EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Brussels, 23 June 2017

COST 032/17

DECISION

Subject: **Memorandum of Understanding for the implementation of the COST Action "Quantum Technologies with Ultra-Cold Atoms" (AtomQTech) CA16221**

The COST Member Countries and/or the COST Cooperating State will find attached the Memorandum of Understanding for the COST Action Quantum Technologies with Ultra-Cold Atoms approved by the Committee of Senior Officials through written procedure on 23 June 2017.

MEMORANDUM OF UNDERSTANDING

For the implementation of a COST Action designated as

COST Action CA16221
QUANTUM TECHNOLOGIES WITH ULTRA-COLD ATOMS (AtomQTech)

The COST Member Countries and/or the COST Cooperating State, accepting the present Memorandum of Understanding (MoU) wish to undertake joint activities of mutual interest and declare their common intention to participate in the COST Action (the Action), referred to above and described in the Technical Annex of this MoU.

The Action will be carried out in accordance with the set of COST Implementation Rules approved by the Committee of Senior Officials (CSO), or any new document amending or replacing them:

a. “Rules for Participation in and Implementation of COST Activities” (COST 132/14);
b. “COST Action Proposal Submission, Evaluation, Selection and Approval” (COST 133/14);
c. “COST Action Management, Monitoring and Final Assessment” (COST 134/14);
d. “COST International Cooperation and Specific Organisations Participation” (COST 135/14).

The main aim and objective of the Action is to explore quantum technology with ultra-cold atoms and exploit it in real-life applications like gravimetry and inertial navigation, and in fundamental applications such as precision measurements and the search for violation of the standard model. This will be achieved through the specific objectives detailed in the Technical Annex.

The economic dimension of the activities carried out under the Action has been estimated, on the basis of information available during the planning of the Action, at EUR 48 million in 2016.

The MoU will enter into force once at least five (5) COST Member Countries and/or COST Cooperating State have accepted it, and the corresponding Management Committee Members have been appointed, as described in the CSO Decision COST 134/14.

The COST Action will start from the date of the first Management Committee meeting and shall be implemented for a period of four (4) years, unless an extension is approved by the CSO following the procedure described in the CSO Decision COST 134/14.

TECHNICAL ANNEX

OVERVIEW

Summary

AtomQT aims at putting Europe in the pole position in the race towards the **Second Quantum Revolution**. AtomQT's mission is the creation of a large network of expert groups on cold-atom quantum physics that will **act as a catalyst in the rapid development and commercialization of quantum technology** based on ultra-cold atoms and Bose-Einstein condensates.

The vision is to establish **Europe as the leader both in fundamental research as well as real-world commercial products** that will harness the unique quantum mechanical features of cold atomic ensembles. This will lead to groundbreaking advances in amongst others metrology, cryptography, communications and computations, biology, and geology. AtomQT will contribute to this development by providing a **crucial platform for information exchange and coordination** of research. It will also be the catalyst for the fledgling quantum industry.

A further priority of the AtomQT network will be **outreach**. The education of the general public and the information provided to policy and decision makers and (inter)national regulatory bodies will facilitate considerably the progress of the second quantum revolution and ensure its long term viability.

Areas of Expertise Relevant for the Action	**Keywords**
● Physical Sciences: Ultra-cold atoms and molecules ● Physical Sciences: Quantum physics ● Physical Sciences: Metrology and measurement (theory)	● Quantum Technologies ● Ultra-Cold Atoms ● Quantum Sensors and Applications

Specific Objectives

To achieve the main objective described in this MoU, the following specific objectives shall be accomplished:

Research Coordination

● Coordinate the research activity among units and research areas working on topics relevant for quantum technologies with cold atoms.

● Foster the interchange between academia and industry in order to advance the development and adoption of quantum technologies with cold atoms.

● Provide input for future market applications of quantum technologies.

● Disseminate research results to the general public and to stakolders in the field of cold atom quantum technology.

Capacity Building

● Training the next generation of cold-atom quantum physicists.

● Improving Capacity through Communication: AtomQTech puts it as one of its objectives to provide a communication platform for established and new groups. This will be achieved through a series of conferences, through its website and through a series of topical meetings.

1. S&T EXCELLENCE

1.1. CHALLENGE

1.1.1. DESCRIPTION OF THE CHALLENGE (MAIN AIM)

The unprecedented level of preparation, manipulation, control and detection of quantum systems achieved during the last few years has positioned quantum technology as one of the most relevant emerging technologies. Within this field, ultracold atoms are the prime technology for many applications such as atomtronics, quantum simulators, quantum information and quantum metrology. They are also an ideal testbed for other fields like quantum computing and simulation. Ultracold atoms are already opening promising markets in inertial navigation (essential for GPS-denied environments), computation, biomagnetic imaging, and ground surveys for mineral exploration, construction and archaeology.
The Main Challenge of the COST Action Quantum Technologies with Ultra-Cold Atoms (AtomQTech) is to ***explore quantum technology*** with ultra-cold atoms and to ***exploit it in real-life*** applications like gravimetry and inertial navigation and in ***fundamental applications*** such as precision measurements and the search for violation of the standard model.
The Quantum Industrial Challenge lies in exploiting the opportunities of afforded by quantum mechanics by combining ***real industrial interest*** with the ***fundamental research***. The first companies (some of which are co-proposers of AtomQTech) are already entering the market with real quantum products. A recent survey[1] shows that the European industry's interest in quantum technologies, from big companies is growing. There is strong commercial interest in macroscopic quantum devices such as quantum gravimeters for oil exploration or long-distance quantum cryptography systems, or even complete Bose-Einstein Condensate machines. However, to sustain this newly found momentum, the community need to invest in more efficient communication between academia and industry.
The Human-Resource Challenge lies in the fact that there is a considerable shortage of qualified quantum technology experts. Much more investment in the training of people to seize intellectual potential is needed. The full range of geographic, age and gender opportunities must be utilised.
The European Challenge is not to be left behind in this rapidly advancing field. The recently announced FET-Flagship on Quantum Technologies is a huge step in this direction. However, it needs to be accompanied by actions to ***coordinate the research and disseminate the results***. For the rather narrow field of "Quantum Technologies in Space" there is a relatively new cost Action (QTSpace). This leaves open the Atom Quantum Technologies with fundamental or "real-world" applications, which is exactly what AtomQTech aims to address. Even though AtomQTech's interest lies mainly in earthbound applications, AtomQTech will also aim to support and synergise with QTSpace in questions of Atom Quantum Technologies.

