NEWSLETTER N.9, June 2020

The Quantum Technology Group of Mauro Paternostro at Queen's University Belfast. *Credits: QUB*.

TABLE OF CONTENTS

UPDATE OF WORK DONE - Where we are

On the occasion of the end of the second Reporting Period, we would like to assess the current state of play of the work within TEQ for the period January 2019-Jun 2020.

Work Package 1: Trapping

Yb:YLF nanocrystals (NCs) are now routinely synthesized and can be successfully trapped in optical traps. Current efforts are geared towards (1) controlling the size and shape to control and study their dynamics in the optical trap and (2) increasing the photoluminescence quantum yield (PLQY) to enable optical refrigeration to reduce the internal temperature of the NCs:

(1) Initial attempts to control the size and shape of the NCs by changing the temperature of the NC synthesis were not fully reproducible. Therefore, we moved to a two-step synthesis. First, relatively small NCs of well-defined bipyramidal shape are synthesized. Second, additional precursors are added to induce the growth of a shell of YLF or Yb:YLF around the NCs. This controllably increases the size and also changes the shape, increasing the aspect ratio [see Fig. 1].

(2) We are attempting to increase the PLQY to above 97%, required for optical refrigeration. Our approach is to grow YLF shells without Yb around Yb:YLF NCs, so that the emitting Yb ions are not affected by the NC surface, surfactants and solvent. While this increases the PLQY (from ~60% to ~85%) the increase is not yet sufficient and not fully reproducible. We are currently investigating the causes of PL quenching by systematically varying the Yb concentration and the solvent.

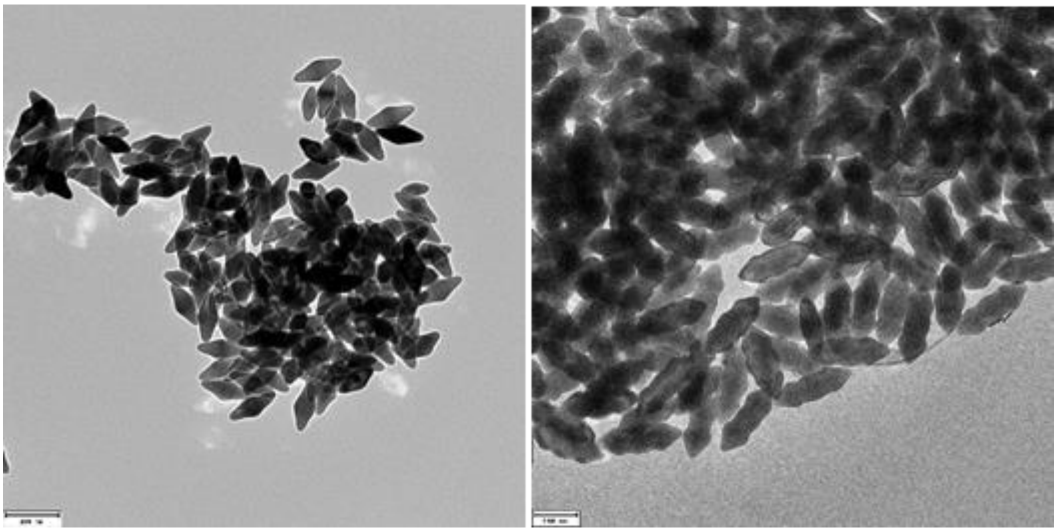

Figure 1. Left : core Yb :YLF NCs, longest axis 165 ± 22 nm, aspect ratio 2.2.

Right :core-shell Yb :YLF@YLF NCs, longest axis 343 ± 47 nm, aspect ratio 3.1.

