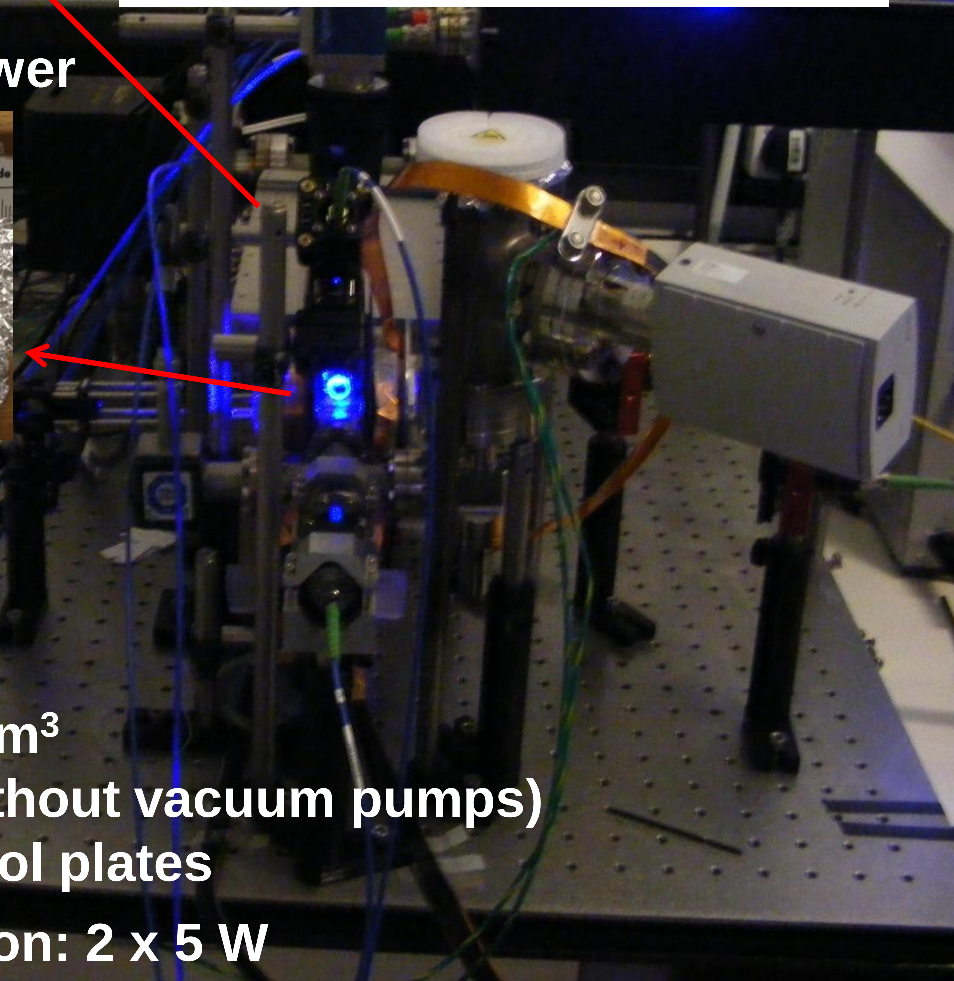
2nd generation Sr atomics unit - I





Permanent Zeeman Slower

Science Chamber



Atomics:

