-Future payloads for Space-

Exploiting possibilities with Integrated Photonics

EPIC MEETING ON NEW SPACEC,

ESA, ESTEC
September 13, 2019

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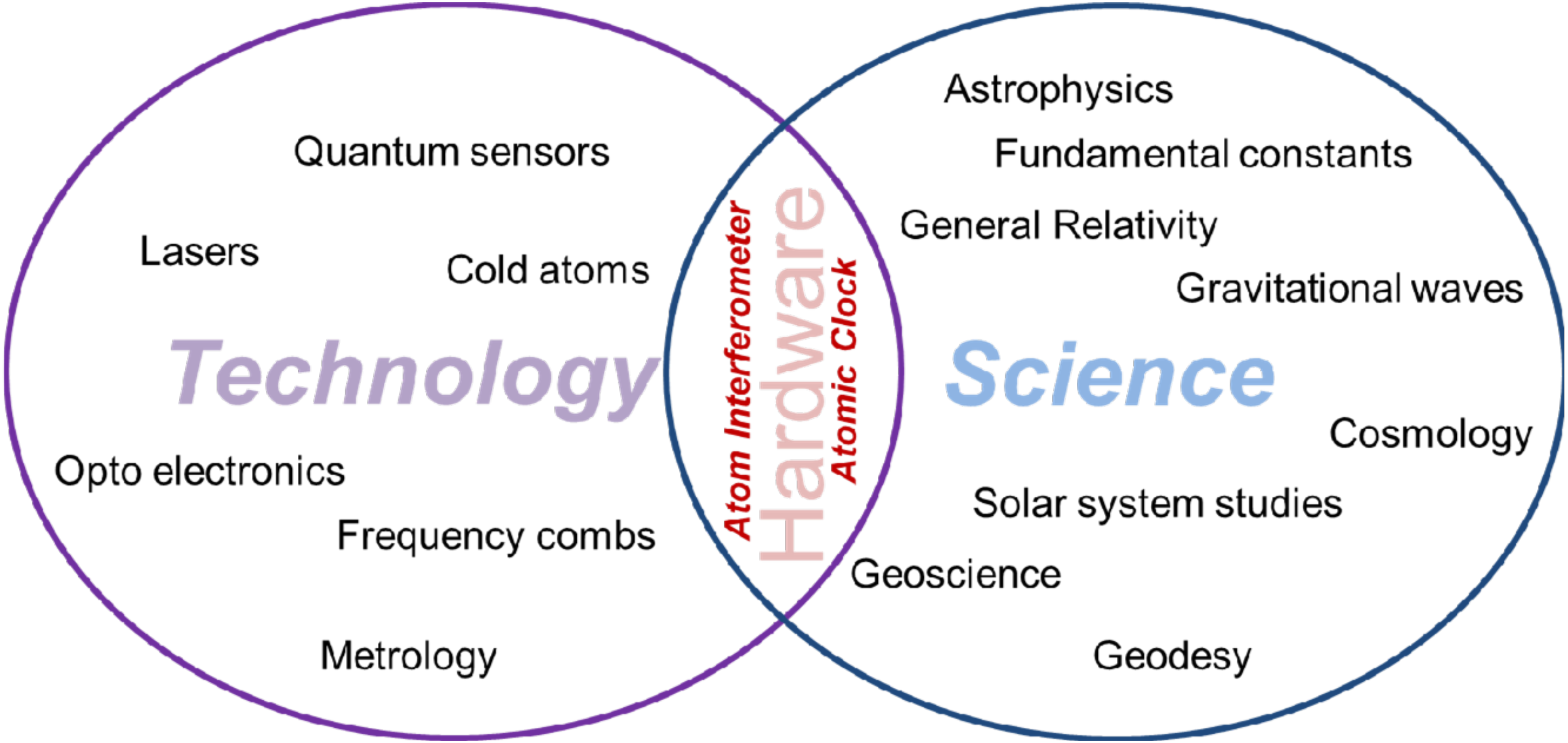
European Space Agency