1.1.2. RELEVANCE AND TIMELINESS

Timeliness: Quantum Mechanics gave us a theory to describe the ***microscopic world*** with astonishing accuracy. Its impact touched all aspects of our lives, from computers to lasers and medical imaging. This, however, is only the beginning. The challenge now is to tackle the ***macroscopic quantum world***.[2] We have learned only recently how to produce pure quantum

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[1] Quantum Technologies - Opportunities for European industry: Report on a round table discussion and stakeholder meeting, published on 14/12/2015 (link)
[2] J.P. Dowling and G.J. Milburn Phil. Trans. R. Soc. Lond. A 361:1809 1655--1674 (2003)

objects, with millions of atoms, that are in superposition or in entangled states, and how to perform quantum assisted measurements at an unprecedented level of accuracy. Quantum Mechanics is only now starting to make a direct impact in other sciences and is just starting to find its way into real-life applications. The AtomQTech Action has to be seen in the context of a major move towards the application of quantum technologies. The UK is operating a £270M research programme into QT and the EU recently launched a 1B€ FET-Flagship on quantum technologies. AtomQTech aims at serving as a central communication hub in this major move.
Relevance to Europe: In many regions of the world, manufacturing and labour costs are much lower than in Europe. To remain competitive, Europe can only rely on innovation and its ability to transition fast from basic research to high-tech products. Other countries are already heavily investing in quantum technologies: China, for example, is home to the world's largest atomic fountain and one of the most precise atom gravimeters and has made cold atoms a strategic priority.[3] Similarly, the United States have a very strong research programme in quantum applications, which is mostly funded by the US military but also by industry. Europe is the leader in many aspects of the research and application of Quantum Mechanics, especially with ultra-cold atoms and interferometry. This COST Action aims at taking advantage of Europe's role as a world-leader in the field of quantum technologies based on ultracold atoms and at aiding the transfer of this knowledge into real-world designs of new quantum devices.
Relevance of the technology: Cold atoms are invaluable tools in quantum applications because of their unique quantum behaviour and exquisite sensitivity. Much of the basic research underpinning many quantum technologies – such as quantum memory, communication and processing – has been performed in this arena. Many of these technologies are being miniaturised with the aim of taking them out of the laboratory and into commercial devices. Examples include miniature gravimeters,[4] inertial navigation[5] and magnetometers[6]. The emerging area of atomtronics is expected to speed up this process considerably.
Cold atom technologies are having a major impact also on our understanding of some of the most pressing questions facing physics by probing the fundamental laws of nature at an unprecedented accuracy. Examples include Einstein's special and general relativity (equivalence principle, gravitational waves), the constancy of fundamental physical constants, and extensions of the Standard Model. Some of this can be done by table-top experiments, other challenges need larger infrastructures, which require support of Europe as a whole. This will create a lasting focal point, which can be exploited also by researchers from smaller European states.

1.2. SPECIFIC OBJECTIVES

1.2.1. RESEARCH COORDINATION OBJECTIVES

Objective 1.1) Coordinate the research activity among units and research areas working on topics relevant for quantum technologies with cold atoms.
The primary objective of AtomQTech is to boost interactions and collaborations among scientists and research groups, with the synergy resulting in improved quality and quantity of the output as well as the speed at which results can be reached. Quantum Technologies based on ultra-cold atoms is an inherently interdisciplinary subject requiring input from a large variety of fields, which range from laser physics and quantum optics to quantum engineering and the physics of many-body systems. It is a key-objective of AtomQTech to provide a platform for the efficient exchange of information between these sub-fields, which is crucially needed if Europe is to maintain its leading position in a rapidly evolving field. The most important specific output will be the number of short term exchanges, communication platforms (well-maintained

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[3] Space Science & Technology in China: A Roadmap to 2050 Springer, Heidelberg (2010)
See especially Strategic Goals 1.4 & 3.4
[4] The iSense FET project:www.isense-gravimeter.eu/
[5] The MatterWave project: matterwave.eu
[6] N. Behbood et al. *Applied Physics Letters* **102:17** (2013)

dedicated website and Facebook pages), conferences, round tables discussions and the reports of the working groups, especially the roadmaps.
Objective 1.2) Foster the interchange between academia and industry in order to advance the development and adoption of quantum technologies with cold atoms.
A recent survey[7] shows strong interest in quantum technologies from European companies. Also, an increasing number of smaller companies[8] work on engineering and realizing quantum devices, ranging from established supporting technologies to the realisation of actual quantum devices with cold atoms. It is therefore the second primary objective of AtomQTech to promote the industry-academia interchange both through common meetings, working groups, and focused visits of researchers (especially also early-stage researchers) to such companies. An important part of this objective is to increase awareness of intellectual property rights (IPR) and provide guidance and training on identification, protection, exploitation, and management of IPR. The specific output will be a sharp increase in IPR generated, in the number of collaborations/partnerships between industry and academia and the number of spinoffs generated.
Objective 1.3) Promote the dissemination of results beyond the traditional boundaries.
The wide dissemination of results is vitally important especially in a rapidly developing field, which is naturally at the border between many different areas of fundamental and technological innovation. An important objective of AtomQTech is the support of an interdisciplinary and intersectoral exchange of ideas not only through the dissemination of results via peer-reviewed journals, but specifically through more targeted publications in industry journals, meetings and conferences to communicate novel and state-of-the-art results in the field of cold atom quantum technology to a wider public and stakeholders.

1.2.2. CAPACITY-BUILDING OBJECTIVES

One of the main factors that will determine Europe's success in the exploitation of quantum mechanics is the attainment of a critical mass of researchers and research laboratories available. *If nothing is done, then Europe risks becoming a second-tier market player*.[9] Therefore the capacity-building objectives have to focus on exploiting the existing skill base to its maximum and widening it through targeted training and dissemination of results.

Objective 2.1) Training the next generation of cold-atom quantum physicists.
There is a current lack of physicists trained in quantum technologies in general. The primary *Capacity-building Objective* of AtomQTech is to train a new generation of commercially aware physicists skilled in cold-atom quantum technologies. This will be done through the organisation of one or two summer schools per year on cold atom technologies training a total of 250 young quantum physicists. AtomQTech will also organise four conferences on the topic, with special sessions specifically aimed at non-specialists. Furthermore, a targeted exchange scheme will allow ESRs to visit other laboratories in both academia and industry. The impact will be a considerably increased European human resource capacity in cold atom quantum technologies.
Objective 2.2) Improving Capacity through Communication.
The expected increase in funding e.g. through the 1B€ FET-Flagship will attract many new research groups into the field. AtomQTech puts it as one of its objectives to provide a communication platform for established and new groups. This will be achieved through a series of conferences, through its website (highlights, news, directory of researchers & research groups, industrial interest and a job portal), and through a series of about eight topical meetings. Working Group (WG3) of AtomQTech has the objective of improving the public's understanding and appreciation of quantum phenomena and their technological implications. Conversely, communication with a wide audience will help us to identify needs and societal