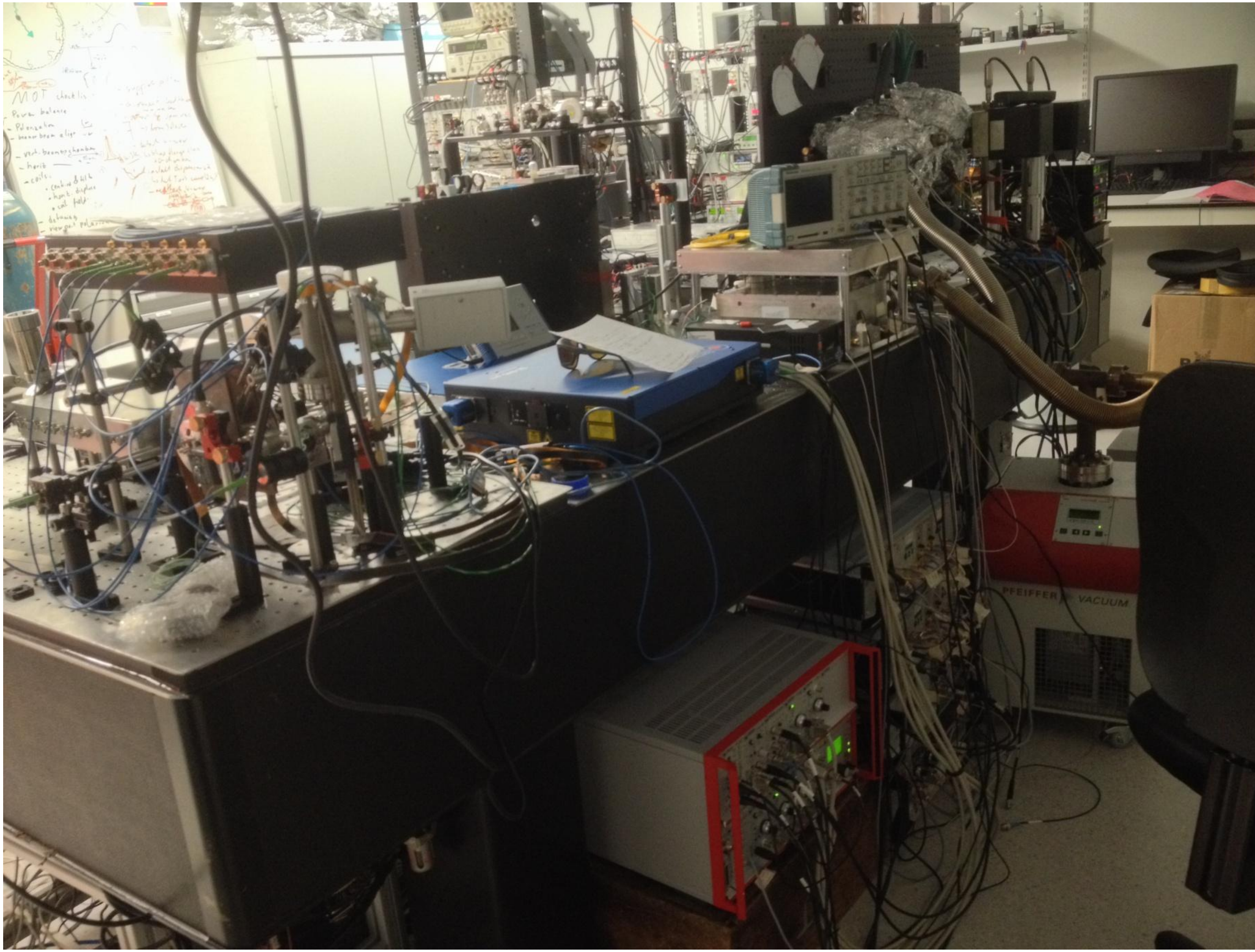
Volume: 35 x 35 x 80 cm^3

Weight: 14 kg (8 kg without vacuum pumps)