Summary

- Role of Engineering Directorate in ESA
- Topics and domains of ongoing focus at ESA
  - Current development approach [Development commonalities used, where possible]
- Exploiting Integrated Photonics
- New Initiative at ESA to support very challenging payload goals
  - C-COOL
- Conclusions

Technology driven application links



Attractiveness of Space Laboratory

+as a unique environment to study and apply physics+

- Pure unperturbed, gravitational-less, environment
  - Near ideal for laser cooled experiments permitting long interaction times (gravitational de-coherence is reduced)
  - Earth's gravity is a limitation for the very high performance optical frequency standards (those with FFI of $1x10^{-18}$or better)- Go to space!
- Can tailor the gravitational interaction (with payload) by optimum flight trajectory design
- Global surface access of the mass being orbited
- Vacuum Conditions (dispersion free) !

Science in space is a complex, expensive and a lengthy process

Matter Wave Interferometry (MWI/CAI)in Space

- Why cold atoms?
  - Study/observe internal structure of free atoms (≠ solid state physics)
  - Atom waves potentially more interesting than electron or neutron waves (neutral + rich internal structure)
  - **Interaction with external electric fields and gravity**

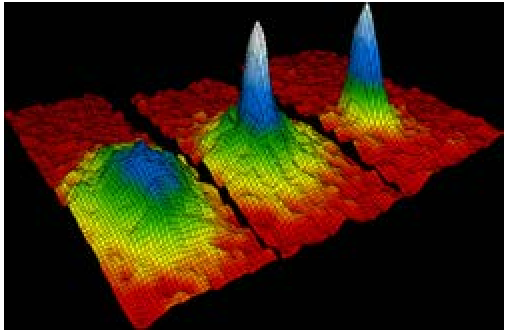
- BUT: RT atom speeds ~ 300 m/s
  - Atom beams have low coherence ➔ difficult to handle as waves
  - Limited observation time (few ms) on a table-top experiment

- Low temperature physics
  - 4K (LHe) He thermal velocity ~ 90 m/s
  - Cryopump effect: condensation ➔ no gas phase

- Laser cooling techniques:
  - **Magneto Optical Traps (MOT) < 10μK ~ cm/s**
  - Adiabatic Expansion
  - Raman Cooling
  - Velocity Selective Coherent Population Trapping
  - Evaporative cooling in magnetic or optical traps ~ 100nK
  - Sympathetic cooling (involving more than one species)

$$\lambda_{dB} = \frac{h}{p}$$

$$\Delta x \Delta p \sim \hbar$$



Velocity-distribution data of a gas of rubidium atoms, confirming the discovery of a new phase of matter, the Bose–Einstein condensate.

MWI system Applications

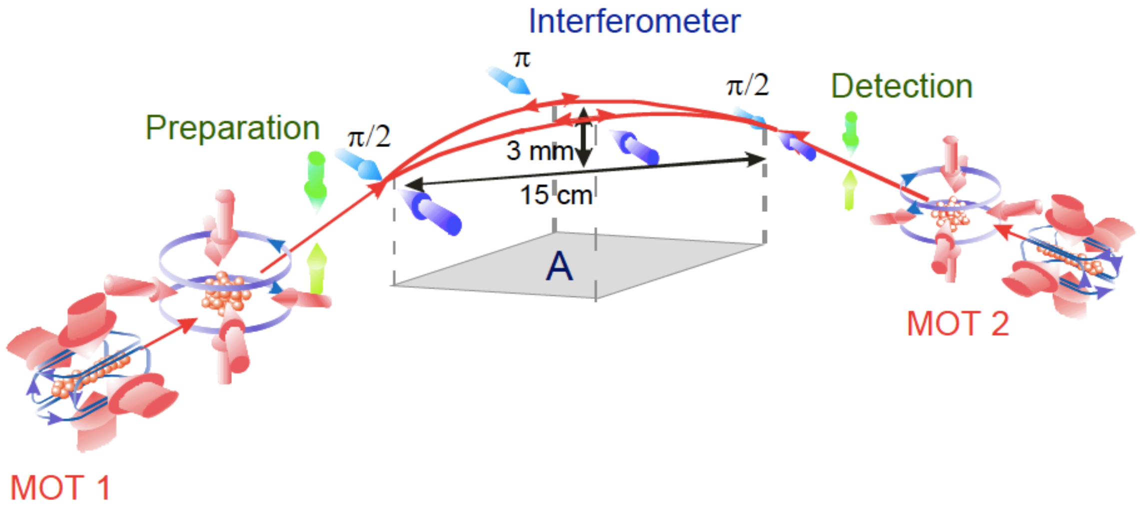
- Acceleration, rotation rate
  - Inertial sensors (e.g. gyro, accelerometer) for navigation
- Magnetic field measurement
  - Earth monitoring, Planetary exploration
- Gravity field measurement, Geodesy
  - Earth monitoring, Planetary exploration
- Frequency dissemination/transfer
  - Lens-Thirring effect, Gravitational red-shift
- Einstein Equivalence principle
  - LPI, LLI, and WEP.
- Gravitational wave detection