[7] Quantum Technologies - Opportunities for European industry: Report on a round table discussion and stakeholder meeting, published on 14/12/2015 (https://ec.europa.eu/digital-single-market)
[8] Some of which are members of the AtomQTech consortium.
[9] EU Commission Staff Working Document on Quantum Technologies SWD(2016) 106 (2016)

relevance as a main cornerstone of any innovation process and draw on a wide range of competencies.
Objective 2.3) Improving the European skill base by supporting and promoting geographic and gender balance.
One main limiting factor in the implementation of quantum technologies is the limited amount of available brain power. AtomQTech aims at improving access to two sources of quantum physicists that are still largely underused: female scientists and those from countries with a smaller research base. Women are extremely underrepresented in quantum physics, e.g. in 2015 less than 7% of invited speakers at quantum conferences were female. A similar bias exists geographically, with only a handful of countries maintaining experiments in cold-atom quantum technologies, which ***challenges the very concept of the European Research Area***. It is an objective of AtomQTech to improve the ***balance in gender and geography***. Special care will be taken in the selection of speakers during meetings, summer schools and conferences, and targeted exchange schemes will be specifically aimed at these groups..

1.3. PROGRESS BEYOND THE STATE-OF-THE-ART AND INNOVATION POTENTIAL

1.3.1. DESCRIPTION OF THE STATE-OF-THE-ART

Ultracold atoms and molecules offer an unprecedented degree of control, pushing the frontiers of quantum technologies and allowing high impact applications in atomtronics, quantum simulators, quantum information and quantum metrology. Diode and transistor-like atomic devices as well as matter-wave analogues of Superconducting Quantum Interference Devices (SQUIDs) have been recently demonstrated.[10] Ultracold atoms are ideal candidates to simulate quantum systems ranging from condensed matter to high-energy physics. Initialisation, manipulation and read-out techniques for ultracold atoms together with their inherent scalability and large coherence times have opened promising prospects for quantum computation. Nowadays, applications ranging from frequency standards to tests of fundamental physics benefit from spectacular levels of accuracy and stability of atomic clocks and atom interferometers. On the “big science” scale, there are space-born cold atom proposals the Atomic Clock Ensemble in Space (ACES) and the Space-Time Explorer and QUantum Equivalence Principle Space Test (STE-QUEST) are space mission projects with ultracold atoms in microgravity environments. Earthbound “big science” projects are for example ground-based cold-atom interferometers for geology and gravitational wave detection. Smaller scale quantum sensors based on ultra-cold atoms include ultrasensitive gyroscopes, magnetometers, gravimeters and gravity gradiometers with applications in navigation, biomagnetic imaging and archaeology. Companies are already starting to offer quantum products based on laser-cooled atoms, some of which are aimed at real-world industrial applications.

1.3.2. PROGRESS BEYOND THE STATE-OF-THE-ART

The major topics in which AtomQTech is expected to facilitate to a considerable progress beyond the state of the art are on the ***technological*** side: ***atomtronics***, non-invasive ***field sensing***, ***acceleration/rotation*** sensing and the ***miniaturisation*** of sensors. On the more ***conceptual/fundamental side,*** AtomQTech will focus on exploring the use of ***entanglement*** and ***squeezing*** in realistic improvements of sensors. Finally, AtomQTech hopes to contribute considerably to the new topic of ***large-scale quantum sensors*** (MIGA, VLBAI, SAGE etc.), in which Europe is emerging as a new leader.
On the technological side, AtomQTech expects to see the first coherently guided ***atomtronic circuits***, which will give rise to new devices such as miniature Sagnac interferometers. The resulting huge increase in coherent interaction time will lead to many novel applications. The ***non-invasive field sensors***, which will be developed during the network, will include

[10] S. Eckel et al. Nature **506**, 200-203 (2014). G. W. Biedermann, et al Phys. Rev. A **91**, 033629 (2015).

microwave sensors for electronics and magnetometers for bio magnetism (brain/heart), where there is already strong commercial interest present in the consortium. AtomQTech expects to contribute to the development of the standardisation of ***cold atom technologies*** like atom chips, which are advancing very rapidly and are now starting to become the platforms of choice for many new experiments and sensors. Since the first ***commercial sensors*** based on atom quantum technologies have appeared only very recently, they still have an extraordinary potential of improvement, which however depends heavily on the successful academia-industry interaction this network is striving to provide.

On the more fundamental side there has been considerable progress on finding ways to exploit not only ***squeezing*** but also other forms of ***entanglement*** to generate large improvements in real measurement using atoms. This will be further deepened and implementations will be sought both in the academic and industrial domains. Finally, there has been a recent movement towards largescale atom quantum sensors, with large atomic fountains (VLBAI), or very long base-line atom interferometers (MIGA, ELGAR), and space based atom interferometers (STE-QUEST) and clocks SAGE.

1.3.3. INNOVATION IN TACKLING THE CHALLENGE

It is clear that only a large-scale collaborative effort can realistically address our goals. The Action aims at providing an anchor and checkpoint for the disperse communities involved in quantum technology. AtomQTech will help to establish the synergies required. The Action involves the main EU actors in each sub-field and ***combines the necessary complementary expertise***. AtomQTech will intertwine applied mathematics, theoretical computer science, quantum information and technology, photonics technology, atomic and molecular physics, and condensed matter/solid state physics. Hence, AtomQTech will facilitate the integration of a remarkably wide variety of technological, experimental and theoretical techniques that are mature in their respective subfields. By involving industrial partners, AtomQTech will establish ***cross-fertilisation between science and industry*** research perspectives to deliver market-ready devices. This feature is decisive and puts the effort in an advantageous position with respect to international competitors. AtomQTech will put specific efforts to form a young generation of researchers with a new interdisciplinary profile resulting from the integration between the subfields involved in our research. AtomQTech will establish an online forum and create off-line open spaces and science festivals organised by the stakeholders.

1.4. ADDED VALUE OF NETWORKING

1.4.1. IN RELATION TO THE CHALLENGE

The AtomQTech network joins major experts on the experimental, theoretical and technological aspects of ultracold atom physics and technology, from its fundamentals to its applications. From the fundamental side, this includes the study of quantum coherence with matter waves, quantum correlations, effects of interactions, novel quantum phases, entanglement, etc. Concerning applications, the network partners are experts in atom interferometry, sensing, metrology, high-precision tests, gravimetry, etc., with several partners being involved in individual developments towards technological and commercial exploitation. Putting together all this expertise, the network will allow a much more efficient exchange of ideas and concepts, and will lead to a faster transfer of fundamental concepts towards applications.