Concurrently, INFN has designed a completely analog alternative to the digital DC source designed by AU. This source has a 4-times lower noise level (2.2nV/√Hz) and, combined with recently improved low-noise amplifiers, fulfils the noise requirements (25-30nV/√Hz) at the required output voltage (~50V). It is however not used at the moment due its lack of flexibility in dynamics settings, in contrast with its digital somewhat noisier counterpart. A AC+DC power supply with voltage output of 350V, a 100 kHz bandwidth (for frequency tuning of the AC) and low noise (130nV/√Hz) was also designed at INFN. These requirements were met by considerably changing the classical amplifier-mixer-in-cascade approach for a more suitable one. AC and DC inputs are both fed to the same power amplifier, each one with a different gain. The AC+DC output is then relieved of its DC component by filtering. Noise coherency is thus granted, since AC and AC+DC are essentially the same signal.

Also, AU has studied the impact of voltage noise of the radio-frequency (RF) source onto motional heating of an ion. It was found that such noise at the axial trap frequency ω_z can contribute to heating of the trapped particle. Compared to the DC noise spectral density $S_V^{DC}(\omega_z)$, the RF one, $S_V^{RF}(\omega_z)$, contributes though more than 5000 times weaker to axial heating of the particle! It was also found that a phase noise < - 70 dBc is required for efficient loading of the ion probably due to otherwise radial parametric heating.

Finally, silica nanoparticles have been successfully loaded and trapped at ambient pressure and room temperature at UCL, in the blade trap designed by AU [Fig. 2]. Voltage noise of the low noise electronics produced by INFN and AU have been measured and compared to electronics previously used at UCL. Within the frequency region that the trapped nanoparticles oscillate, the new electronics have improved the voltage noise by approximately 2-4 orders of magnitude. Loading of single silica nanoparticles has also been demonstrated with the new electronics and stable trapping down to pressures of 9x10-7 mbar (the limit of the current set-up) has been achieved.

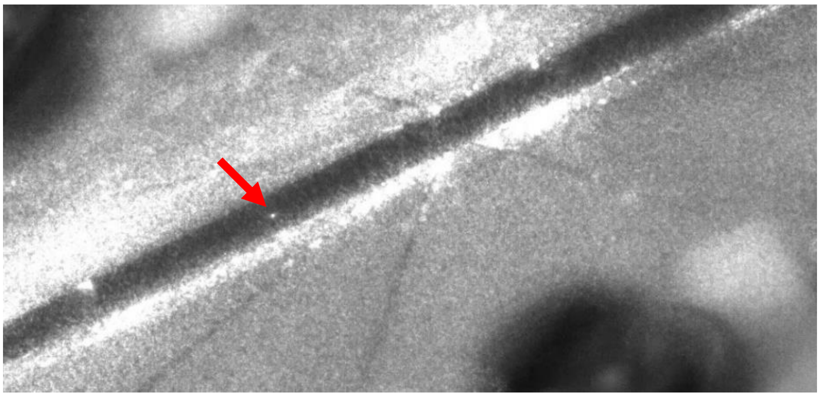

Figure 2. A silica nano-particle trapped in the blade trap.

In parallel, an electrospray source recently built at AU is being tested and will soon be attached to an existing cryogenically cooled ion trap, in which Ba+ ions are now routinely loaded and laser-cooled [Fig. 3]. This system will enable trapping and cooling (via their Coulomb interaction with the directly laser-cooled Ba+ ions) of complex molecular ion species, and might within TEQ be used to study effect of quantum mechanics on a complementary few nm length scale.

