Community Workshop on Cold Atoms in Space: ESA/Technology inputs

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ESA ESTEC

24/09/2021

Some historical Perspective

HYPER	2001
ESA Workshop on Optical Atomic Clocks	2005, 2007, 2009, 2011, 2013, 2015, 2017, 2019, 2021, 2023?
HISPAC	2008 ESA HQ (ESA Directors, C Cohen-Tannoudji,…) Presented the conclusions of an ESA project report (*Optical Atomic Clocks for Space*). Conclusions are still as relevant today as in 2008 (ESA CN 21641/08/NL/PA)
STE-QUEST	CDF 2011, 2012 & 2013 Industrial studies
FTAP	2011 ESA ESTEC Emphasis placed on developments on *Magneto Optical Trap (MOT)* *-TEC-MM had initiated Technical Assessment studies in 2010-*
This meeting	New Emphasis?

Outline of Presentation

- Cold Atoms for Space systems (CAI/MWI & OAFS/Clocks)
  - Focus on two fields; Rb (K, ..) MWI/CAI, Sr (Sr+, ..) OAFS/CLOCKS
- Some recent ESA developments
- Other ongoing initiatives
  - Other ESA initiatives including early flight opportunities (C-COOL,..)
  - Opportunities offered by this initiative

- ESA Agenda 2025 and Quantum Cross Cutting Initiative CCI (Eric)

- Inputs to the Community Roadmap (Pierre)

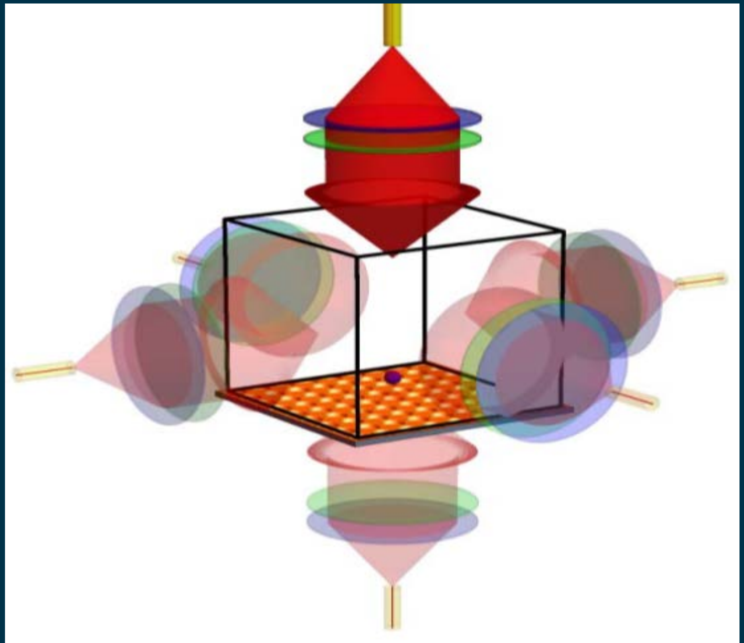
Ongoing/Completed Developments

- Rb MOT (projects ongoing since 2011)
  - All optical (Cool atom reservoir)
  - Hybrid (combine all-optical with magnetic chip) to reach BEC

- Lasers
  - Cooling & Raman (for pulsed CAI system)

- Laser Frequency Offset Control (LFOC)
  - Not specifically defined requirement
  - OFC (partial octave under certain conditions) could suffice
  - Integrated photonic OFCG being examined for compatibility

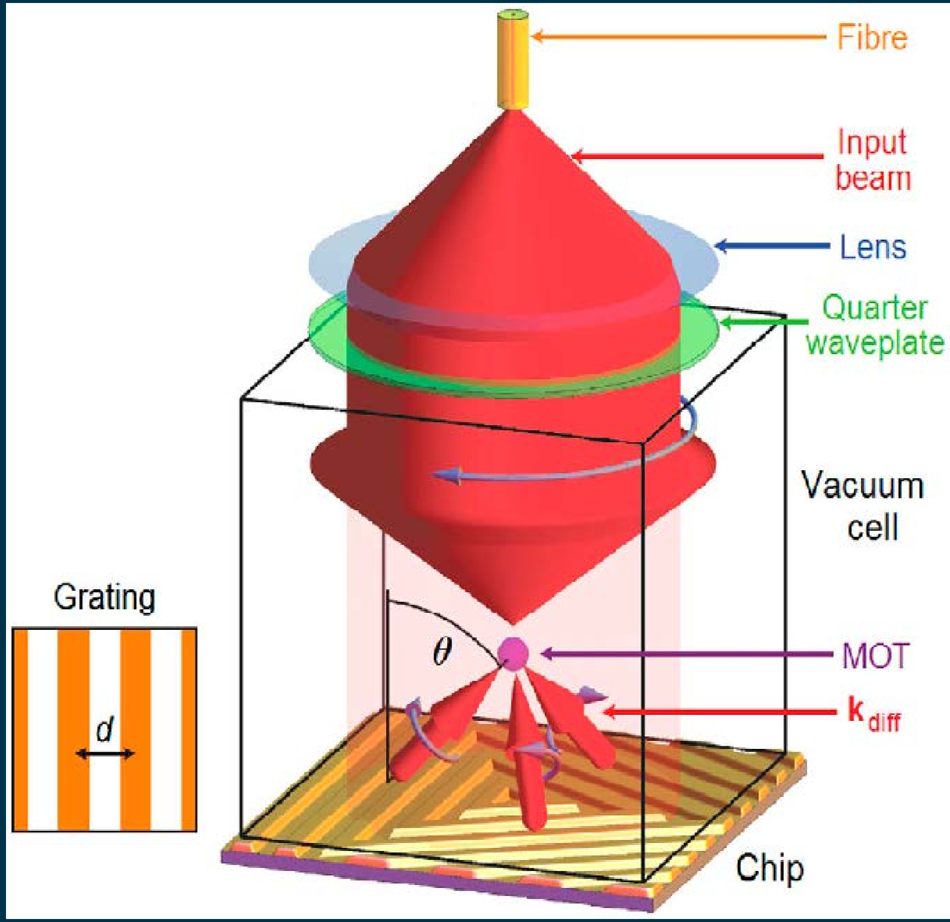
Rb MOT with Micro-fabricated Gratings – G-MOT



nature
nanotechnology

SENSORS
A magnetic hunt for bacteria
CARBON NANOTUBES
Separated by a trench
NANOWIRES
Going over arrays with a fine-toothed comb

Laser cooling meets nanotechnology



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

Magneto-Optical Trap = MOT (spatially-varying magnetic field + laser + optics)

Near-term targets:

- Increased phase space density of atomic clouds
    - Gray molasses (sub-Doppler cooling) in gMOT
    - Enhanced loading of optical dipole trap
    - Evaporative cooling toward degeneracy in optical dipole trap (desire)
- Road-mapping for future space applications
- Integrate activity within larger European consortium

Next-stage targets:

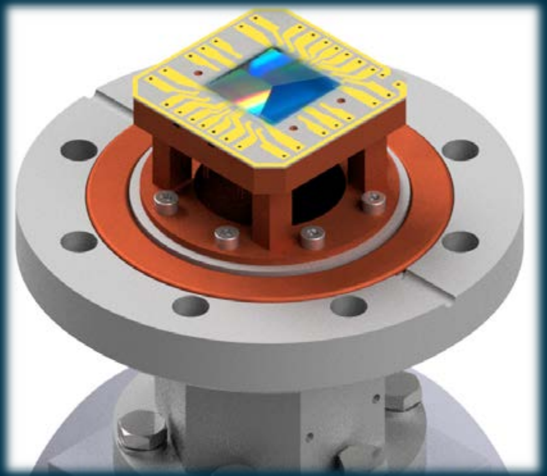
- Compact, self-contained atomic platforms
- Two-stage cooling of Yb and Sr, Mg ?

Rb HYBRID TRAP; G-MOT + MAGNETIC CHIP

Goal: Creation of a Bose-Einstein Condensate (BEC) from a single-beam grating magneto-optical trap (gMOT) with an atom chip.