The network will allow participants to share intermediate and preliminary results and enter into new collaborations by enabling visits among groups involved in the network and the organisation of meetings and common conferences. The possibility of travelling, meeting other experts in the same domain and exchanging ideas will be especially important for the formation of the new generation of researchers in quantum technologies, e.g. PhD students and post-docs. In conclusion, the Action will provide the essential funding to shape this emerging community.

AtomQTech presents a ***unique chance for Europe to coordinate and consolidate the multiple efforts*** around the topic of fundamentals and applications of ultracold atoms to quantum technologies.

1.4.2. IN RELATION TO EXISTING EFFORTS AT EUROPEAN AND/OR INTERNATIONAL LEVEL

Quantum technologies are now seeing an unprecedented rise in activity. It is clear that now is the time for Europe to face this challenge to consolidate its technological lead or else to see companies from the US and Asia take the most benefit from its commercial exploitation. Without a concerted effort to coordinate and facilitate the exchange of information, there is a great risk of wasting much of the new resources provided. As stated in the EU working document: ***An ambitious coordinated strategy to support joint science, engineering and application work, including IPR, standardisation, market development, training and public procurement will be needed.***[11] This is exactly what AtomQTech is striving for.

At the European level, the strategy for quantum technologies is still largely fragmented with a few strong national initiatives, e.g., in the UK and Denmark, and a European COST Action on the rather specialised aspect of quantum technologies in space. The need to exchange ideas on an international scale led to the first ever Atomtronics conference held in Benasque in 2015.[12] While this single event already produced a number of novel ideas and new collaborations, a sustained effort is needed.

AtomQTech will focus on cold-atom quantum technologies for fundamental and 'real-world' applications on Earth. No similar network structure exists on this size in Europe, nor anywhere else in the world. There is a COST network on "quantum technologies in space", which is aimed at large collaborations dedicated exclusively to the exploitation of quantum technologies specifically for space missions. Only a few smaller, disconnected networks of Future and Emerging Technology (FET) actions exist in Europe (MatterWave, iSense, COQUIT etc.), which are limited to a few groups and do not federate the whole community.

On a national scale, there are large differences among the countries in terms of funding possibilities. Only a few countries such as the UK and The Netherlands have invested significantly in quantum technology hubs. In the UK, the investment in quantum technology reaches £270m. However, this scale of investment is not realised in most of the other EU countries, which display a large, dangerous delay with respect to international competitors (i.e. USA, Singapore, China) and cannot afford on a national scale the funding of such an initiative. AtomQTech presents an excellent opportunity, where an EU action will play a major role in shaping the scientific strategy on a worldwide scale and help Europe to develop key technological resources (see impact section below for details).

2. IMPACT

2.1. EXPECTED IMPACT

2.1.1. SHORT-TERM AND LONG-TERM SCIENTIFIC, TECHNOLOGICAL, AND/OR SOCIOECONOMIC IMPACTS

Quantum physics has had a huge impact on our understanding of physics, which has led to products that transformed our lives (lasers, semiconductor etc.). Now, quantum physics enters a new era in that it starts to have a direct impact on industry and sciences such as biology and medicine. In the last couple of decades, quantum effects have yielded some of the most sensitive and precise sensors to date. Quantum sensors are about to lead to a wave of new technologies that will create many new businesses and help solve many of today's global challenges[13]. New quantum technologies are expected to have a profound impact on many of

[11] EU Commission Staff Working Document on Quantum Technologies SWD(2016) 106 (2016)
[12] http://benasque.org/2015atomtronics/
[13] The Quantum Manifesto, a new era of technology 2016 http://qurope.eu/manifesto

the world's biggest markets. For example, quantum devices will significantly affect the €400 billion global semiconductor industry, gravity sensors will change the €2.2 trillion oil and mineral industries. There is already an active interest for example from the construction industry in atom quantum sensors to identify pipelines and underground structures[13]. Magnetic atom-quantum sensors will have a strong impact in the medical imaging of bio-magnetism. The emerging quantum technology market is estimated to reach multibillion-Euros per year.[14]

The short-term Scientific and Technological Impact of AtomQTech will lie mainly in an increased communication, coordination, and cooperation. This will lead to an increased information flow on one hand within academia and on the other between academia and industry and vice versa. This flow is especially important for the smaller players and the fledging quantum industry. For industry, the impact is crucial to overcome the valley of death between the invention and the commercial break-even-point. Some of the industrial members of AtomQTech have already products in the market place, but need to widen their customer base considerably by further developing their quantum sensors, which at this point can only be done in collaboration with academia. ColdQuanta, for example is selling complete Bose-Einstein Condensation machines, which could be developed into a new standard matter-wave interferometer. Existing atom interferometric sensors will need academic input e.g. to increase their accuracy for them to become the industry standard for absolute gravity sensors.
Similarly, the academic side will profit from the input from industry as to the market needs and opportunities, as well as real world conditions and industrial norms, grade specifications and commercial reality. Also, industrial knowledge and techniques will have a major impact on research, e.g. use of advanced silicon technologies for atom-chips. The impact of the increased inter-sectoral communication will help to guide research towards real-world solutions such as portable commercial gravimeters and gyroscopes, as well as making available high-tech technologies e.g. to the atomchip community. Inversely, it will lower the barriers to the uptake of quantum technologies in industry. The increased inner-sectoral communication will foster novel fundamental breakthroughs as well as lowering the entry-threshold for newly established groups, which is especially important at the periphery of Europe and in the COST Inclusiveness Target Countries.
Another important impact of the increased information flow due to AtomQTech is to reinforce Ultra- Cold Atom Experiments as an important testbed for the development of other quantum technologies such as quantum computers and quantum simulators.

The Long-Term Scientific Impact of AtomQTech will be that Cold Atom Technologies will become an important tool well beyond the confines of specialised atom-physics laboratories. A key ingredient will be the fostering of novel technologies by AtomQTech such as the emerging field of atomtronics, bio-magnetic quantum imaging for medicine and biology, and spatially resolved gravitometry, as well as the expected enormous increase in sensitivity of planned and proposed large-scale atom-quantum interferometers. The impact on fundamental physics of the predicted increase in sensitivity will yield stringent tests of Einstein's weak equivalence principle in space (e.g. STE-QUEST), or the earth-bound detection of gravitational waves (e.g. MIGA or ELGAR)[15]. Another important impact will be on the study of quantum non-equilibrium states. The increased accuracy of atom clocks will lead further stringent tests of the physics of the standard model. Another very important scientific impact of AtomQTech will be that Atom Quantum Technologies will become standard tools in such diverse fields as geology and geodesy (gravity sensors), medicine and material science (magnetic and RF/microwave field sensors) and information science (quantum simulators/computers).