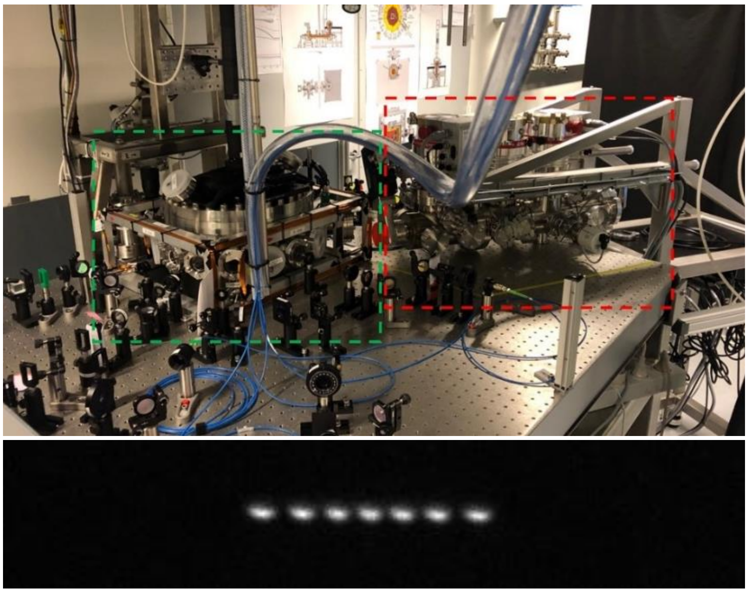

Figure 3. Above: Cryogenically cooled ion trap (green square) and electrospray source (red square) to be used for experiments with complex molecular ions. Also shown are various optical elements used to deliver the light needed to laser cool a co-trapped atomic ion (Ba+). Below: a CCD image of a chain of 7 Ba^{+} ions.

Work Package 2: Cooling

The work on WP2 is a combination of four parts as described in the DoA.

Low-noise electronics: The low noise electronics developed for the Paul trap, including the AC source produced by INFN, and the DAC system (Aarhus) for controlling the DC voltages on the Paul trap has been brought together and implemented into the trap at UCL. First tests confirmed the required low noise at the trap frequencies. However, longer tests of this system where the motional noise/temperature were to measured, were abruptly halted by the shutdown of UCL due to covid-19 on the 17th of March. The shutdown is ongoing but expected to be lifted on the 13th of July.

Centre-of-mass cooling: UoS and UCL have already demonstrated parametric feedback cooling, but more recently, UCL has also implemented and compared both velocity damping and parametric feedback in the Paul trap. This was undertaken to understand which of these schemes is better for cooling to the lowest ultimate temperatures in the TEQ trap. Our experiments have shown a ten-fold improvement using velocity damping and this is backed up by theoretical studies undertaken during the lockdown period when access to the labs has been prevented. Feedback cooling has yet to be implemented in the Paul trapped developed specifically for TEQ by Aarhus. This, however, has been constructed at UCL and this work will be carried out once lab work commences in the later part of July. Both linear and quadratic cavity cooling of a silica nanosphere levitated in the Paul trap has been carried out. It was shown that the quadratic cooling is analogous to parametric feedback cooling where the feedback is automatically applied by the cavity. Similar temperatures in the mK range where obtained but non-thermal distributions are created by this type of cooling. Linear cooling in Paul trap is limited by frequency noise in the laser.

Internal cooling: TUD has continued to develop methods for synthesis of doped Yb:YLF doped crystals. Their measurements have shown increasingly better quantum efficiencies which is required for internal-state cooling via spontaneous anti-Stokes fluorescence. While these particles are still shown to heat in the trap we have verified that undoped YLF particles do not heat and represent one of the few optically trapped particles that can potentially be taken into high vacuum without particle loss due to melting. UCL has implemented velocity damping feedback cooling on these particles but has shown that in an optical trap they become dynamically unstable and are lost from the trap. UCL has modelled this motion and identified the main dynamical features in both linear and circularly polarized light.

Analysis of decoherence: Experiments performed at the lowest pressures have confirmed that the primary source of decoherence for the Paul trap experiments is the motional heating due to electric field noise in the traps. This has been addressed via the electronics developed at INFN, and the trap and electronics at Aarhus. As stated above this will be tested as soon as the lab at UCL reopens in July.

Work Package 3: Testing

In WP3 we have been working to continue the realization of the ultimate TEQ experiment. This has multiple aspects and work was done together with TEQ partners from other WPs. Several meetings were held amongst TEQ partners and many discussions by phone, Skype and email.