Recent Achievements:

Manufactured grating atom chip & placed in test facility



ESA contract: University of Hannover

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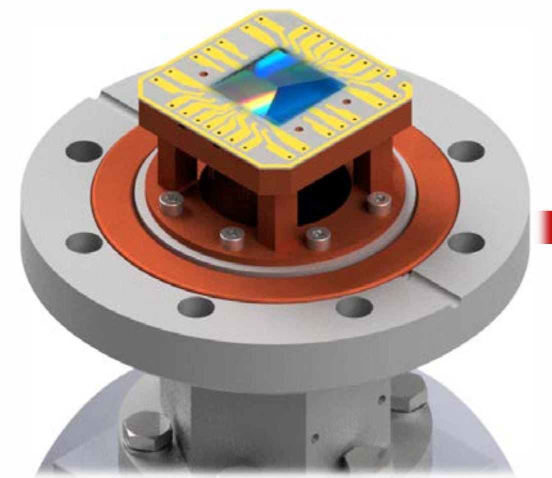
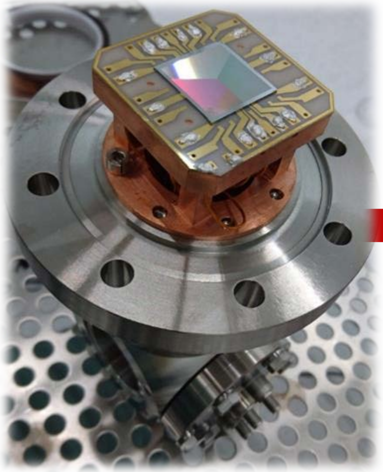
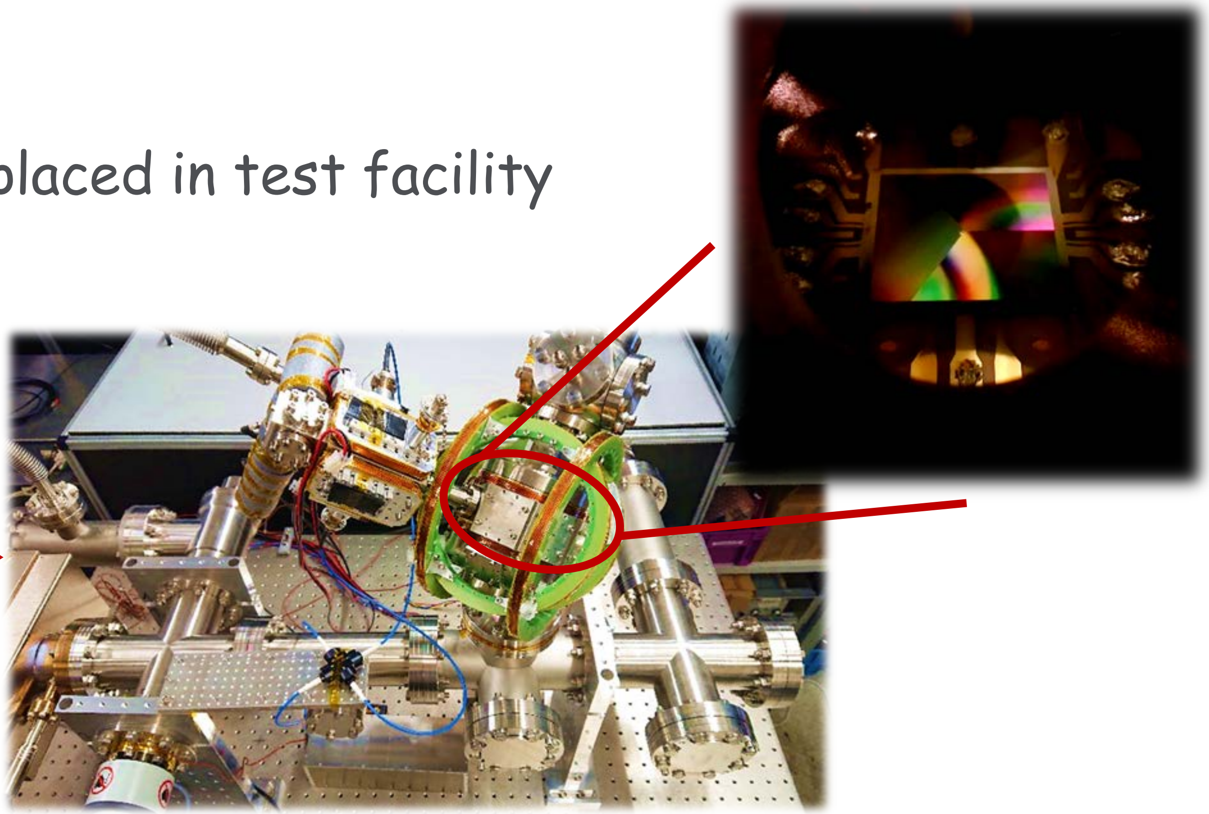


CAD



Manufactured



Placed in test facility IQO

Rb Cooling / Raman laser source

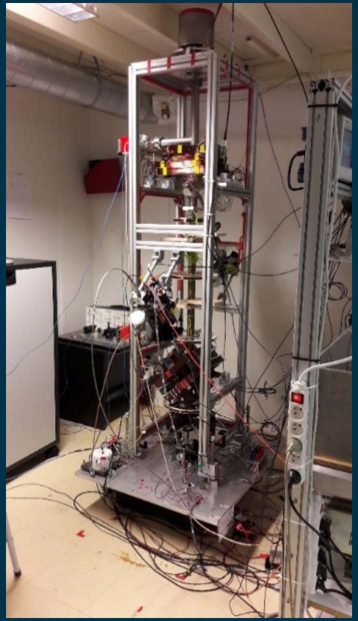
Muquans-iXBlue (France) ESA CN: 4000116740

- Develop a cooling/Raman laser system with enhanced operational features
  - For high-precision measurements of acceleration gradient and rotation with atom interferometry.
- TRL3 → TRL4 (breadboard validation in laboratory environment).
- Project content
  - Technological review and proposal for a demonstration architecture
  - Laser system manufacturing and integration of the demonstrator
  - Functional and performance tests, including tests on cold atoms (SYRTE)

Rb Cooling / Raman laser source

Conclusions of the activity

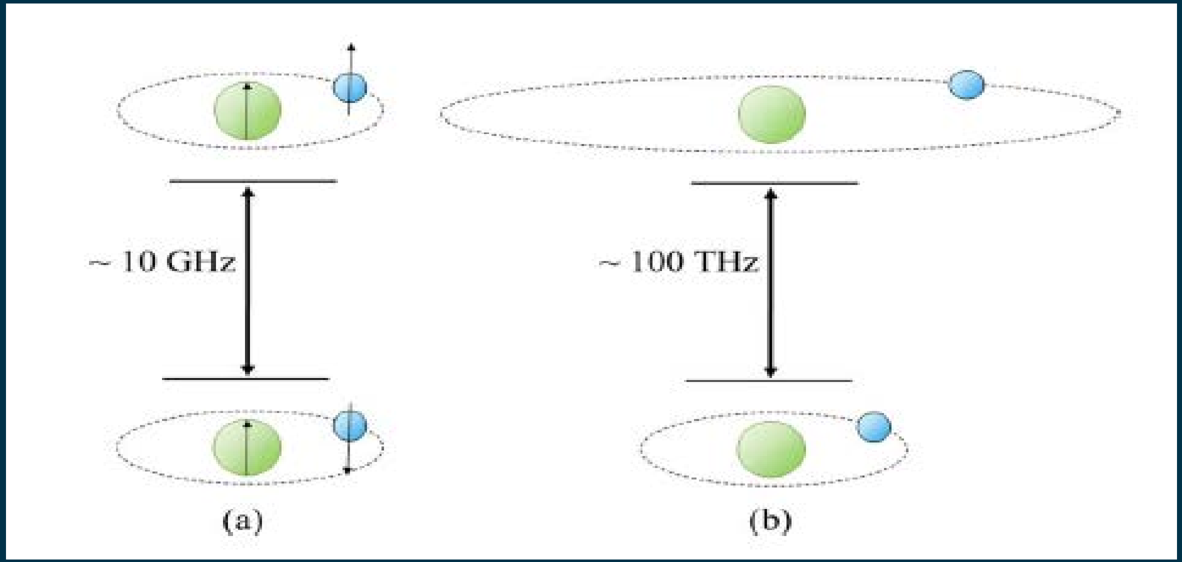
- Laser System (LS) designed, integrated and tested
  - Met ESA's project specification
  - Shows technology is mature (TRL 4)
- Relevance of frequency doubled technology
- LS validated on cold atom gradiometer at SYRTE
- Significant step towards future system phase 0 studies
  - Technical risk greatly reduced
  - Focus now on qualification and precise instrument architecture



Atomic Frequency Standards

(a) Radio Frequency (RF) Frequency Standards

1GHz (MASER), 6.8GHz (Rb), 9.2GHz (Cs)..