The Long-Term Technological and Socio-Economic Impact of Atom Quantum Technologies will come from them becoming part of the normal economic activity. Ultra-sensitive imagers of the biomagnetism of the brain and heart, will have an impact on the $32 billion medical imaging market. Improved geological surveying will impact the survey of

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[14] The UK Quantum Technologies Strategic Advisory Board (link to pdf) 2015
[15] Dimopoulos et al. *Phys. Lett.* B **678** 37 (2009); ELGAR is a proposal for a EU-Large Scale Facility

underground resources such as oil, minerals, and water. The increased precision and miniaturisation of interferometric gravimeter devices will make possible non-destructive surveying for archaeology or construction. The latter is important since undocumented cavities, power lines and other services cause many deaths and disruption to the building industry. Atomtronic devices will impact inertial sensing markets arising from the need to work in any GPS-denied environment. GPS is crucial to Europe's transport infrastructure, which in critical circumstances needs to be protected from GPS jamming or other outages.
A crucial long-term socio-economic impact will be the development of human capital. AtomQTech's focus on geographic and gender distribution will draw many more women into the quantum sciences and increase the involvement of less research-intensive countries. This will make more human resources available, reinforce the European Research Area, and widen the science base considerably. Similarly, the outreach activities will contribute towards a better appreciation by the general public of quantum mechanics both as a pure science and as an economic opportunity.

2.2. MEASURES TO MAXIMISE IMPACT

2.2.1. PLAN FOR INVOLVING THE MOST RELEVANT STAKEHOLDERS

The four main stakeholders for this COST Action are academia, industry, (inter)national agencies, and the general public.

Academia is already heavily involved in AtomQTech with many of its European leaders involved at the proposal stage. Others will be invited to join in the very first phase of the Action. AtomQTech will extend its reach beyond Europe and include the leading groups from the US, Australia and Asia. Some of these groups are already members of AtomQTech. AtomQTech plans to extensively use teleconferencing to enable also those international members to take part in all MC meetings, even if they cannot be physically present
Industry has already expressed a strong interest in AtomQTech with some of Europe's leading manufacturers of quantum enhanced devices being co-proposers. Also, here, AtomQTech has reached outside of Europe to include the biggest US producer of ultra-cold atom quantum devices. An important aim of AtomQTech is to ***include all major European companies*** engaged in the field. AtomQTech will contact the companies and invite them to join the Action. A biannual newsletter aimed at industry will strengthen the involvement of industry. Importantly, the ***active presence of industry representatives*** at conferences and meetings will be sought. Workshops on IPR and industrial quantum designs will naturally be led by industry. There should be several industry representatives in the management board.
(Inter)national agencies play a very important role in steering research. It will be crucial to the success of AtomQTech to further the understanding of quantum technologies amongst decision makers both in national and international agencies and governments. AtomQTech will actively lobby both on a national and international level for a greater appreciation of (atom) quantum technologies. This will be done e.g. by inviting officials to take part in roundtable discussions and workshops. AtomQTech will also strive to coordinate the communication between the cold-atom community and the European Flagship on Quantum Technologies.
The general public is still blissfully unaware of the concept of quantum devices and their potential and implications. Without this appreciation long term support of quantum technologies is severely at risk. AtomQTech has a dedicated Working Group for outreach. AtomQTech intends to engage the general public through a number of events to be organised by its members with central support and encouragement. AtomQTech will have a dedicated person with journalistic experience to help publicise the research outcome of the members of AtomQTech as well as other important news in the field of quantum technologies.

All four groups will be actively engaged and actively involved in events organised by AtomQTech, which will include biannual training schools (TS), at least six research workshops (RW), four round tables (RT), short-term scientific missions (STSM), science festivals (SF) and public talks (PT). TS, RW and RT will be organised directly by the WG of AtomQTech. The

STSM will be promoted by AtomQTech but initiated by the partners involved. Since SF are aimed at the local audience they will be organised by the members of AtomQTech themselves. However, the contributions will be publicised by AtomQTech and experiences shared amongst its members.

2.2.2. DISSEMINATION AND/OR EXPLOITATION PLAN

Dissemination: Quantum technologies based on cold atoms is a rapidly evolving and growing community. It is therefore a prime aim of AtomQTech to ensure a rapid dissemination of research results amongst the specialists working in the field. It is also important to bring this information to the other interested groups (e.g. industry) and to the general public.
The scientific and technical results of the different WG of the COST Action will be published in peer-reviewed ***high-impact journals*** with open access publications being mandatory if the Action budget was involved. All major results will also be presented in **international conferences** and workshops. AtomQTech will maintain a ***website*** which will report the latest achievements and announce the activities of the COST Action. This web site will contain a networking section (including a directory of skills) and there will also be a news section.
Outreach is an important part of AtomQTech. AtomQTech will actively utilise extensively ***networking channels*** like professional and social networks such as ***LinkedIn, Facebook and Twitter***. A Facebook page, for example, combined with the other activities can be a powerful means to attract the attention of the general public as well as the academic audience. A dedicated section will contain ***high-school teaching*** materials, e.g. class room posters, as well as **outreach** content for the general public. The aim is to encourage scientific vocation among children and teenagers, with special focusing on gender balance. A biannual newsletter will be aimed at decision makers and industry.
Exploitation: The field of quantum technologies based on atoms is a crucial point of its development. Many of the basic ideas have already been developed; however, as they become directly useful in the real world ***much IPR will be generated***. Physicists are often very good at generating new knowledge, however they often find it very difficult to exploit and protect it. AtomQTech aims at aiding the generation of IPR, its protection and exploitation through the following measures: 1) The ***generation of IPR*** requires, next to the necessary background in quantum physics, an ***awareness*** of the requirements of the market. AtomQTech will provide this through dedicated industry-academia sessions at its conferences and workshops, as well by organising industry-academia round tables and short-term exchanges. 2) It is crucial both to industry and to academia that the IPR be well protected. To this aim AtomQTech will organise ***specific IPR training sessions*** at their summer schools and ***academia-industry workshops***.[16] 3) No IPR is useful if it is not exploited. AtomQTech will provide an important platform where academics will meet industry and can ***explore any possible avenue of exploitation of IPR***. An important element will be the generation of a directory of interested parties on both sides. Industry leaders will also be invited to speak at summer schools to give insight into the structure of invention and product cycles in industry.