A large part of our work on WP3 has been on implementation of the 300 mK cryostat at Southampton and is working to specs (temperature, vacuum, vibration), which has been reported in detail already (see milestone/deliverable reports). The cryo has been finally installed at UoS and we have started to perform tests of mechanical vibrations and other noises. The mechanical noise level in both horizontal and vertical directions is compatible with the noise levels needed to achieve the scientific target of the ultimate TEQ experiment.

Further we have been performing experiments based on magnetic levitation as an alternative realization for the TEQ experiment at UoS and to mitigate risks associated with implementing the ion trap. We have published two papers on the results of the magnetic trap, with one further paper in preparation. A permanent magnet of some ten micrometers in diameter has been levitated above a superconductor, and the particle position was detected by a SQUID. The experiment has already confirmed bounds on CSL at a comparable level with the most recent cantilever experiments. This is a promising route for TEQ and tests can be performed deeper into the CSL parameter space by reducing the size of the magnet by a factor of 5 or so. This is a promising optional route to achieve the scientific targets of TEQ.

Moreover, we have been working together;

- with AU and UCL to define and build the ion trap for the TEQ experiment: The prototype TEQ blade ion trap has been built by AU and assembled by UCL, where also particles have been trapped in the TEQ trap.
- With INFN, UCL and AU to define the electronics for the ion trap: INFN have designed and build low-noise electronics boards for ion traps (DC and AC divers, amplifiers and power supplies) at AU and UCL. Both AU and UCL have detected a significant reduction in electronic noise.
- With UCL and QUB we have been doing a very detailed study of the detection schemes (optical: with and without cavity, SQUID, electrical) for the TEQ experiment, based on experiments done at UCL and UoS. A related report/paper has been published entailing a classical approach to

describe the detection, and QUB are working on a quantum version of this study – which is ultimately needed to understand the performance of the TEQ experiment. It became apparent that all discussed detection techniques have limitations, but the choice is with optical detection. Soon after the study had been completed UCL demonstrated a new detection method based on image reconstruction after CCD detection at low light power and therefore low disturbance of the particles motion by the detector, which has now been identified as the detection technique for the ultimate TEQ experiment at UoS.

- Together with UniTs, we have performed experiment and submitted a paper on testing CSL with a layered mass and have set the so far strongest bounds on CSL model by mechanical oscillators.
- We have performed joint studies with QUB on decoherence of macroscopic quantum states, which is at the heart of the TEQ project. One paper has been published and two more are in preparation.

All of the experimental work on WP3 has come to hold by mid-March 2020 because of laboratory closure under covid-19. Until the writing of this report, work could not be restarted. This has cause a serious delay to all experiments, including the further testing of the cryostat, implementing the trap into the cryostat and testing ideas for particle loading.

Work Package 4: Enabling

The second reporting period of TEQ has seen the work on WP4 focus on the drawing of bounds on paradigmatic models such as the Continuous Spontaneous Localisation (CSL) and the Schrödinger-Newton (SN) ones. The first is one of the simplest yet significant collapse models proposed so far, and embodies the first models against which a theory for falsification of collapse mechanisms should be gauged. Within the context of the non-interferometric tests around which TEQ is built, the UniTs and QUB teams assessed the effects that CSL has on the rotational degrees of freedom of an optomechanical system comprising cylindrical mechanical oscillators trapped both spatially and rotationally. They showed that the angular degrees of freedom offer significant sensitivity to the potential effects of collapse mechanisms, which allow for the setting up of strong bounds on the parameters characterising the model itself. As for the SN model, a phase-space approach has been chosen to go through the evaluation of the effects that such mechanism on the Wigner function of mechanical motion, which is experimentally accessible. The effects entailed by SN are appear to be too weak to be detectable through non- interferometric tests. QUB has then addresses "macroscopicity" in configurations that adhere to the scenarios at the core of TEQ. The team has adopted a measure of macroscopic quantumness based on phase space approaches, which offers good perspectives of experimental implementation bypassing full state tomography. The results gathered through such study showed that the best results, in terms of macroscopic quantumness of a mechanical system, are achieved by subjecting the field driving the mechanical motion to homodyning.