(b) Optical Frequency Standards (100's THz)

Single trapped ion standards

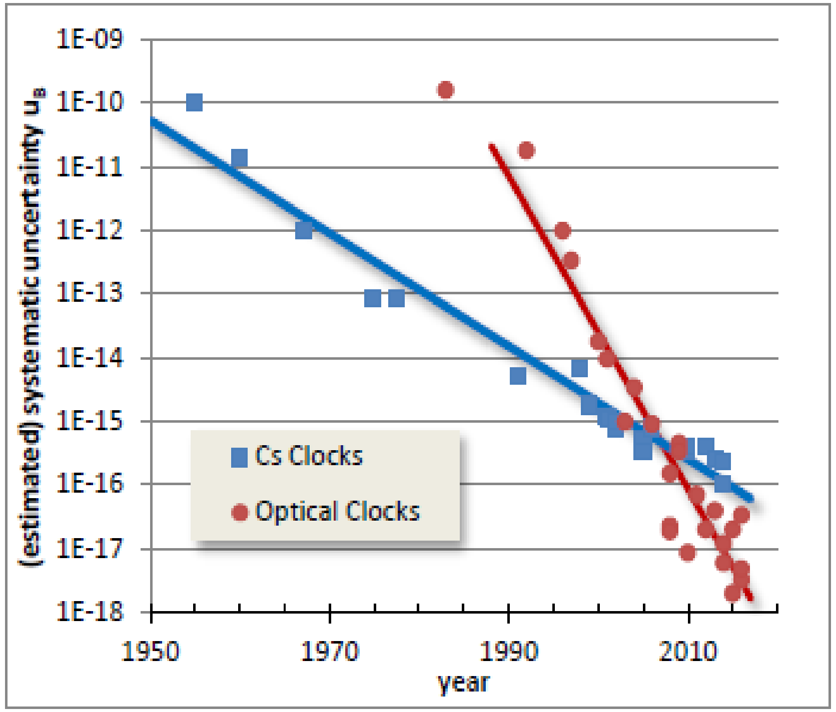
Sr+, Yb+, Ca+, Hg+, Al+ (Quantum Logic)

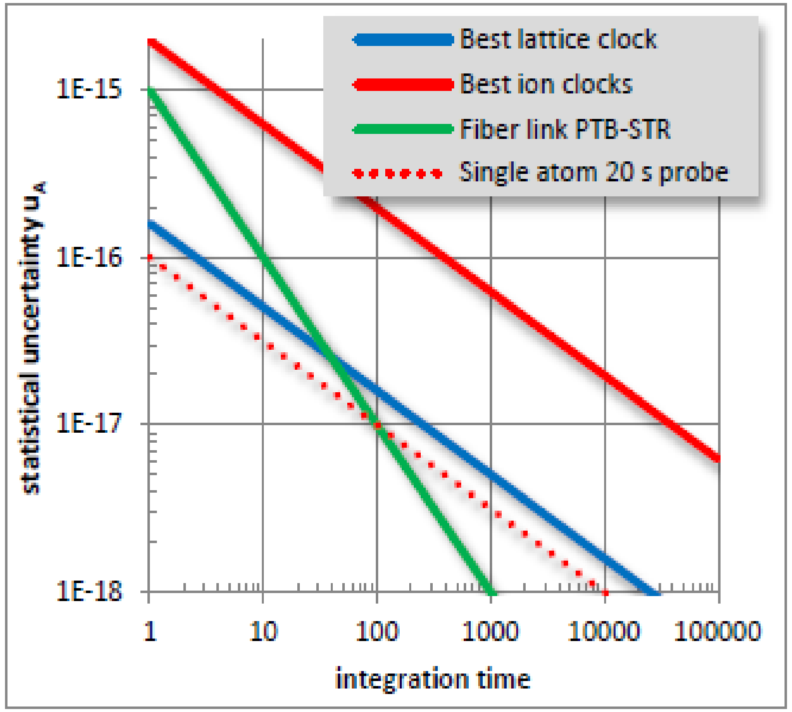
Neutral Lattice standards

Sr, Yb, Hg, Mg, ….

Performance Evolution

Report on Progress in Physics, Vol 81, No. 6, 2018





Historical development of clock Inaccuracies (systematic uncertainty) for Cs microwave clocks and some of the most accurate optical frequency standards.

Typical instability (Allan Deviation) for
-single ion (Al+, Chou et al 2010) [Red]
-single-ensemble neutral atom lattice clocks [Sr-lattice – blue]
-Al-Masoudi et al., (2015)
-Nicholson et al, (2012)
-instability given by MDEV of a 1400km fiber link between PTB and Strasbourg (Raupach et al,2015) [Green]

Principal sub-system elements

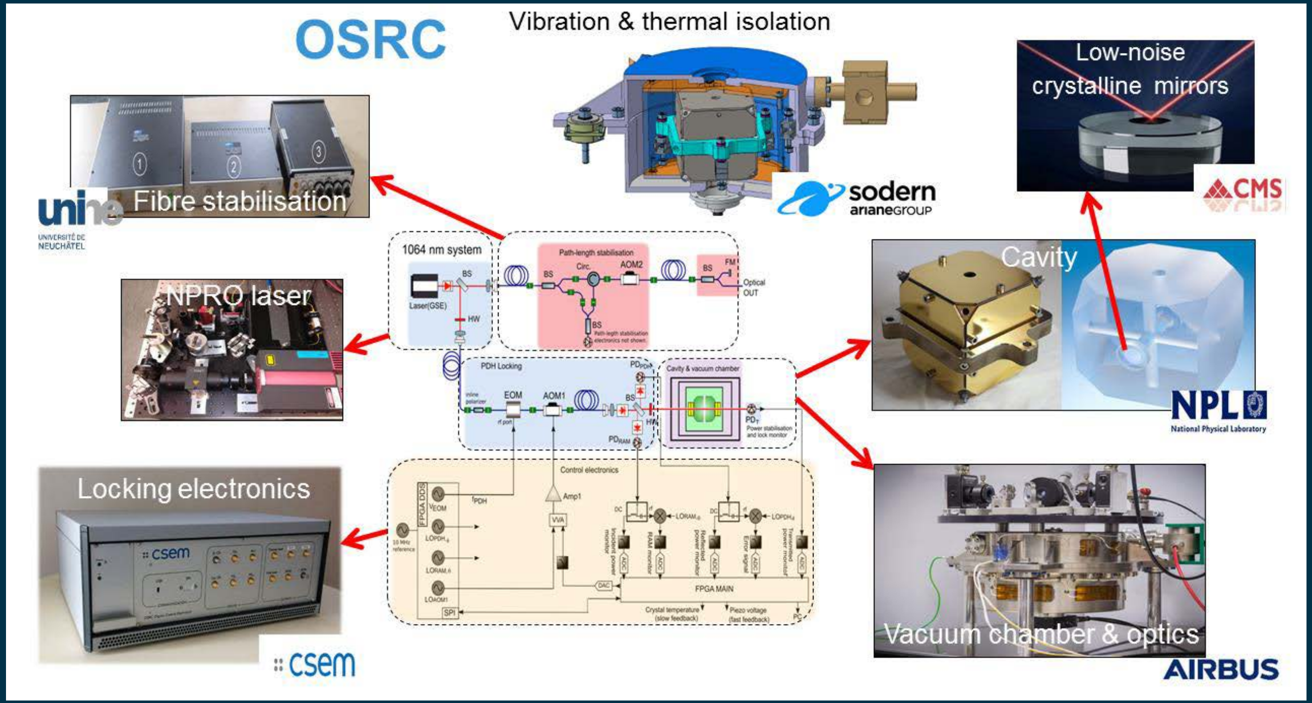
- Optical Stabilising Reference Cavity (OSRC) (<Hz linewidth lasers)
  - Vibration/acceleration insensitive opto mechanical system
- Laser frequency control Unit
  - Wavelength knowledge, frequency drift and duty cycle control
- Cooling and trapping lasers; to prepare and control atomic medium (neutral or ion)
- Optical frequency Comb
  - Phase coherent link between 100’s THz and countable frequency
- Atomic Reference Unit (ARU)
  - [MOT (Blue & Red) + Lattice trap / Ion trap system] in vacuum