Black-body-shift control plates

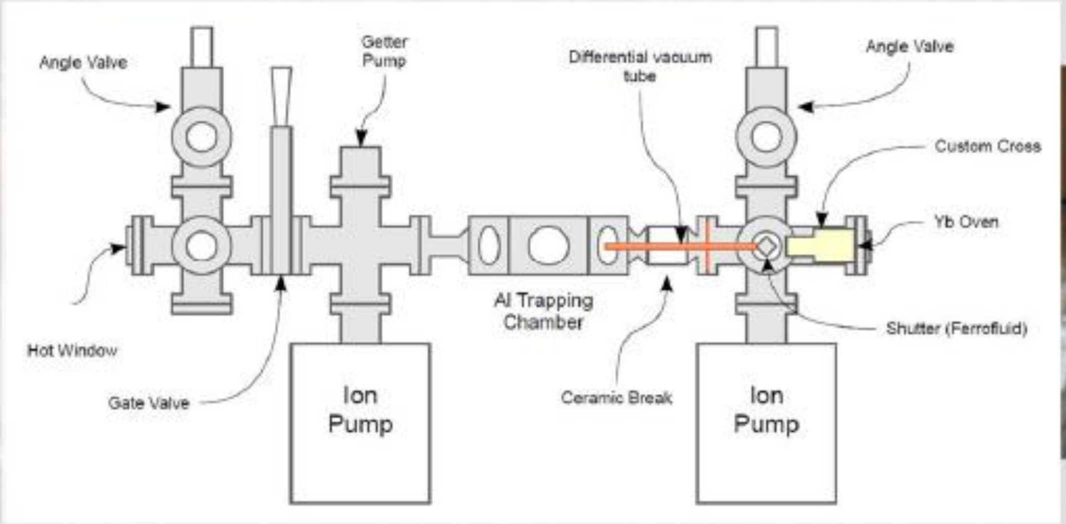
Coil power consumption: 2 x 5 W

Integration of laser systems with advanced atmoics for Sr @ UoB: In progress



2nd generation Yb atomics unit - 2

c) design and development of compact vacuum system for Yb (compatible with loading without Zeeman slower)



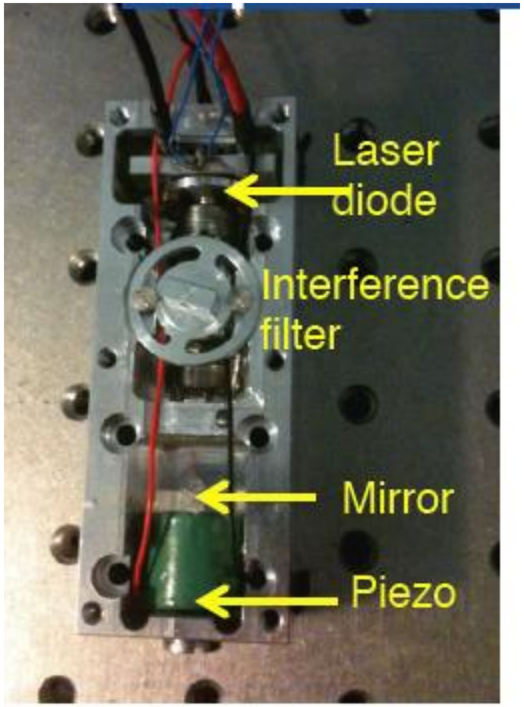
apparatus (and stationary twin system) currently being set up