Commercially oriented

Basic science

Matter Wave Interferometry (MWI/CAI)in Space

- 2D MOT loads 3D MOT with high flux ~ 10^9 atoms/s
- 3D MOT cools atom clouds ~ 10^8 ^{87}Rb atoms <10μK
- Atomic state preparation for atom optics sequence
- Raman π/2–π–π/2 sequence
- Detection by fluorescence



$$\Delta\varphi_{light} = \frac{4\pi}{\lambda c}\vec{\Omega}\cdot\vec{A}$$

$$\Delta\varphi_{atom} = \frac{4\pi}{\lambda_{dB} v}\vec{\Omega}\cdot\vec{A}$$

$$\Delta\varphi_{atom} = \frac{mc^2}{\hbar\omega}\Delta\varphi_{light}$$

(Potential) 10^{11} improvement!

- Same surface covered
- Quantum projection noise limited (same # photons and atoms)

Optical Atomic Frequency Standards: Generation

- Based on narrow (Quantum forbidden) optical transitions in laser-cooled atoms or ions
- Frequencies (***f***) ~10^5 times higher than rf, ***Δf << 1 Hz***
- Q-factor ~10^{15} (or even higher)
- Better time resolution (clock “ticks” faster)
- Potentially very high stabilities

The Fractional Frequency Instability FFI relating to the parameters above:

instability $\sigma \propto \frac{\Delta f}{f} \frac{1}{(S/N)}$

Adding noise terms, an expression for the FFI, based on atomic detection gives:

$$\delta_{\text{atom}} \approx \frac{1}{\pi Q}\sqrt{\frac{Tc}{\tau}} \times \sqrt{\frac{1}{N} + \frac{1}{Nn} + \delta^2}$$

Under specific conditions the fundamental limit due to Quantum Projection Noise (QPN) could yield a potential clock stability of

$$1\,x\,10^{-17}/\sqrt{\tau}$$

Optical Atomic Frequency Standards: Distribution/Transfer

Radio Frequency (RF) Transfer Techniques

Target Fractional Frequency Instability (FFI) $\Delta\nu/\nu = 10^{-15}$

For ν = 10 GHz (Cs) [RF atomic frequency standards], $\Delta\nu$ = 10μ Hz

Phase (ϕ) we would need to be controlled at the level of 1/100000 of one cycle !!

Optical Frequency Transfer Techniques

Target Fractional Frequency Instability (FFI) $\Delta\nu/\nu = 10^{-15}$

For ν = 429 THz (Sr) [Optical atomic frequency standards], $\Delta\nu$ = 0.43 Hz

Phase (ϕ) we would need to be controlled at the level of $\approx$ 0.4 of one cycle. **OK**

Improved capability from OACs will benefit from evolving remote high-accuracy optical clock frequency comparison techniques:

- Terrestrial [dedicated optical fibre transfer]
  [shared Quantum links]
- Satellite – Ground [Optical]

Optical Atomic Frequency Standards

Space Applications

- Optical Navigation; Optical analogue to RF (GPS/GALILEO/GLONASS..)
  - GNSS positioning
  - Deep Space Navigation