OSRC-1 SYSTEM LAYOUT

OSRC EM in ESTEC, February 2020

EM = Engineering Model
TRL = 6

Full OSRC system layout

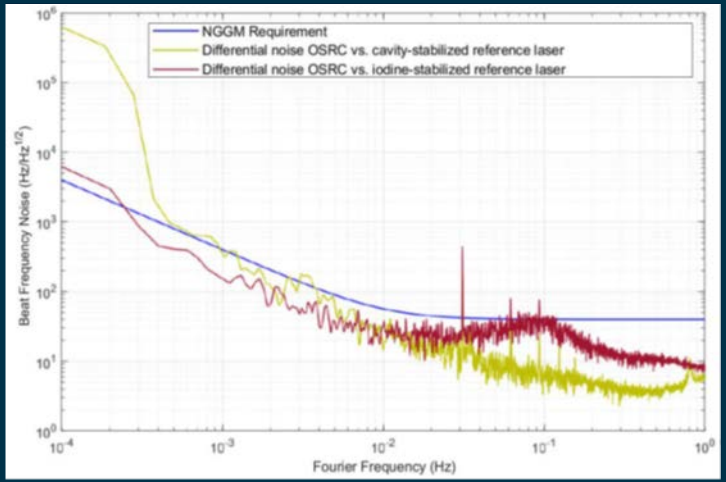


Seven (7) nation OSRC consortium; D, A, F, I, IRL, CH, UK

OSRC Engineering Model:Performance

Achievement OSRC-1

NSD performance after Environmental tests



Final optical test on OSRC-1

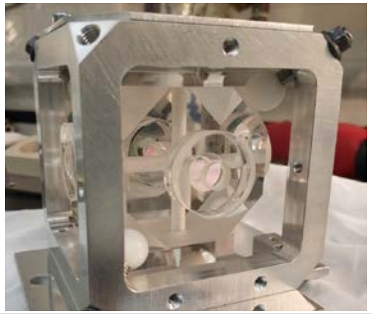
- Completed in November 2019 @ Airbus D&S
  - Performance before and after environmental verified
- NGGM, LISA performance requirement verified $30\ Hz/Hz^{1/2}$
- Baseline design for NGGM (Phase A study in preparation)
  - OSRC-1 performance provided as applicable RD on ITT

Construction of OSRC-2

- Strontium (Sr) wavelength (698nm/1396nm) Crystalline mirrors
  - Manufactured
- Cavity spacer for OSRC-2
  - Manufactured and polished
- Update of vacuum conditions
  - In preparation
- Improvement of thermal management
  - In preparation
- Full system evaluation with Sr system
  - Following TRR 2
- Evaluation of early flight opportunity
  - Ongoing

Development of Clock Control Unit CCU
ESA Contract Number: 4000117290 (TRP), TO: E Murphy

- CCU targeted a compact vibration-insensitive optical cubic cavity-stabilized unit for referencing all the cooling and auxiliary lasers for a strontium atom space optical clock
- The dual axis cubic cavity itself is stabilized to Sr clock laser light on one axis
- Cooling / auxiliary wavelengths simultaneously stabilized to orthogonal cavity axis via separately modulated Pound-Drever-Hall discriminants for feedback to lasers
- Complete CCU comprised 2 Eurorack units: cavity/opto-electronics & control electronics units
- CCU transferred in cavity-operational mode to PTB for successful verification of SOW functional performance
- Radiation testing of CCU cavity/opto-electronics unit without performance degradation



Dual-axis cubic cavity in mounting frame

CCU cavity / optoelectronics unit

Recommendations arising from the CCU TRP contract outputs:

- Significant opportunity for evolution of CCU design by making use of the dual-axis ULE cubic cavity to frequency stabilize the clock laser light directly on a very high finesse cavity axis using novel crystalline mirror coatings
- This reduces the requirement for 2 independent reference cavity units to 1, where the leading cubic cavity vibration-insensitivity plays a critical role in the satellite environment
- The CCU results demonstrated some ULE material anisotropy in the orthogonal axes, indicating the need for monitoring of the constancy of the axis-to-axis transfer function
- Improved insulation will also be needed to counter thermal cycling on the satellite platform
- Significant SWaP improvement offered by upgrade from discrete component analogue control circuitry to digital electronics, with latter incorporated into a single cavity unit

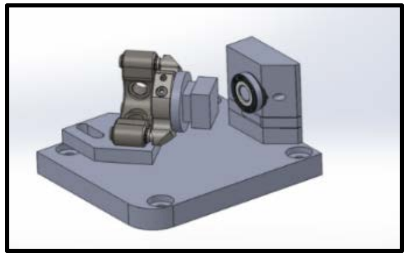
These considerations have led to a **GSTP de-risking design upgrade** proposal recently submitted for ESA evaluation, to feed through to a future CCU MAIT with increased TRL 5/6

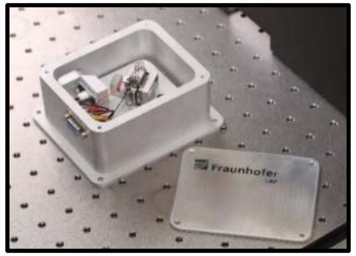
Development of High Reliability lasers at 461nm and 689nm (Sr Lattice) and 422nm (Single trapped Sr Ion) [STOPCLOCS]

ESA Contract Number: 4000116340, TO: E Murphy

Delivered and tested laser systems to specification at 422 nm, 461 nm and 689 nm

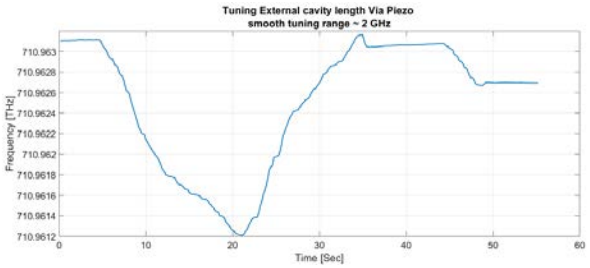
422 nm – GaN EC-diode laser



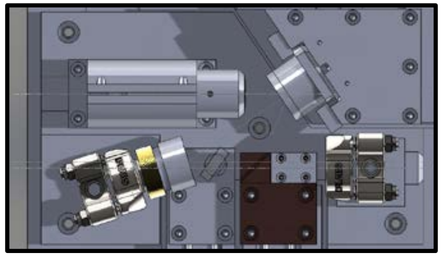


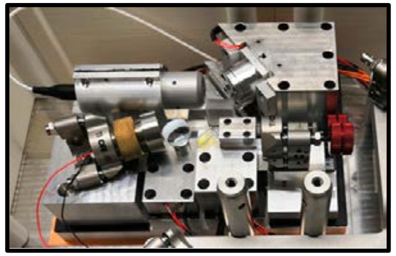
Used custom GaN growth at TopGaN lasers to hit target wavelength directly without frequency doubling using a custom housing.

- 10 mW single-mode fibre coupled single frequency operation.
- 2 GHz smooth tuning observed
- 5 MHz linewidth measured



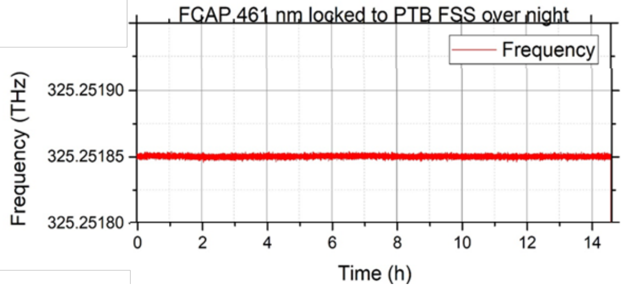
461 nm – frequency doubled SDL



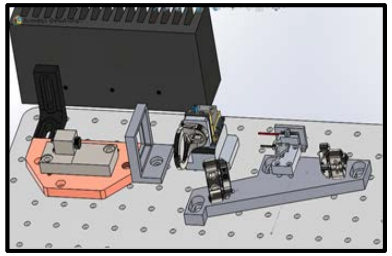


Using high-power thin disk laser, custom epitaxy and intra-cavity frequency doubling to offer high-performance at 461nm in a compact geometry.