HEINRICH HEINE UNIVERSITÄT DÜSSELDORF

Lasers and Frequency Combs

MenloSystems GmbH

399 nm cooling laser
30 mW; size: 8 x 3 x 2.7 cm^3



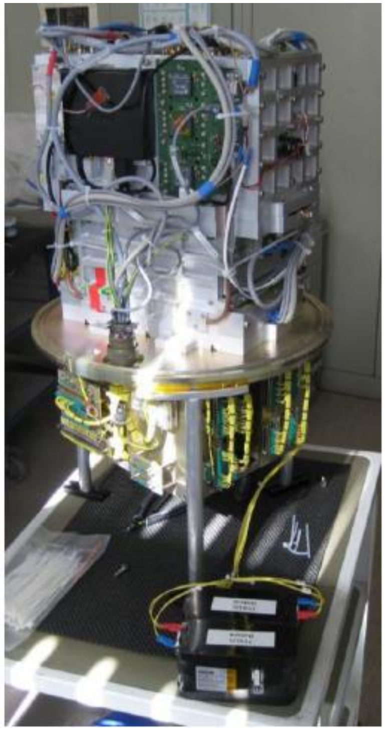
Freq. Doubling Wave guide

Leibniz Universität Hannover

UNIVERSITY OF BIRMINGHAM

Fibre Combs: Menlo Systems

2.2 x 10^{-18} instability at 30.000 s



Sounding Rocket Test Due in Nov 2013

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

2007: Discovery of microresonator frequency combs

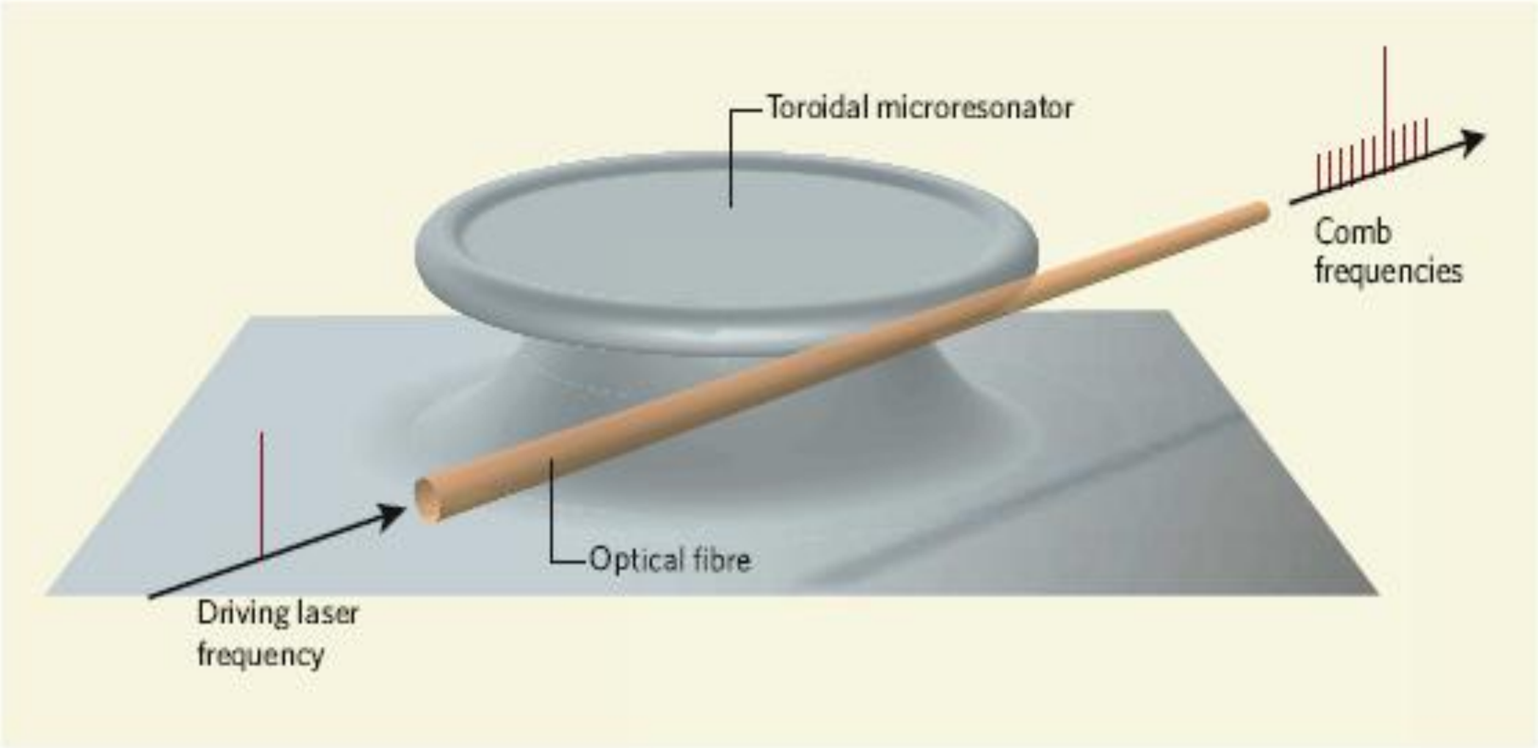
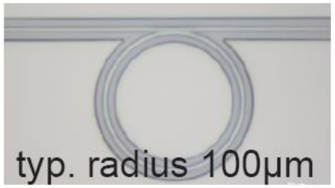
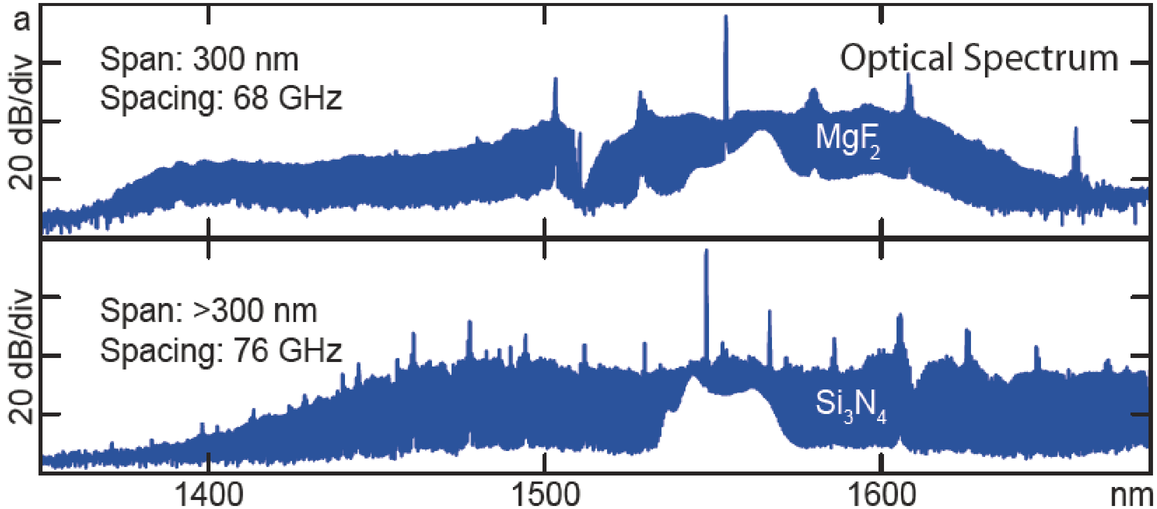


