SEVENTH FRAMEWORK PROGRAMME
THEME 3
Information and Communication Technologies

Grant agreement for: Small or medium-scale focused research project
STREP – CP-FP-INFSO

Annex I - "Description of Work"

Project acronym: COMPAS
Project full title: COmputing with Mesoscopic Photonic and Atomic States
Grant agreement no.: 212008

Date of preparation of Annex I (latest version): 14 February 2008
Date of approval of Annex I by Commission: ***18 February 2008***

List of Beneficiaries

Beneficiary Number *	**Beneficiary name**	**Beneficiary short name**	**Country**	**Date enter project****	**Date exit project****
1(coordinator)	Université Libre de Bruxelles	ULB	BE	1	36
2	Max-Planck-Gesellschaft	MPG	DE	1	36
3	Institut de Ciencies Fotoniques	ICFO	ES	1	36
4	Univerzita Palackého v Olomouci	UP	CZ	1	36
5	University of St. Andrews	USTAN	UK	1	36
6	Universitaet Potsdam	POTSDAM	DE	1	36
7	Centre National de la Recherche Scientifique	CNRS	FR	1	36
8	Kobenhavns Universitet (Niels Bohr Institute)	NBI [1]	DK	1	36
9	Danmarks Tekniske Universitet	DTU	DK	1	36
10	Friedrich-Alexander-Universität Erlangen-Nürnberg	FAU	DE	1	36

* Please use the same beneficiary numbering as that used in the Grant Agreement Preparation Forms
** Normally insert "month 1 (start of project)" and "month n (end of project)"

[1] The short name of Kobenhavns Universitet (Niels Bohr Institute) is NBI in the present document except for the tables on pages 3 and 50, where it is UCPH.

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PART A

A1. Budget breakdown and project summary

A.1.1 Overall budget breakdown for the project

A3.2:
What it costs

Project Number 1	212008	Project Acronym 2	COMPAS

One Form per Project

Participant number in this project 8	Participant short name	Estimated eligible costs (whole duration of the project)					Total receipts	Requested EC contribution
		RTD / Innovation (A)	Demonstration (B)	Management (C)	Other (D)	Total A+B+C+D		
1	ULB	184,000.00	0.00	80,000.00	0.00	264,000.00	0.00	218,000.00
2	MPG	160,000.00	0.00	0.00	0.00	160,000.00	0.00	120,000.00
3	ICFO	112,000.00	0.00	0.00	0.00	112,000.00	0.00	84,000.00
4	UP	160,000.00	0.00	8,000.00	0.00	168,000.00	0.00	128,000.00
5	USTAN	112,000.00	0.00	0.00	0.00	112,000.00	0.00	84,000.00
6	POTSDAM	112,000.00	0.00	0.00	0.00	112,000.00	0.00	84,000.00
7	CNRS	448,664.00	0.00	0.00	0.00	448,664.00	0.00	336,498.00
8	UCPH	268,000.00	0.00	0.00	0.00	268,000.00	0.00	201,000.00
9	DTU	268,000.00	0.00	0.00	0.00	268,000.00	0.00	201,000.00
10	FAU	180,664.00	0.00	0.00	0.00	180,664.00	0.00	135,498.00
TOTAL		2,005,328.00	0.00	88,000.00	0.00	2,093,328.00	0.00	1,591,996.00

A.1.2 Project summary

In the recent years, continuous variables (CV) have emerged as a viable and very promising alternative to the traditional quantum bit-based approaches to quantum information processing. Encoding CV information onto mesoscopic carriers such as the quadratures of light modes or the collective spin of atoms offers several distinct advantages, such as the deterministic generation and manipulation of entangled states of light and atomic ensembles, or the interface between light and atoms allowing the implementation of a quantum memory. This toolbox of available operations has recently been significantly extended by conditional photon subtraction, which allows the generation of highly nonclassical states with negative Wigner functions. This opens access to the realm of non-Gaussian operations, which are essential to several critical applications such as CV entanglement distillation or CV quantum computing. By building on these recent spectacular achievements, the present project aims at carrying out exploratory research on mesoscopic CV quantum information systems, with the ambitious ultimate objective of designing the first small-scale quantum processor using this CV toolbox. In an interplay between theory and experimental research, the consortium will investigate the hitherto unexplored potential of CV quantum computing and will address all necessary steps on the way to mesoscopic CV processors. This includes the engineering of non-Gaussian operations on photonic and atomic states exploiting the measurement-induced or actual nonlinearities between light and atoms, CV quantum computing with cat states or cluster states, CV entanglement distillation, error correction, and quantum repeaters. It is anticipated that the present project will have a strong impact on the future of ICT-related technologies and further strengthen the pan-European cooperation in a research area where Europe has started to establish itself at the leading edge.