- 150 mW single-mode fibre coupled single frequency operation.
- 1.4 GHz smooth tuning observed
- 1 MHz linewidth measured

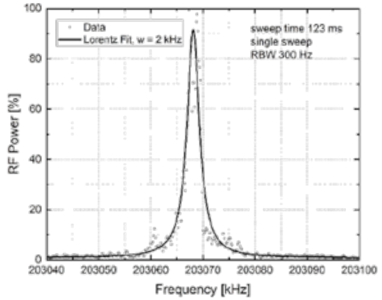


689 nm DPSS Pr doped fluoride



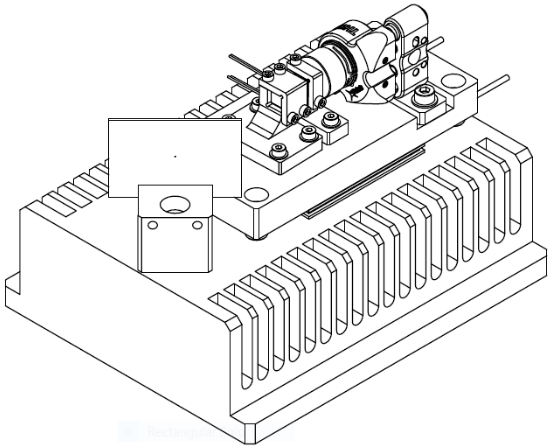
GaN-diode pumped praseodymium laser offers wide spectral output from 680-720 nm suitable for a range of cooling requirements

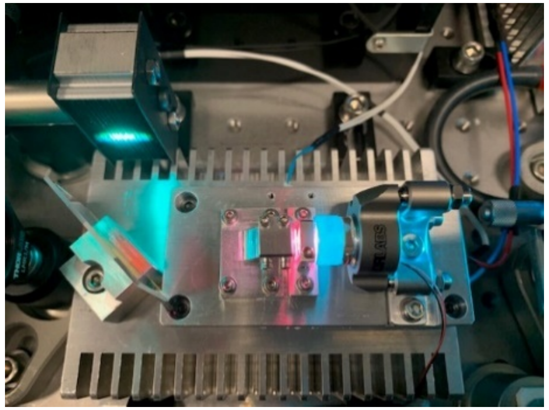
- 140 mW free-space single-frequency operation at 689 nm
- 1.2 GHz smooth tuning observed
- 1 kHz linewidth when locked to CCU



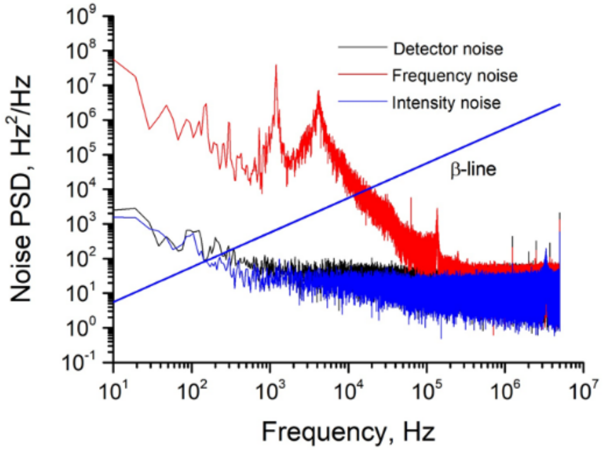
Development of a High Power, High Spectral Purity, red-detuned Lattice laser at 813nm for neutral Strontium [STELLAR]
ESA Contract Number: 4000117717, TO: E Murphy

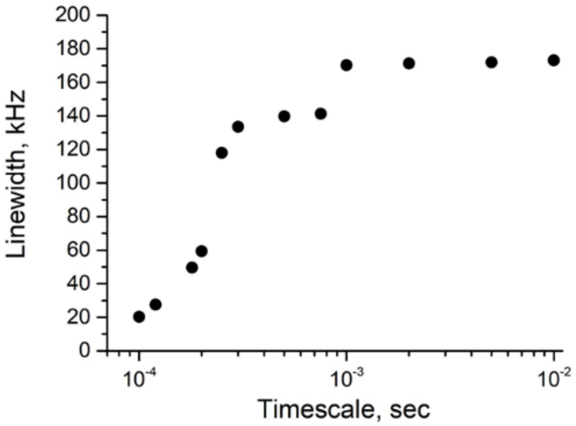
- A novel **microchip laser** architecture based on a **diode-pumped Ti:sapphire** laser has been proposed and implemented.
- **165 mW** output power from a primary fiber port with <1% power stability.
- **+/- 600 MHz** tunability around ν_{mag}
- **< 2 MHz** frequency drift.
- **100 kHz** linewidth (**35 kHz** when locked to the lattice cavity at SYRTE).
- The total laser noise is sufficiently low to ensure atoms lifetime > 1 s in the SYRTE lattice set-up (minimum time necessary to perform spectroscopy).





Frequency noise and linewidth characteristics





Development of a High Power, High Spectral Purity, red-detuned Lattice laser at 813nm for neutral Strontium [STELLAR]
ESA Contract Number: 4000117717, TO: E Murphy

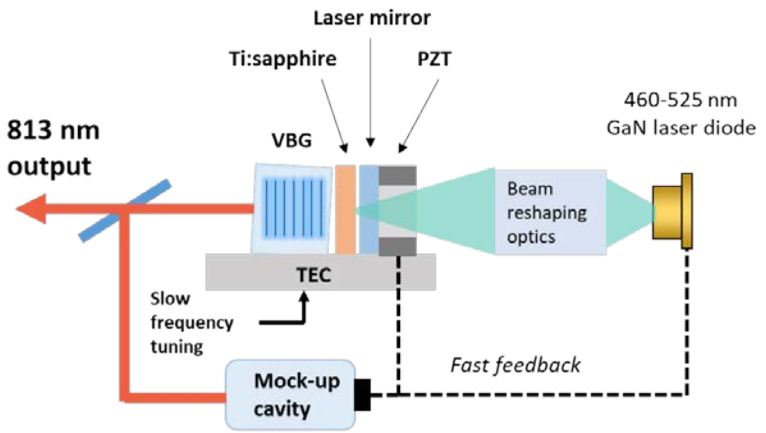
De-risk activity aims to improve the performance of the diode-pumped Ti:sapphire laser at 813 nm further with a new pump module and ruggedised laser cavity design.

This will lead to:

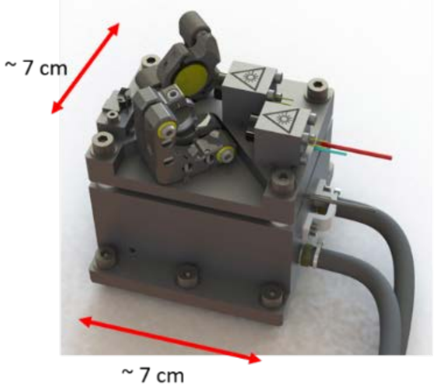
1. Higher average output power.
2. Better frequency stability and narrower linewidth.
3. A factor of 4 reduction in overall system footprint.

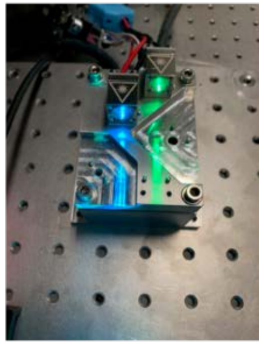
The key de-risk activities:

- Design and test of a highly compact, dual-wavelength pump module.
- Implementation of the improved-design VBG for operation at room temperature.
- Low-weight optical components for faster feedback.
- Implementation of EOM if required for further linewidth reduction.
- Common ruggedised platform and enclosure for the whole system.
- Comprehensive laser characterisation and analysis.