Image credit: S. Cundiff News&Views, Nature, Dec. 20, 2007

Del Haye,Schliesser,Wilkins, Holzwarth,Kippenberg, Nature, **2007**
Del Haye, Arcizet, Schliesser, Holzwarth, Kippenberg, Phys. Rev. Lett., **2008**
EU & US Patent application "Optical Comb Generator using Microresonators"
TJ Kippenberg, Holtzwarth, Diddams, Science **2011**

Universal dynamics of microresonator combs





Crystalline MgF2 and SiN resonators can generate broadband, low repetition rate combs > 1000 lines.

However: For low repetition rate significant phase noise is observed..

T. Herr et al. Nature Photonics 2012 (July)

T. Herr arXiv.org
http://arxiv.org/abs/1211.0733

The Space Optical Clocks Project – Summary

- The SOC project aims at an ISS mission
  - with 10 x improved performance compared to ACES
  - with qualitatively new possibilities (wide network of ultraprecise, transportable ground optical clocks)

- Development of optical lattice clock breadboards:
  - *Modular approach*
  - *Robust subunits: transportability demonstrated*
  - *Low power consumption feasible (diode lasers, magnet coils, oven,…)*
  - *Compact dimensions feasible*
  - *Operation parameters compatible with high-performance clock operation*
  - *Clock transitions observed (8 Hz, 200 Hz)*
  - *2nd generation units with further reduction in size and increase in robustness under way*
  - *Clock accuracy and stability characterizations under way*
  - *More accurate and simpler frequency combs*

- Lattice clocks appear compatible with a space clock for the ISS

- Other activities on optical clock technology development for space (e.g. STE-QUEST mission candidate, FOKUS project (space frequency combs),…)