2.3. POTENTIAL FOR INNOVATION VERSUS RISK LEVEL

2.3.1. POTENTIAL FOR SCIENTIFIC, TECHNOLOGICAL AND/OR SOCIOECONOMIC INNOVATION BREAKTHROUGHS

The newly found ability to precisely control quantum states especially in the atomic domain will almost certainly lead to major breakthroughs and applications. Governments[17] and companies[18] worldwide are investing substantially to unleash this potential. The quantum technologies based on cold atoms, AtomQTech is striving to support, have a very large

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[17] Examples include the flagship of the EU, the UK quantum hubs, a number of Sonderforschungsbereiche in Germany.
[18] Large companies include Google, Microsoft, Intel, Toshiba, Seagate and IBM. Examples of smaller companies include muQuans, idQuantique, cold Quanta

potential for innovation both on a fundamental level and in real-world applications. With respect to their return/risk trade-off they can be divided into three different categories: The ***technological breakthroughs***, the ***scientific breakthroughs*** and the **large-scale experiments**.

The main technological breakthroughs that AtomQTech is striving to facilitate are geared toward real-world applications of atom quantum technologies such as ***quantum-based sensors*** for gravity, acceleration, rotation and magnetic fields. In the short-term (3-4 years), the main breakthrough facilitated by AtomQTech will be technological in nature: the first near-commercial ***transportable quantum-based sensors*** for gravity mapping, acceleration, rotation, and magnetic fields. AtomQTech will also see considerable improvement of the first existing commercial gravity sensors. These will find application in markets, where the precision and accuracy of sensors is paramount and their cost is outweighed by the economic impact they generate. Examples include the search for rare metals or oil (gravity sensors), inertial navigation in GPS denied environments (acceleration and rotation sensors), gravity mapping for construction and archaeology (portable gravity sensors)[19], medical imaging of the bio-magnetism of the heart and brain. A prime example illustrating ***the potential return***, is the 2.5-trillion-dollar oil and gas industry. The current oil prices are relatively low, however, even in the near future new sources must be found. Moreover, the sensitive and reliable portable gravity sensors envisaged here would have a major impact with huge economic returns.[20] Similar arguments hold for the search for rare earth metals, for which Europe and America is almost entirely dependent on China and the monitoring of groundwater resources in times of climate change. The 15-billion-dollar market for medical imaging is another target with the emerging field of biomagnetism. Finally, atom based quantum technologies are becoming more and more the standard tools for physics research. One aim of AtomQTech will be to further the development of standardised components, the impact of which will be to facilitate the design and construction of new quantum sensors both for commercial and scientific applications. These include commercial cold atom sources or even complete BEC machines. The ***risk level*** for the development of the sensors is relatively low, since the first prototype devices have already been demonstrated successfully. The intensive industry-academia communication envisaged by AtomQTech will support the further technological improvements in size, data rate, and reliability, which are prerequisites for wider industrial uptake. An important fact mediating risks is that many of the main European and American industrial players in Atom Quantum Technologies are members of AtomQTech. Therefore, the ***return/risk balance is excellent*** for the technological breakthroughs fostered by AtomQTech.
More ***scientific breakthroughs*** are required to tap the full potential of entanglement and squeezing. Even though there has been much recent progress in achieving large amount of squeezing and entanglement,[21] this has yet to be used to improve measurements of scientific or real-world quantities. Much theoretical and experimental work is still required for these techniques to achieve the level of maturity, which would warrant commercial application. The ***potential return*** of using these advanced quantum measurement techniques is best demonstrated in the case of matterwave interferometry, where normally the precision of a measurement scales as the square root of the number of atoms. Using squeezing or entanglement, however, one can reach the Heisenberg limit, where it scales directly with the number of particles. Using one million atoms this is equal to an improvement of three orders of magnitude and thus potentially a ***huge gain in precision***. The enormous accuracy and precision afforded by atom clocks and atom interferometry is now becoming a prime tool for fundamental physics, e.g. for the search in a time-variation of fundamental constants, Einstein's equivalence principle, or a departure from the standard model via parity violation at ultra-low energies. One of the purposes of AtomQTech will be to speed up the uptake of these new technologies (especially in the COST target countries) and to foster further research

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[19] The Quantum Technologies Strategic Advisory Board National strategy for quantum technologies - A new era for the UK (https://www.epsrc.ac.uk/newsevents/pubs/quantumtechstrategy) (2015)
[20] S. Rippington and C. Anderson **12:1** 42-44 (2015)
[21] Onur Hosten et al. **529:7587** 505--508 (2016) and R. Schmied et al. **352:6284** 441--444 (2016)

aimed on one hand at improving these technologies and on the other hand making their application easier through standardisation and information exchanges. The **main return** would be improved techniques both for the established and upcoming laboratories and therefore a much-increased pool of people and experiments. Given the enormous potential of these novel techniques, the ***risk is very low*** with respect of novel science. The current financial climate in Europe makes the ***risk with respect to uptake*** in the COST Target countries more acute and thus the need for the Action AtomQTech to play a role. Therefore, the ***return/risk balance is very good with respect to the scientific breakthroughs*** as well as their spreading into new countries.
One emerging field of atom quantum technologies are large-scale experiments, such as ***large-scale quantum sensors*** (MIGA, VLBAI, SAGE etc.), in which Europe is rapidly becoming a new world leader. Here, the ***return*** of an investment in AtomQTech would be on one hand a much-needed improvement in communication of and participation in these national efforts. On the other hand, AtomQTech will strive to act as a central uniting platform aimed at coordinating the theoretical and experimental efforts on the challenges and opportunities afforded by such experiments.

3. IMPLEMENTATION

3.1. DESCRIPTION OF THE WORK PLAN

3.1.1. DESCRIPTION OF WORKING GROUPS

To further the research coordination objectives (1.1, 1.2 and 1.3 in section 1.2), there will be three Working Groups (WG) split along thematic lines: WG1: Break-Through Technologies, WG2: Atom Technology goes Commercial, and WG3: Physics and Society. Note that each of the WGs will contribute explicitly to the capacity-building objectives defined in 2.1, 2.2 and 2.3, which will be addressed in each of the three WGs, e.g. through workshops (Obj.2.1&2.2) and summer schools (Obj.2.1&2.3). There will be considerable synergies between the different WGs in the form of joined workshops and conferences. Each WG committee will consist of a WG leader(WGL) and three committee members, which will be elected at the kick-off meeting.

WG1) Break-Through Technologies
According to objective 1.1, this WG will facilitate the advance of novel atom-quantum technologies by fostering closer European collaboration between the main players and the numerous upcoming groups, especially in the COST Inclusiveness Target Countries (ITC) and Near Neighbour Countries (NNC).
Tasks:
T1.1) Identification and dissemination of potential breakthrough areas
T1.2) The key technologies/science in need of dissemination amongst the partners and beyond.
T1.3) Organise targeted meetings.
T1.4) Facilitate and promote exchanges especially of Early Career Investigators (ECI).
Activities:
A1.1) Compose a report on T1.1 and T1.2 within the first 10 months.
A1.2) Create in consultation with all major players a roadmap for T1.1
A1.3) Develop a strategy to disseminate the technologies/science identified in T1.2.
A1.4) Organise at least one session at a major conference per year in synergy with existent structures.
Milestones:
Identification on T1.1 and T1.2.
Major Deliverables:
D1.1) Roadmap towards future quantum atom technologies T1.1. by year 2
D1.2) Report on T1.2 in year 2.
D1.3) Four to six sessions at major conferences and workshops
D1.4) Organise three to four summer schools.