New high-power pump module design





Ultralow-noise lasers for optical atomic clocks

COOL

Compact
Optical
clOck
Laser

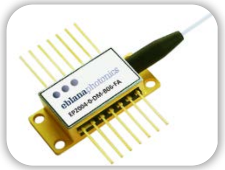
The Need:

Optical atomic clocks & quantum systems require compact low noise lasers

The Solution:

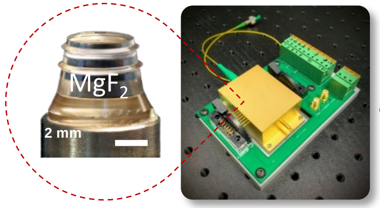
Combine compact lasers from Eblana with MicroR's microresonator technology

COOL Technology



Laser color

Microresonator



eblanaphotonics

MicroR systems

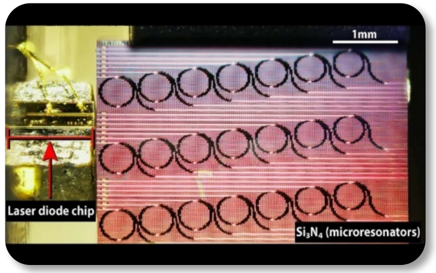
x25 size reduction in a versatile platform

x100 noise reduction

- Eblana provides one of the only sources of high visible quality lasers
- MicroR's microresonator are some of the narrowest optical filters that exist

COOL Future

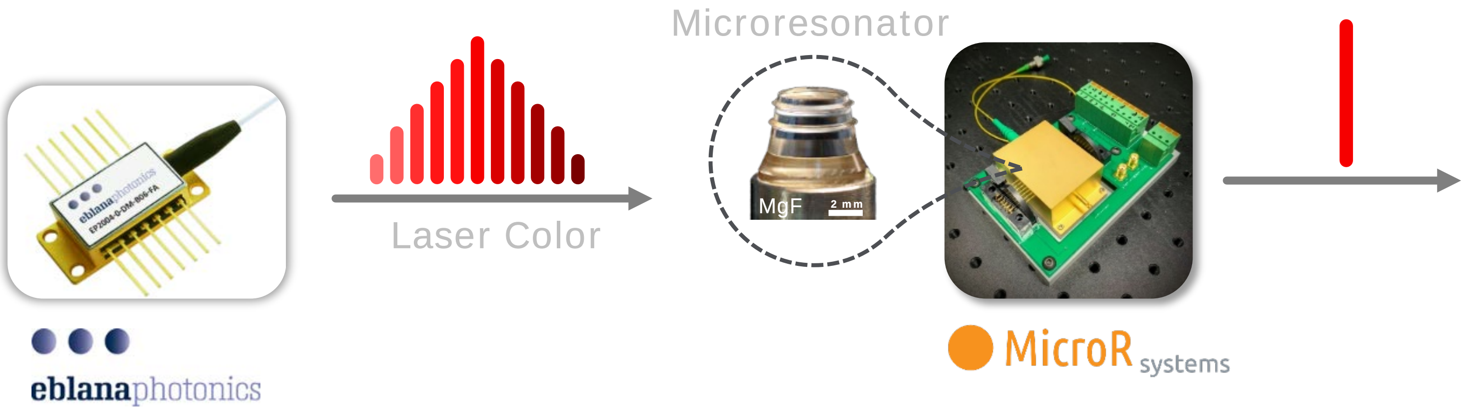
- Combine lasers & microresonators to create even more compact lasers & frequency combs
- **Applications:** LIDAR, Telecom, Clocks

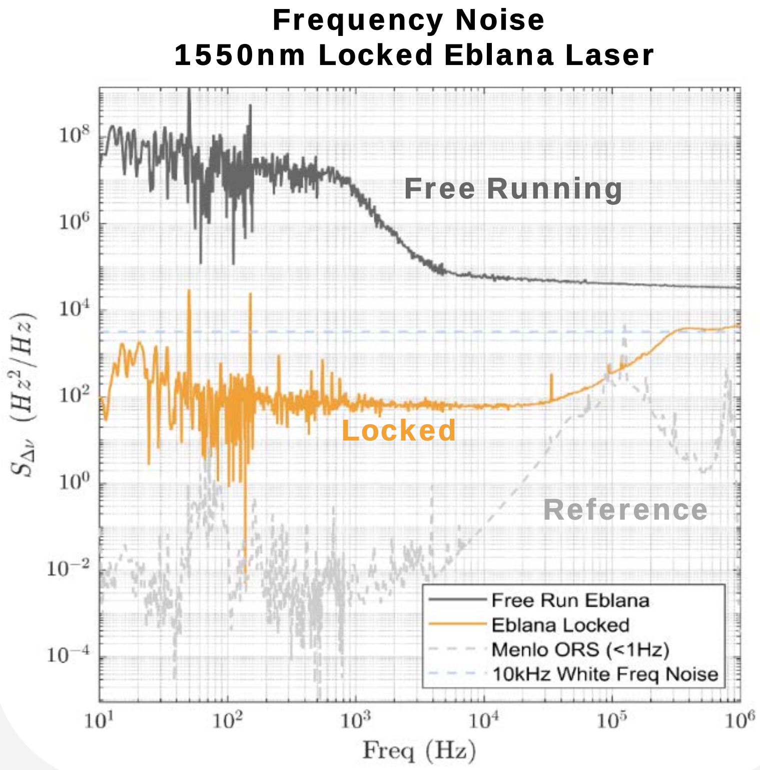


MicroR systems

Contact: john.jost@microrsystems.com

COOL Technology





COOL Results

- Demonstrated 200 Hz linewidth 1550nm Laser system using servo control
- Working towards 689nm system
- Demonstrated Microresonators with quality factors of 10^8 at 689nm

x25 size reduction in a versatile platform

>x100 noise reduction

Contact: john.jost@microrsystems.com

EPFL

esa
European Space Agency

Microcomb applications

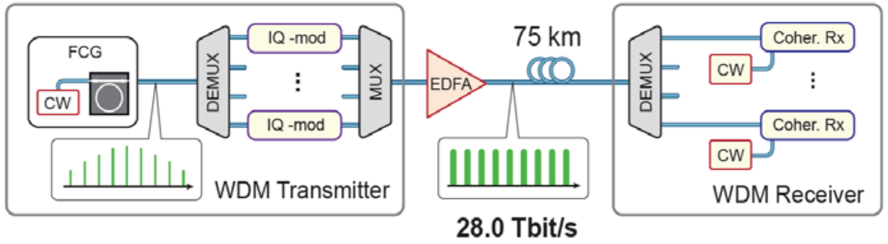
1 m

5 mm

State of the art 2020:

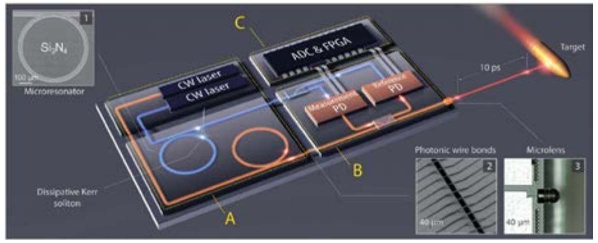
System-level demonstrations:

Telecommunication >50 Tbit/s



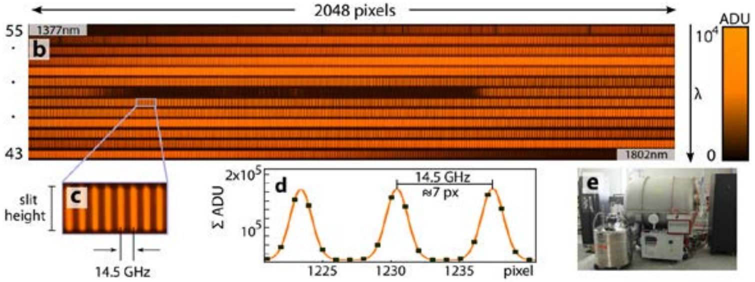
Marin-Palomo et al., Nature, 2017

Ultrafast LIDAR



Trocha et al., Science, 2018

Astronomical spectrometer calibration:



Obzrud et al., Nat. Phot, 2019

Patents: include fabrication of ultralow-loss microresonators, comb and soliton generations, soliton applications

- **Waveguide fabrication method (Photonic Damascene process)** US62/156,923, T. Kippenberg, M.Pfeiffer, A. Kordts
- **Single and multiple soliton generation device and method**, US10270529B2, M. Karpov, V. Brasch, T. Kippenberg
- **Generating optical pulses via a soliton state of an optical microresonator**, US9348194B2, T. Herr, M. Gorodetsky, T.J. Kippenberg,
- **Generating optical pulses via a soliton state of an optical microresonator coupled with a chip based semiconductor laser**, International patent application PCT/EP/2018/075029
- **Signal processing apparatus and method for transmitting and receiving coherent parallel optical signals**, US10651820, T. Kippenberg, C. Koos, P. Palomo, J. Kemal