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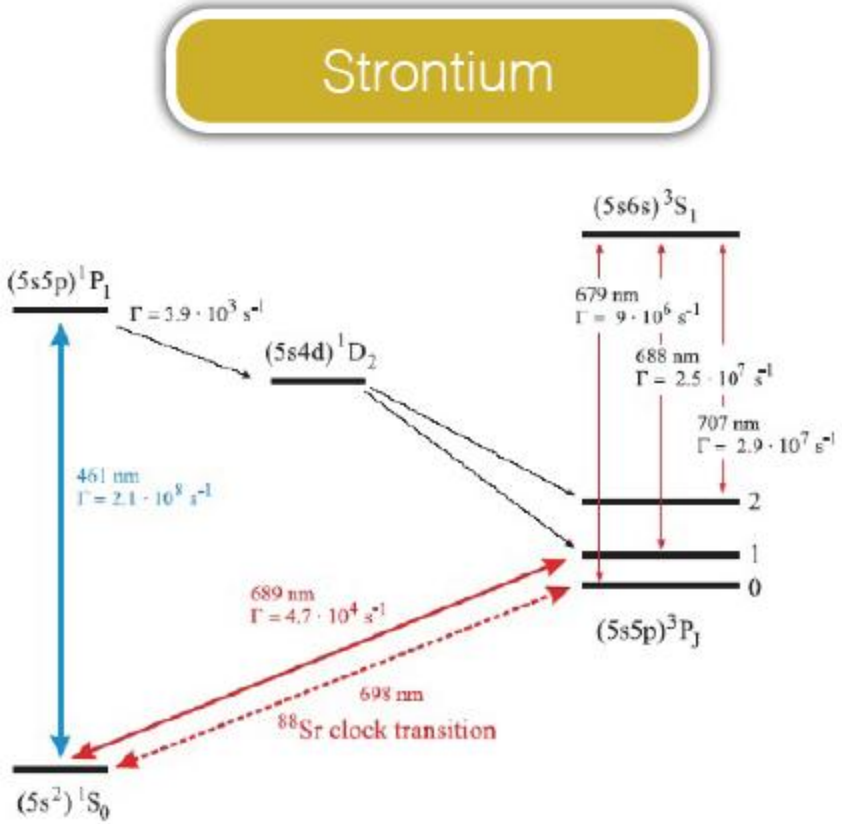
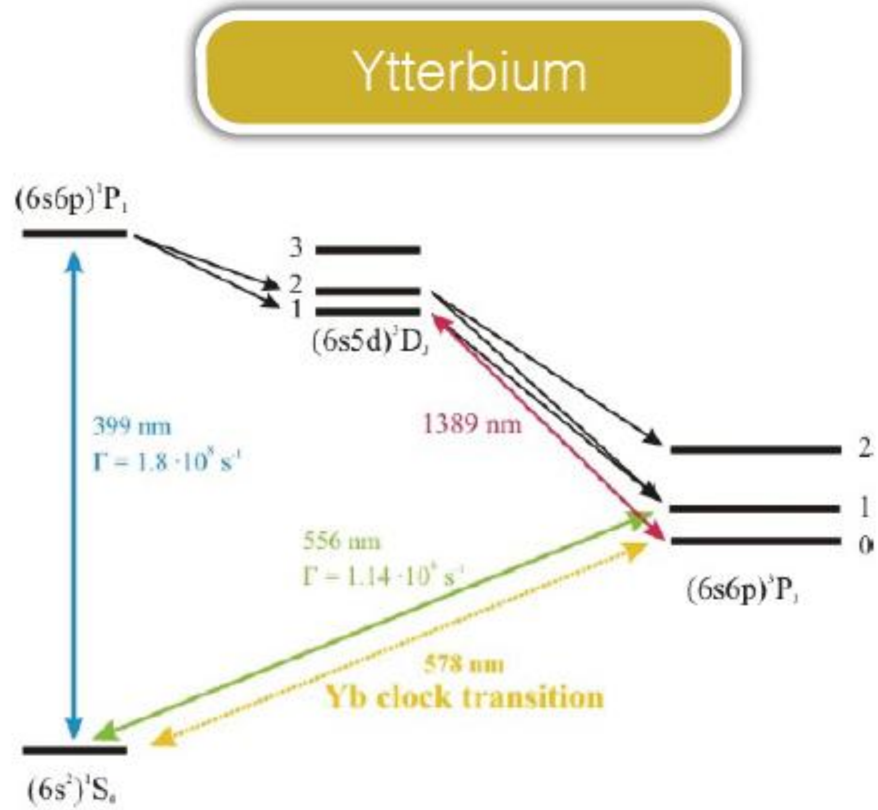
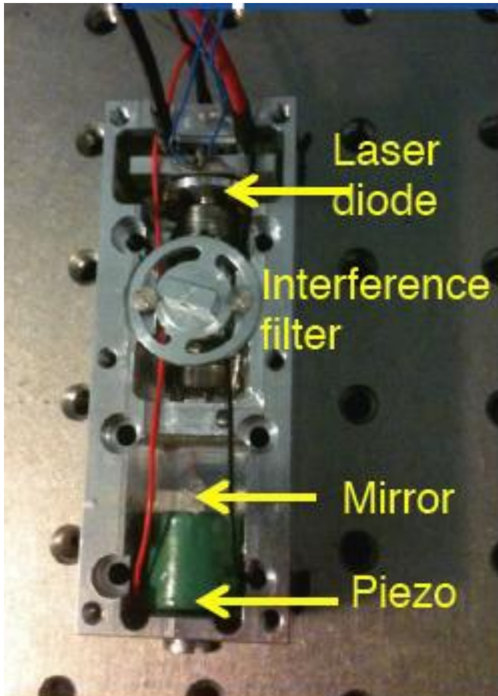
Electronic levels relevant for laser manipulation and spectroscopy performed with the Sr- and Yb- clocks