- Telecommunication
  - tight synchronization of digital networks

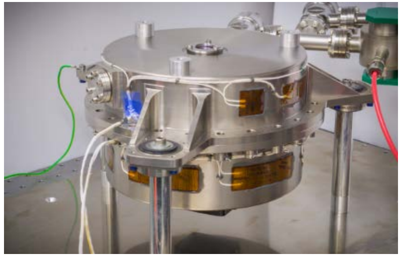
- Master clock in space for time and frequency distribution

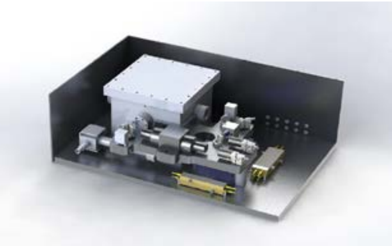
- Fundamental Physics; fundamental constants, general relativity, Dark matter searches

- Chronometric geodesy and gravimetry
  - 1^-18 corresponds to 1cm height difference [Complimentary to gravimetry]
  - Global GEOID determination

Optical atomic Frequency Standards & clocks: Development

- Atomic Reference Unit: Laser cooled (single ion in electromagnetic trap) or laser cooled neutral atoms in lattice light trap
- Optical Local Oscillator: CW laser pre-stabilised to ultra-low drift reference cavity & which interrogates the atomic reference [<10mHz linewidth]
- Atomic State Control: Lasers used to prepare and control atomic medium (neutral or ion)
- Laser System Interface Unit: Interface between lasers and Atomic Reference Unit
- Frequency counter: Optical Frequency Comb locked to LO/Reference delivering multiple optical (& rf outputs)





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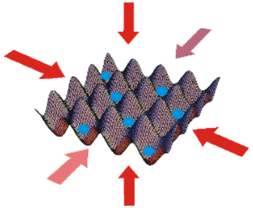

Atomic Reference Unit

(Quantum forbidden transition in ion/atom)

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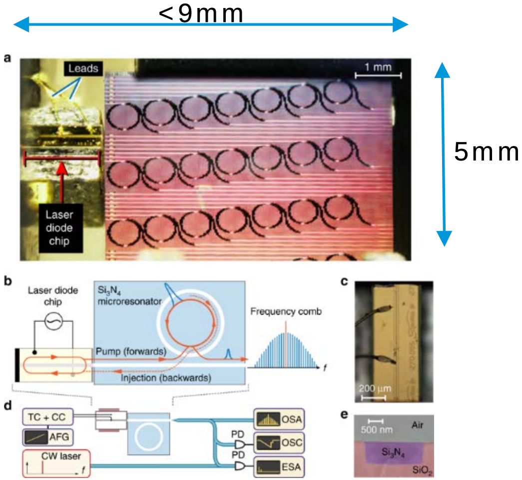
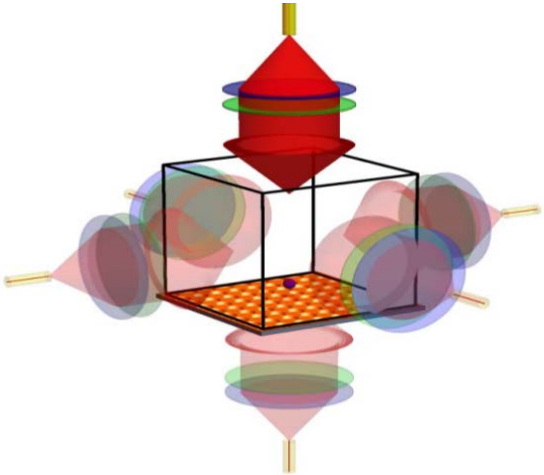
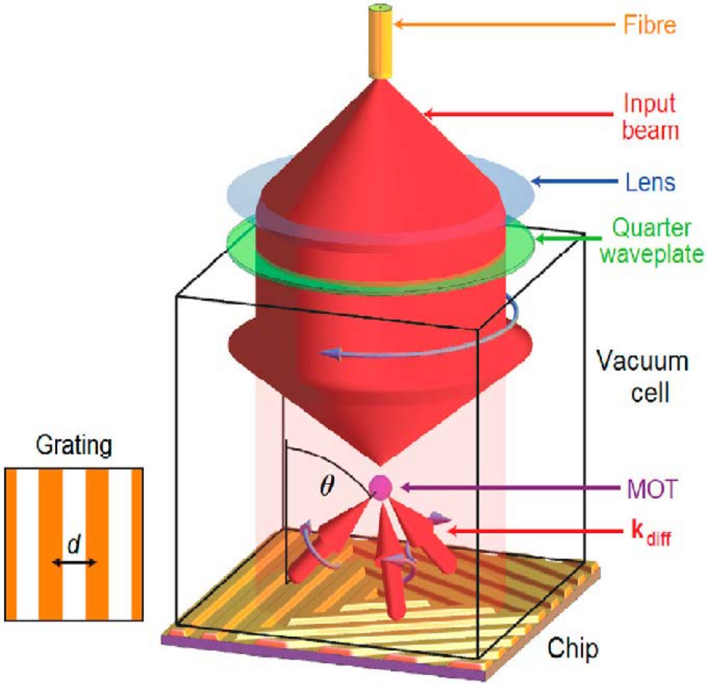