WG2) AtomQTech Goes Commercial

Following objective 1.2, this WG will exploit the potential of atom-quantum technologies focusing on sensors, where Europe is currently world-leader. Examples include gravimetry, navigation and geology, but also technology providers, e.g. lasers.

Tasks:
T2.1) Providing an interface between industry and academia.
T2.2) Scouting new opportunities and providing support.
T2.3) Support academics in commercialisation of their ideas.
T2.4) Function as an efficient industry-academia link.

Activities:
A2.1) Bring together researchers and companies to advance the fledgling quantum-high-tech industry in Europe.

Milestones:
Establishment of a Pan-European platform for quantum-high-tech/ academia exchanges.

Major Deliverables:
D2.1) Two workshops on the commercial exploitation of academic ideas (possibly in conjunction with D1.3)
D2.2) IPR and start-up training at four summer schools. (Possibly in conjunction with D1.3)

WG3) Quantum Physics and Society

To develop objective 1.3 and 2.2, this WG will focus on the relation between society and academia with respect to atom quantum physics *and technology.*

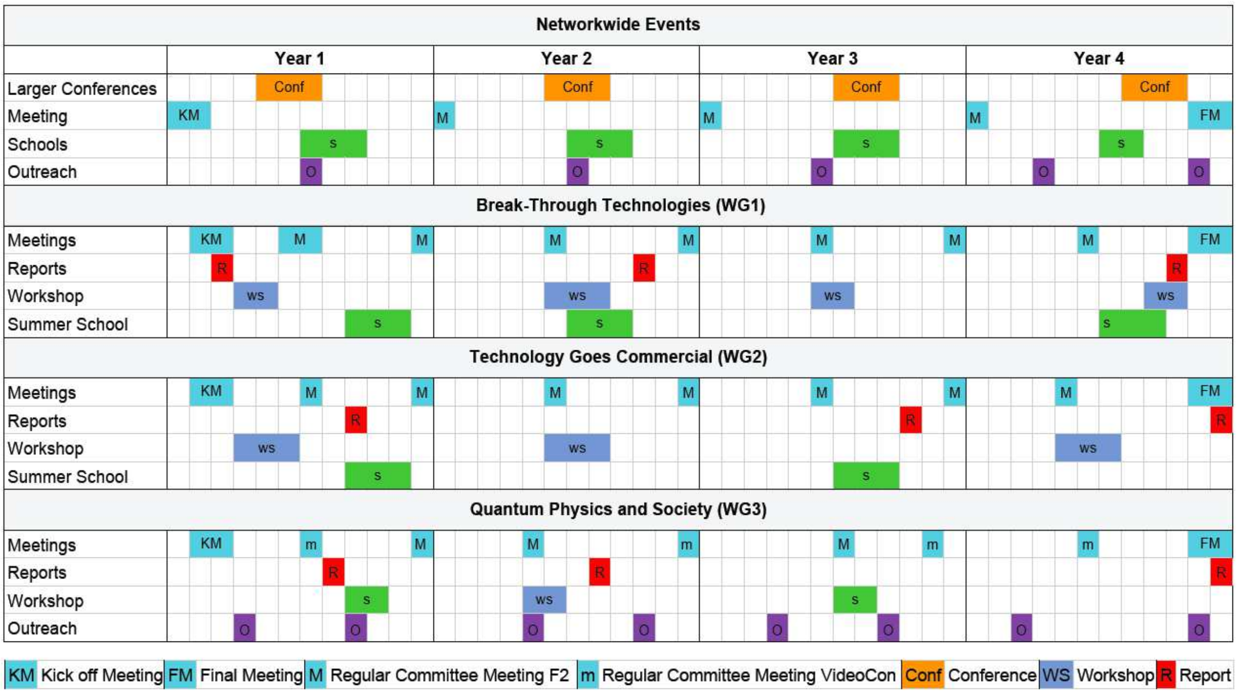
Tasks:
T3.1) Interfacing with policy makers.
T3.2) Provide an outreach platform beyond the standard opening days.
T3.3) Develop a best practice guide for outreach.
T3.4) Interact *directly* with decision makers at the highest level – both nationally and internationally.
T3.5) Address the geographic imbalance in quantum-high technology.

Activities:
A3.1) Seeking actively to influence policy on quantum-high-tech in Europe and nationally through reports and direct contact with decision makers.
A3.2) Directly attack the gender imbalance in the sciences at an early stage of education.

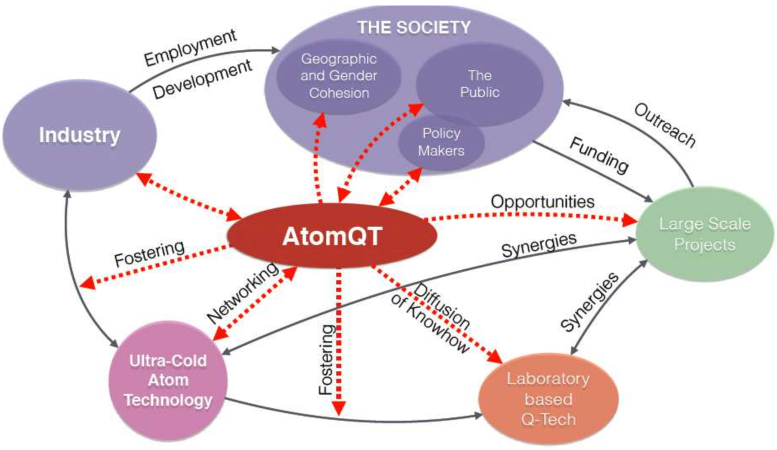
Milestones:
Establishment of lasting direct contacts to decision makers.

Major Deliverables:
D3.1) Organisation of and contribution to at up to eight outreach events.
D3.2) International outreach of key research results from the network.
D3.3) Contributions to two summer schools / conferences.