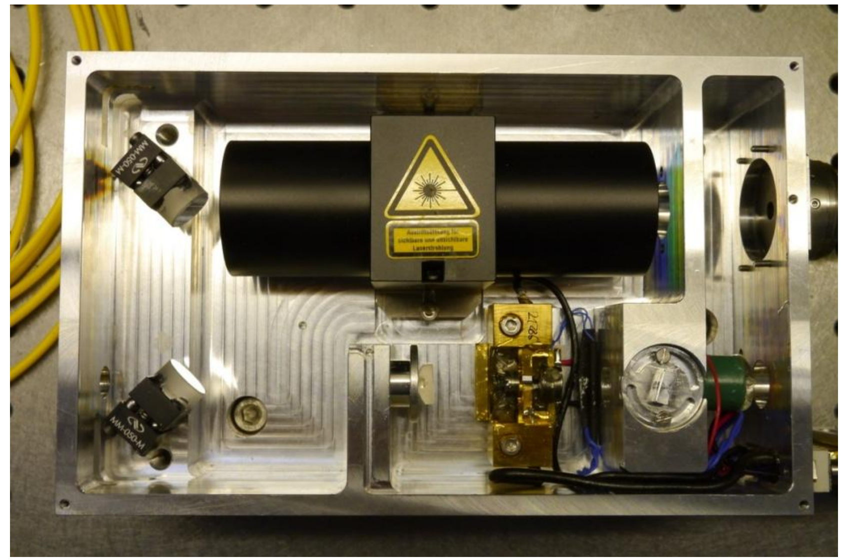


2^{nd} generation Yb lasers

399 nm cooling laser
30 mW; size: 8 x 3 x 2.7 cm^3



759 nm lattice laser; 150 mW out of fiber
TA laser with interference filter – cavity design;
1 MHz frequency control bandwidth;
Size 11 x 18 x 7 cm^3



Cavity: 5.4 cm

1389 nm repumper laser
- 3 mW
- 20 MHz frequency-stability by temperature stabilization
- Size 10 x 10 x 7 cm^3