Nature Communications **volume 10**, Article number: 680 (2019)

Magneto-Optical Traps (MOTs) with Micro-fabricated Gratings – micro G-MOT





Mirror MOT → Grating MOT → Micro fabricated G-MOT

McGilligan J.P, Griggin, P.J, Riis E, Arnold, A;
Scientific Reports, 2017 “Grating Chips for Quantum Technologies”
Array of GMOTs for use in Atom Interferometer

Exploiting Integrated Photonics (InPhot)

- Exploit CMOS-like processing route for system components
  - Analyse payload system designs to implement InPhot components
  - Initiate and promote InPhot component development
- Validate sub-system and full payload system performance
  - Integrate with C-COOL integration opportunities
- Verify the achievement of high reliability and predictable lifetimes
  - Support mission possibilities requiring high performance and high reliability

Relevant Components; InPhot

- Individual elements
  - Channel Waveguide lasers
  - Bandwidth reduction and drift control in the waveguide
  - Waveguide Frequency Modulators; AOM, EOM
  - Non-linear Frequency conversion; poled materials
  - Polarization definition and control
  - Faraday rotation components
  - Beam splitting and recombining
- Chip scale Optical Frequency Combs
- Integrated optic Ion Traps

Recent Achievements supporting InPhot

- *An optical-frequency synthesizer using integrated Photonics*

Nature, Vol. 5 5 7, May 3, 2018

- *Architecture for the photonic integration of an optical atomic clock*

Optica, Vol. 6, No. 5 / May 2019

C-COOL, A (re)new(ed) Approach

- What is C-COOL?
  - CAI-Common Optical Optimisation Laboratory
  - Design, Development, Integration, system evaluation, consolidation and evolution, end to end controlled environmental testing, reliability enhancement
- How many areas are being explored?
  - Group I: Quantum Sensors: Rubidium based Instruments, CAI, Magnetometer, THz lattice clock, Magnetic Navigation
  - Group II: Strontium Quantum Systems; OAFS, Magnetically insensitive CAI
  - Group III: Optical Frequency dissemination; OAFS comparison, CAI node expansion, Quantum network
  - Group IV: Quantum Enabling Future Technologies (QEFT).

Conclusions

- New, (no longer) technologically immature, concepts shall be evaluated early in the development programs
- Shared sub-system development paths are being explored
  - Neutral Sr (optical) frequency standard and Sr MWI
  - Elements of Sr with Rb
  - Proliferation of frequency transfer infrastructure (fiber and free-space), *EU
  - Fundamental Quantum Technologies/Quantum Optics as resource for future missions
- System complexity needs to be reduced for space
  - The past and current approach is based on bulk optics/electro optics/lasers/…
  - The future **must** actively seek to embrace integrated photonics
  - ESA-ESTEC to link EPIC technical competence in a supported program
- *Adopt C-COOL as Test-bed for Quantum Integrated Photonics*

*EU EuroMet, QIA (Flagship program),

esa

Your direct contact in ESA

For Quantum Metrological engineering requirements

and developments for space

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