UniTs worked on the development of a model for the description of the dynamics of non -relativistic scalar matter under a weak stochastic perturbation on top of the background Minkowski metric. This study aimed at understanding the quite contradictory results present in the literature about the preferred basis of such a decoherence phenomenon. The team showed that such inconsistencies are only apparent, and that the current literature results can be described as specific limiting cases of the general model developed by the TEQ members. Such model has then been applied to Mach-

Zehnder matter-wave interferometers in order to estimate their sensitivity to scalar gravitational perturbations. The results showed that matter-wave interferometers are a promising avenue for detecting scalar gravitational perturbations.

Further work has addressed tensorial gravitational perturbations, the construction of a multiparticle and three-dimensional model which implements the gravitational interaction through a continuous measurement and feedback mechanism, and the assessment of the effects of collapse mechanism on the power spectrum of the curvature perturbation in an inflationary context.

OEAW and QUB worked on the development of a framework for the operational definition of events and their localisation with respect to a quantum-clock reference frame in the presence of gravitating quantum systems. The teams found that, when clocks interact gravitationally, the temporal localisation of events becomes dependent on the reference frame. This relativity is a signature of an indefinite metric, where events can occur in an indefinite causal order.

Work Package 5: Management

The management duties of the project were shared among the partners coordinated by the WP Leader and assisted by the WP Co-Leader with the support of the Administrative Officer. Overall, the management of the second reporting period went smoothly and was effective and efficient as the first reporting period. No adjustments were needed in the management structure.

The Steering Committee physically met twice during the year 2019 and planned one physical meeting during the first semester 2020:

- February 2019 (Month 14): the Steering Committee has met in Brussels the day before the Review Meeting to prepare and discuss management issues.
- September 2019 (Month 21): following the Workshop "Redefining the foundation of physics in the quantum technology era" held in Trieste in September 2019, the Steering Committee members have met to discuss management and dissemination issues. After that, project members held a meeting to update on developments of setting up the TEQ experiments and its components,
- May 2020 (Month 29): a project meeting was planned to be held at Aarhus University. It was planned to dedicate a full day to young members of the Consortium to present the results for their research and to further discuss the progresses of the TEQ experiments and theory. The second day would be dedicated to management issues in view of the project second reporting period. This meeting has been cancelled due to COVID-19 emergency.

The team of the University of Trieste (Coordinator) continues to keep the project website up-to-date, in particular the sections regarding News, Activities, Dissemination and Publications, thanks to the common efforts of the partners to share updated information within the Consortium.

Work Package 6: Dissemination

The dissemination of the project was carried out by all the partners coordinated by the WP Leader, assisted by the Co-Leader and supported by the TEQ Administrative Officer and the press offices of the partners. These figures are assisted by the Website Manager, the Social Media Manager, the Consortium Press Officer and the Dissemination & Publication Manager who have been actively worked in close cooperation with each other to ensure an effective dissemination of TEQ and its findings.

The partners promoted the dissemination of TEQ and its findings, specifically press articles and dissemination events.

During the year 2019 and first semester 2020, a total of 9 articles on paper and on-line popular press have been published, mentioning not only the scientific progresses and achievements of the project but also TEQ's side events and communication activities. We are particularly proud of a feature article on the New York Times Magazine (June 25, 2020), written by Bob Henderson, which is professional and personal portrait of Angelo Bassi, professor of Physics at the University of Trieste, as well as leading scientist in the foundations of Quantum Mechanics and PI of TEQ. A Press Release about this can be found on the TEQ website.

In the frame of communication targeting the general public, the Quantum Café initiative was organized again but the University of Trieste in the spring and in the fall of 2019, following the success of the 2018 edition, with the aim of offering an interdisciplinary and inclusive experience combining science, music and theatre to enhance public participation in the scientific arena and in the field of quantum mechanics, in particular. The spring 2020 edition was also planned but had to be postponed to the fall 2020 because of the COVID-19 crisis.