A.1.3 List of beneficiaries

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5	University of St. Andrews	USTAN	UK	1	36
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PART B

B1. Concept and objectives, progress beyond state-of-the-art, S/T methodology and work plan

B.1.1 Concept and project objective(s)

Today's information society is more than ever relying on the secure transfer of sensitive information over public communication networks such as the Internet. In 1994, Peter Shor, from Bell labs, invented a quantum algorithm for the factoring of large numbers, which is exponentially faster than any classical algorithm[3]. If a quantum computer[4] capable of running this algorithm can be built, it would threaten the security of Internet communications because Shor's algorithm could then be used to decipher messages encrypted using widespread public-key cryptosystems such as RSA (Rivest-Shamir-Adleman). Remarkably, in addition to posing this potential threat, quantum physics also provides a revolutionary solution to the problem of secret communication in the form of quantum cryptography[5]. This technique offers the possibility for unconditionally secure communication, whose security is guaranteed by the laws of quantum physics instead of unproven hypotheses on the computational hardness of certain mathematical tasks such as factoring. These seminal discoveries have stimulated, over the last decade, the dramatic development of quantum information science – a young interdisciplinary field aiming at exploring the many novel opportunities offered by quantum physics for processing information. It is nowadays widely recognized that quantum technologies have the potential to revolutionize the way we compute and communicate.

In the recent years, so-called *continuous variables* (CV) have emerged as a viable and extremely promising alternative to the traditional quantum bit-based approaches to quantum information processing[6,7]. Encoding CV information onto *mesoscopic carriers*, such as the quadrature components of light modes or the collective spin degrees of freedom of atoms, has been proven to offer several distinct advantages, making CV a tool of major importance for the development of future informational and computational systems. Several experimental breakthroughs have been achieved that support this promise, for example, the deterministic generation of entangled or squeezed states in optical parametric amplifiers, the high-rate quantum distribution of secret keys using off-the-shelve telecom components[8], or the highly efficient coupling of light with atoms, allowing the demonstration of a quantum memory for light[9] as well as the inter-species quantum teleportation[10]. The toolbox of operations that are

[3] P. W. Shor, Proc. 35nd Annual Symposium on Foundations of Computer Science **124**, IEEE Computer Society Press (1994).

[4] M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information* (Cambridge University Press, Cambridge, England, 2000).

[5] N. Gisin, G. Ribordy, W. Tittel, and H. Zbinden, Rev. Mod. Phys. **74**, 145 (2002).

[6] S. L. Braunstein and P. van Loock, Rev. Mod. Phys. **77**, 513 (2005).

[7] *Quantum Information with Continuous Variables of Atoms and Light*, edited by N.J. Cerf, G. Leuchs, and E.S. Polzik, (Imperial College Press, London, 2007).

[8] F. Grosshans, G. Van Assche, J. Wenger, R. Brouri, N.J. Cerf, and P. Grangier, *Quantum key distribution using Gaussian-modulated coherent states,* Nature **421**, 238 (2003).

[9] B. Julsgaard, J. Sherson, J.I. Cirac, J. Fiurášek, and E.S. Polzik, *Experimental demonstration of quantum memory for light,* Nature **432**, 482 (2004).

[10] J. F. Sherson, H. Krauter, R. K. Olsson, B. Julsgaard, K. Hammerer, I. Cirac, and E. S. Polzik, *Quantum teleportation between light and matter*, Nature **443**, 557 (2006).

available for the manipulation of mesoscopic CV states has even been recently extended with conditional photon subtraction[11,12], a process which enabled the generation of non-classical states with negative Wigner functions. This has opened access to the realm of *non-Gaussian operations*, which are essential to several critical applications such as CV entanglement distillation or CV quantum computing. In view of these recent spectacular achievements, due, for many of them, to members of the present consortium, all conditions appear to be met today for the success of a focused research project that explores the various opportunities offered by this CV toolbox to reach concrete informational and computational goals.