3.1.2.GANTT DIAGRAM



3.1.3.PERT CHART (OPTIONAL)



3.1.4.RISK AND CONTINGENCY PLANS

Organisational Risks: There might be a problem in agreeing on the priorities of the network (objectives 1.1 and 1.2) ***Likelihood***: Small, since the priorities are well-laid out and have been agreed upon in advance. ***Contingency*****:** Any disagreement will be seen by the industry WG panel using a majority voting scheme.
IPR Risks are inherent with larger consortiums involving industry. ***Likelihood*****:** If not addressed from the very beginning: high. However, there will be Memorandum of Understanding (MoU) addressing this issue directly. Partners will be required to sign IPR agreements before engaging on joint projects. ***Contingency*****:** Should an IPR problem arise the Core Group (CG) of AtomQTech will mediate.
Societal Risks come from a lack of understanding of quantum physics in industry and amongst the general public. This can lead to a reduction in funding during AtomQTech (Objectives in 1.2) and with Industry reluctant to take up new technology and instruments when existing solutions are well understood. ***Likelihood:*** medium. ***Contingency:*** Improve information flow to industrial sector; inclusiveness in workshops pitched to educate about the new technology.

Scientific Risks: In raising the TRL, there is a risk that obstacles remain in terms of optimising size, weight and power consumption (SWP). This is a medium risk as much of the physics is understood, but there are many additional requirements to satisfy. For example, lasers can be miniaturised, vacuum chambers are being reduced in size, atom chips can be used, lighter vacuum chambers can be used, better engineering of components, and some systems engineering can be used to make the results more attractive to industry. ***Likelihood:*** very low. ***Contingency:*** Failure to achieve all or most of the SWP requirements would reduce but not eliminate market possibilities in the future. Academics could pursue a reduced set of SWP reduction targets.
Additional Scientific Risks: There are risks in taking experiments into a non-laboratory environment where there are mechanical vibrations and electrical noise. Other scientific risks are that entangled states for interferometry may be hard to produce; squeezed states may have insufficient squeezing to produce interferometric improvement; gravity sensors may be too sensitive to background density noise; rotation sensors may be too sensitive to linear accelerations. ***Likelihood:*** medium. ***Contingency:*** These risks are generally spread across projects and with several different approaches to different devices the risk to the overall vision is reduced if only a few projects are affected.

3.2. MANAGEMENT STRUCTURES AND PROCEDURES

Management structure: The decision body of the network will be the **Management Committee (MC)**, consisting of up to two representatives of each COST Country that has signed the Memorandum of Understanding (MoU). The MC is in charge of the coordination, implementation, and management of the Action's activities as well as supervising the appropriate allocation and use of the COST funding with a view to achieving the Action's scientific and technological objectives. The practical management of the Action will be performed by the **Core Group (CG)**, which will consist of the **Action Chair (AC)** and its **Vice-Action Chair (VAC)**, the **Working Groups Leaders (WGLs),** the **Short-Term Scientific Mission Coordinator (STSMC)**, the **Training School Coordinator (TSC)**, and an **Equal Opportunities Officer (EOO)** will be part of the C. AtomQTech will strive to maintain an excellent gender and country balance in the Action. The Action Chair, who preferably should be a member of the institution administering the financial aspects of the Action, will handle the external contacts with COST, e.g. financial and administrative questions where appropriate with support of the WGLs.

The Elections of the (V)AC and the WGLs by the Management Committee of the Action will take place at the kick-off meeting and should last for the duration of the Action. As the Action grows, vice-members can be appointed by the Action Chair as required, but need to be approved by the MC.

The Management Procedures: The committees meet twice per year, with at least one of the two meetings being a physical meeting as per COST rules. Meetings, roundtables, and workshops will be organised by the respective WG Leaders. All communication between meetings will be done by electronic means, i.e. either by email or via the Action’s dedicated website. To this end a website with the appropriate infrastructure will be set up (protected area for each WG collection of reports, applications, forms etc.).

The CG will meet biannually and further communicate by web-based interfaces and conference calls**,** with the purpose of coordinating and organising the Action’s scientific and networking activities in line with the objectives that will be specified in both the Memorandum of Understanding (MoU) and the approved Work and Budget Plan.

The MC will convene annually e.g. at one of the conferences (co)organised by the Action. At the meeting, all relevant decisions will be taken and a round-table discussion on the progress of the Action will be held.

The Working Groups: The MC will elect WG Leaders (WGL), to ensure effective and close cooperation among participants within a WG and between different WGs. At least one annual workshop or/and training school will be organised for each WG, where researchers will present progress in research, identify bottlenecks and future perspectives, which will be communicated to the MC. Together with the MC, the WGs identify and prioritise the most relevant research topics. Additional WGs will be formed according to upcoming needs for specific activities. At least two additional larger conferences will bring all WGs together to ensure exchange of scientific progress in the Action.

The Training Committee (TC) will consist of a **ShortTerm Scientific Mission Coordinator (STSMC)** and **Training School Coordinator (TSC)** and their Vice persons (**VSTSMC and VTSC**). It will be responsible for setting up the programme of course and further to connect existing training activities among partner centres. Trainees at all partner centres will benefit from the world-class expertise established at each individual centre. The schools will be open to all Early Career Investigator (ECI) from the network but also for interested persons from outside the network. Special attention will be paid to geographic and gender balance as well as to the active involvement of ECI in the meetings and conferences but also in organisation of Training Schools.

The External Advisory Board will consist of at least three eminent scientists and three industry leaders. A strong contribution from outside the EU will be sought. The role of the external advisory board is to advise the MC on the organisation and focus of the conferences, workshops and on the content of the training programme.

3.3. NETWORK AS A WHOLE

At the proposal stage, the network of proposers consists of 31 Proposers and spans the whole of Europe and the AtomQTech network **covers all major components of quantum technologies** with cold atoms: magnetic and gravity sensors, atoms in free-fall and on compact guided matter waves devices, miniaturisation of the sensors (lasers, optics, vacuum), others on improving detection systems and others focusing more on fundamental aspects like atomic interactions. The AtomQTech network contains also a number of ***eminent theorists*** some of whom specialized on theoretical models for the sensitivity and noise of atom interferometers.
The quantum industry in Europe is still at a very early stage of development with only a handful of companies selling the first quantum-enhanced products. AtomQTech is very proud to have attracted many of the main European companies in the field already at the proposal stage.
The communication capacity network as a whole will profit from experience of the network members, but will also be directly supported by a (part-time) publishing assistant.
Many of the partners have already taught in training events on cold atom based quantum technologies. Some have initiated and organised key events in the field. There is certainly a critical mass to train the next generation cold-atom quantum physicists.
Further multiplier effects are expected through the geographic and gender distribution. AtomQTech is also extremely successful in attracting many of the top European female researchers in the field: ***43% of the proposers of AtomQTech are female*** leading to ***full gender parity*** in all of its committees. To support and encourage their activity is a primary objective of this Action. Given the extreme underrepresentation of female physicists in general and in cold atom sciences in particular this is an important step forward.
In many respects quantum technologies using cold atoms is still at an early stage of development where key technologies are mastered only by a handful of laboratories worldwide. Europe’s success in quantum technologies will also depend on an influx of knowledge from abroad.