To ensure that all this information is stored and shared, the Publications and Dissemination Manager collects quarterly updates from the partners about publications, various news and dissemination activities to keep the project website up-to-date while having ready and updated information for the project Newsletters.
Moreover, besides Facebook and Twitter pages, the social media activity of the project was enriched by the creation of a Linkedin profile in June 2019 that shares scientific endeavors, news and publications while connecting with relevant stakeholders.

As part of the broader communication strategy of the project with the aim of promoting external communication to targeted audiences, the project team created a project video trailer. The video combines interviews and video footages from the labs explaining the project in a scientific while accessible way to the general public, the scientific community and funding agencies. The final product is available for all project teams to distribute and disseminate through their channels as a project presentation. The creation of the video is illustrated in the Deliverable report 6.3.
Furthermore, as stated in the proposal and with the aim of disseminating the first results of the TEQ research and of engaging the larger community of physicists, the Workshop "Redefining the foundations of physics in the quantum technology era" was held in Trieste from 16 to 19 September 2019. The Workshop gathered relevant experts in the field of quantum physics combining junior and senior researchers who shared the results of their studies and discussed outcomes. The first results of the TEQ research were successfully disseminated among interested stakeholders and raised much interest.

More specific data about talks can be found below.

PUBLICATIONS

(for more info, please go to www.tequantum.eu, in 'Documents' → 'Dissemination')

Authors	Title	Journal	Volume	Pages	Year
Vinante, A., P. Falferi, G. Gasbarri, A. Setter, C. Timberlake, and H. Ulbricht	Ultralow Mechanical Damping with Meissner-Levitated Ferromagnetic Microparticles	Phys. Rev. Applied	13	064027	2020
Toroš, Marko, Sara Restuccia, Graham M. Gibson, Marion Cromb, Hendrik Ulbricht, Miles Padgett, and Daniele Faccio	Revealing and concealing entanglement with noninertial motion	Phys. Rev. A	101	043837	2020
Castro-Ruiz, Esteban, Flaminia Giacomini, Alessio Belenchia, and Časlav Brukner	Quantum clocks and the temporal localisability of events in the presence of gravitating quantum systems	Nature Communications	11	2672	2020
Baumann, V., and Č. Brukner	Wigner's friend as a rational agent	Quantum Probability, Logic By Springer Link		91-99	2020
Mulder, Jence T., Nicholas Kirkwood, Luca De Trizio, Chen Li, Sara Bals, Liberato Manna, and Arjan J. Houtepen	Developing Lattice Matched ZnMgSe Shells on InZnP Quantum Dots for Phosphor Applications Developing Lattice Matched ZnMgSe Shells on InZnP Quantum Dots for Phosphor Applications	ACS Applied Nano Materials	3	3859-3867	2020
Adler, Stephen L., Angelo Bassi, and Luca Ferialdi	Minimum measurement time: lower bound on the frequency cutoff for collapse models	Journal of Physics A: Mathematical and Theoretical	53		2020
Piscicchia, K., E. Milotti, Amirkhani, and et al.	Searches for the Violation of Pauli Exclusion Principle at	The European Physical Journal C	80	508	2020

	LNGS in VIP(-2) experiment				
De Paolis, L, A Amirkhani, S Bartalucci, S Bertolucci, M Bazzi, et al.	The key role of the Silicon Drift Detectors in testing the Pauli Exclusion Principle for electrons: the VIP-2 experiment	Journal of Physics: Conference Series	1548		2020

DISSEMINATION ACTIVITIES – Where we are

(for more info, please go to www.tequantum.eu, in 'Documents' → 'Dissemination')

During the second Reporting Period (1.1.2019 – 30.6.2020), the dissemination activities held were a total of **149**, addressing over **10 000 people**. During the COVID-19 emergency in early 2020, dissemination activities were held online in the forms of webinars and remote seminars. **67** talks were given to academic audiences, **43** lectures were given to high-school students and teachers while **39** presentations were delivered to the general public.