Common Sub-System Elements

- Matter Wave Interferometry: Rubidium (Rb)
  - Lasers for atom cooling, Raman (780nm)
  - Simplified Offset frequency locks; (OFCG)
  - Magneto Optical Trap (MOT); G-MOT
  - EO modulators, AO modulators; waveguide (where possible)
  - Laser frequency stabilization and drift control; CCU-like system

- Optical Frequency Standard & MWI: Strontium (Sr)
  - Lasers for atom cooling, post cooling, trapping; 461nm, 689nm, 813nm
  - Magneto Optical Trap (MOT); Grating approach extended to new wavelengths
  - EO modulators, AO modulators; waveguide (where possible)
  - Sub Hz laser linewidth reduction at 698nm; Currently OSRC is baseline
  - Amplification at 698nm (MWI) [Required]
  - Laser frequency stabilization and drift control; CCU
  - Micro-Optical Frequency Comb (performance driven)

Projects in preparation / underway

- Sr+ trap – Running
- OSRC-2 (Sr transition at 698nm) – Running [1396/2]
- Waveguide EO modulators – Implementation at 780nm
- CCU-MWU (Engineering Model) – In planning
- Sr lasers; 674nm – 707nm – In planning
- G-MOT at Sr blue(461nm) & Red (689nm) – In planning
- Active ARU [NPI study with NBI Copenhagen]

ESA Agenda 2025 - published 7 April 2021

ESA Agenda 2025

“ESA will immediately launch three new technology R&D initiatives on innovative propulsion, in-orbit servicing and construction, and quantum technologies.”

www.esa.int/About_Us/Introducing_ESA_Agenda_2025

Quantum Technology Cross Cutting Initiative

“Each initiative is focused on a particular theme of interest for the future of the space industry, taking into account the **needs of user programmes and industry** as well as the **potential of technology and R&D**. The implementation of these cross-cutting initiatives **bridges different programmes, technical disciplines and technology levels, encouraging external partnerships**.”

Main Objectives for Quantum Technologies CCI:

- Stimulate ESA internal collaboration
- Boost activities to raise TRL, IOV/IOD and applications for quantum technologies
- Identify and support strategic interests of ESA MS, industry and academia
- Provide increased visibility (internal + external) on ESA quantum activities

Inputs to the Community Roadmap

A Community Roadmap on Cold Atoms in Space:

What does it take to bring Cold Atoms Technologies into Space?

- → The Scientific Case
- → The Technology Roadmap

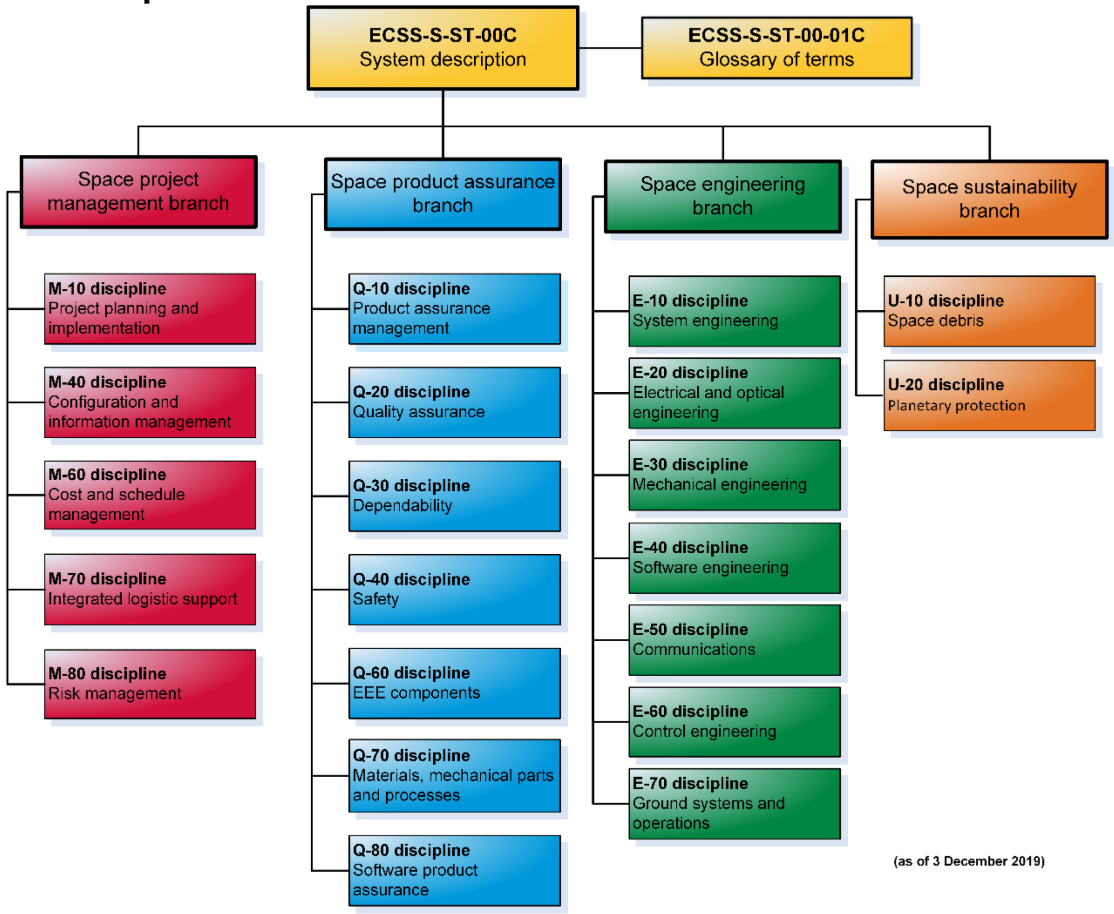
Inputs to the Community Roadmap

The ECSS Standards

- The entry point to any ESA mission
- THE reference for the space community
- Provide applicable requirements in all relevant disciplines
- Describe the methods/processes required for qualification

- Are by definition "generic"
- Have to be tailored to a specific mission
- Are subject to continuous evolution