A detailed list of all talks can be found on the TEQ Website.

ANY OTHER RELEVANT INFORMATION

Angelo Bassi featured on The New York Times

On 25th June 2020 the New York Times published a feature article, written by Bob Henderson, which is professional and personal portrait of Angelo Bassi, professor of Physics at the University of Trieste, as well as leading scientist in the foundations of Quantum Mechanics and PI of the TEQ project.
The results achieved so far by Professor Bassi have already appeared in various scientific journals in the sector, including the prestigious journals *Science* and, for dissemination, *Scientific American*. The article now published in the New York Times Magazine is further recognition of the scientific importance of this research. "Even if the world is ultimately not understandable, there is no reason to believe we have hit the bottom with quantum mechanics", says Professor Bassi in the article who, on the strength of this belief, dedicated the last fifteen years of his research to study models and propose new ideas to verify how quantum mechanics can be falsified.
The article explains how quantum mechanics allows microscopic objects to be simultaneously in two different states that "collapse" in one of the two only when the system is observed. As summarized in the famous and provocative paradox proposed by Schrödinger, the theory predicts that the same thing can happen to a cat locked in a box, which could be alive and dead at the same time, until the moment someone opens the box and "collapses" its state. Professor Bassi's research is focused on alternative models, known as *spontaneous wave function collapse models*, whereby microscopic systems can live in multiple states at the same time, while macroscopic objects are always in well-defined states, contrary to what is foreseen by quantum theory.

Full article at the link:
https://www-nytimes-com.cdn.ampproject.org/c/s/www.nytimes.com/2020/06/25/magazine/angelo-bassi-quantum-mechanic.amp.html

TEQ on the EU Innovation Radar

The TEQ team is delighetd to announce that one of the innovations developed in the project has been analysed by the European Commission's Innovation Radar. Details of this innovation, and how it was categorised by the analysis, are as follows:

- **Innovation Title:** Spectroscopy and characterisation of an isolated single particle held in vacuum.;
- **Market Maturity of the Innovation:** 'Exploring' (based on a method described in this paper);
- **Market Creation Potential of the innovation:** Addresses needs of existing markets.

The Innovation Radar identified as a 'Key Innovator' in the development of this innovation the partners University College London and University of Southampton.
This information will be published on the European Commission's Innovation Radar platform from 20 July 2020, joining the 3600+ EU-funded innovations already showcased on the platform.

TEQ Consortium member Andrea Vinante to start permanent position at CNR Trento

Dr Andrea Vinante, TEQ Consortium member and postDoc at the University of Southampton, has secured a permanent position at CNR Trento (IT) where he is to start on July 1, 2020. Dr Vinante has been working with the Southampton team on the installation and testing of the 300 mK cryostat which will host the low noise TEQ experiment. This career advancement is a great acknowledgement of the value of the work of Dr Vinante and more generally of the whole TEQ team.

Reboot of TEQ experiments after COVID-19 lockdown

TEQ partners have met on June 23 to discuss the rebooting of TEQ experiments at different partner institutions after the COVID-19 lockdown, update on situation in laboratories at each partner institution, discuss opportunities for joint publications based on existing data, coordinate the next steps of experiments and possible redistribution of tasks across the consortium team. The meeting will be held remotely.

Agenda:
- Update on situation of labs at different institutions
- Next technical challenges
- Reporting documents for Reporting Period II
- News and AOB

Participants:
INFN: Catalina Curceanu, Massimiliano Bazzi
AU: Michael Drewsen, Cyrille Solaro
UCL: Peter Barker, Thomas Penny
Soton: Hendrik Ulbricht, Antonio Pontin, Andrea Vinante, Christopher Timberlake,
TUD: Arjan Houtepen, Liberato Manna