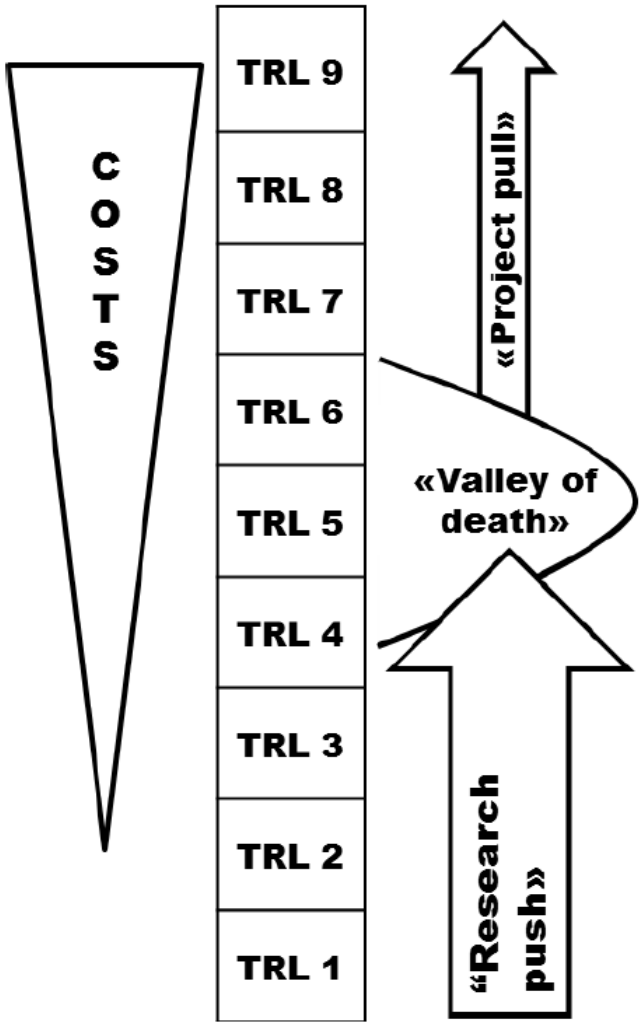
ECSS Disciplines



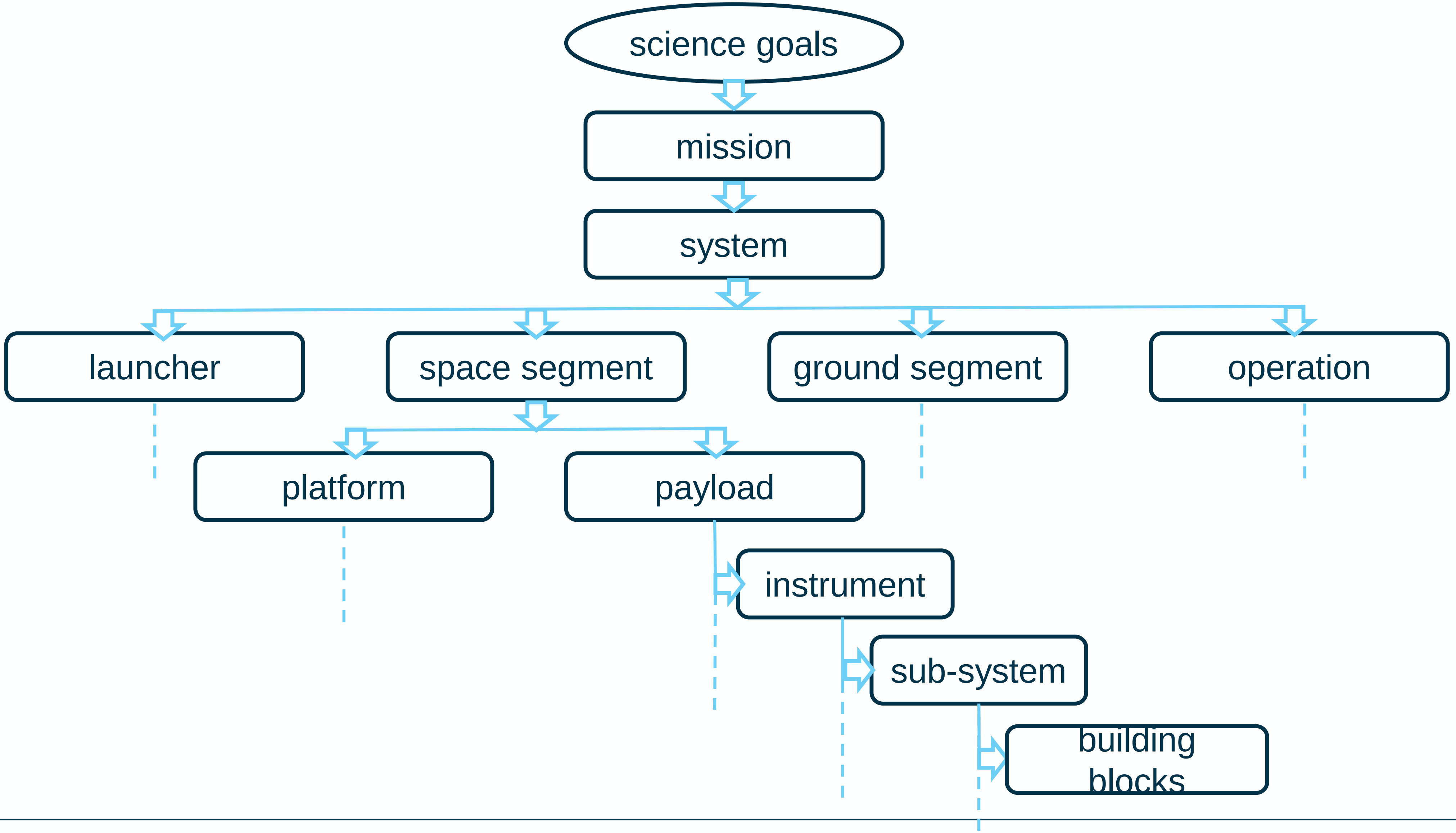
Inputs to the Community Roadmap

The Technology Readiness Levels

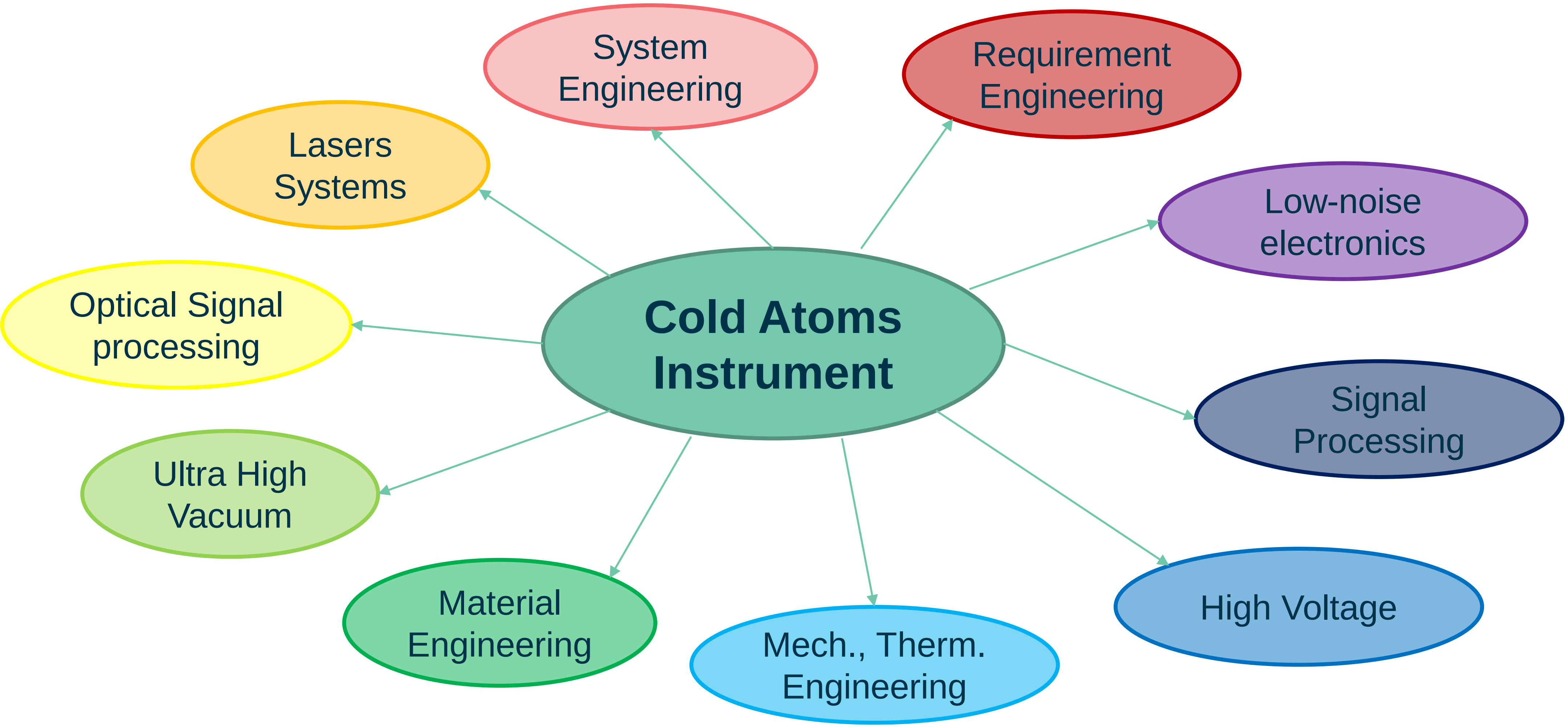
- ISO 16290:2013: Definition of the TRLs and their criteria of assessment
- ECSS-E-AS-11C: Adoption Notice of ISO 16290
- ECSS-E-HB-11A: TRL Guidelines



Inputs to the Community Roadmap



Inputs to the Community Roadmap



Conclusions

- Establish ambitious plans to prepare the foundations for later missions with realistic budgets & schedules
  - C-COOL as a terrestrial vehicle to achieve this
  - Strong science leadership with dedicated industrial involvement & guidance
  - With support from MS's, establish a specific ESA technical program for CAinS
- Explore other possible users for Rb/Sr CAI/MWI payloads; NAV
- Ensure that the Mission TRL is well matched to the new payload technology

- Community Roadmap is an excellent starting point for bringing new technologies into space
- Scientific Case vs. Technology Roadmap
- On Technology:
  - Standards/processes exist and have proven successful
  - Tailoring needed to cover specific mission requirements
  - Multi-disciplinary exercise
- A solid Technology Roadmap is key to future mission success

Thank you for you attention!

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