The present STREP proposal aims at developing exploratory research on mesoscopic CV quantum information systems, both on the theoretical and experimental sides, with the ambitious ultimate objective of designing the first *small-scale quantum processor* using this *CV paradigm*. It addresses the work programme of this call as it concerns an "ICT-relevant research topic of a foundational nature, aiming at a breakthrough". A particular – high pay-off – application that we target is the *CV quantum repeater*, that is, the small processor that is expected to be found in the nodes of future quantum communication networks. Other main challenges that will be addressed also include the development of *CV entanglement distillation*, *CV quantum computing models*, and *CV quantum error correction procedures*. As explained later on, harnessing non-Gaussian states is an absolute prerequisite in order to reach these goals, so that the recent proof-of-concept demonstration of non-Gaussian operations achieved by three teams in the world (two of them belonging to the present consortium), warrants the viability of the present project. COMPAS will build on these successes in order to develop *mesoscopic CV processors*, which should initiate a major step in the future of quantum technologies. In addition to its exploratory nature, COMPAS will thus also pursue a type of research aiming at "refining visionary ideas that have gone past the proof-of-concept phase" in order to "bring them to a further maturity level".

As detailed in the following, the concrete objectives of the project COMPAS are to experimentally demonstrate several computational tasks that represent fundamental steps on the way to mesoscopic CV processors. For instance, it is indispensable to engineer *highly non-Gaussian states* of light and atoms (with negative Wigner functions) in order to achieve most relevant CV computational processes, so that this will be a central objective of the project. In parallel, specific models for CV quantum computing will be investigated (first theoretically, then experimentally), such as one-way computing based on *CV cluster states*. The major role of non-Gaussian quantum states in this context also motivates the investigation of the *nonlinearities* of atomic media (atomic vapors or cold atoms) in order to use them as quantum interface for quantum information or as a means to effect novel photonic quantum gates. Another critical research topic concerns *measurement-induced nonlinearities* as an alternative method to realize informational tasks such as the distillation of non-Gaussian entangled states, a crucial step towards CV quantum repeaters. Finally, "*cat-states*" *computing*[13], i.e., quantum computing based on mesoscopic states, is another theme which very naturally arises on the way to CV computing, so that the generation and "*breeding*" of cat states will be of utmost importance in this project. These various topics will be studied by

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[11] A. Ourjoumtsev, R. Tualle-Brouri, J. Laurat, and P. Grangier, *Generating optical Schrödinger kittens for quantum information processing,* Science **312**, 83 (2006).

[12] J.S. Neergaard-Nielsen, B. Melholt Nielsen, C. Hettich, K. Mølmer, E.S. Polzik, *Generation of a superposition of odd photon number states for quantum information networks*, Phys. Rev. Lett. **97**, 083604 (2006).

[13] T. C. Ralph, A. Gilchrist, G. J. Milburn, W. J. Munro, and S. Glancy, *Quantum computation with optical coherent states*, Phys. Rev. A **68**, 042319 (2003).

theoretical teams of the consortium, and, whenever possible, addressed simultaneously by the experimental teams.

As illustrated in the following table, the present consortium is composed of six theoretical groups (ULB, MPG, ICFO, UP, USTAN, POTSDAM) and four – effectively five[14] – experimental groups (CNRS, NBI, DTU, FAU), each having a leading expertise in quantum optics and quantum information theory. It comprises scientists who have been largely involved in the recent developments in continuous-variable quantum information processing. This strong experimental vs. theoretical complementarity will ensure that the theoretical ideas developed in the course of the project will be demonstrated by the experimental groups in a close collaboration. As a matter of fact, virtually all main research tasks within COMPAS will be carried out jointly by theorists and experimentalists. This anticipated strong interplay between theory and experiments strengthens the need for a supra-national collaborative scale in order to reach the ultimate objectives of the project. Finally, the proposed project duration of 36 months is deemed appropriate in order to assess the general viability of CV quantum computational systems.

Part. no.	Part. short name	Team leader	Nature of work
1	ULB	Nicolas J. Cerf	THE
2	MPG	J. Ignacio Cirac	THE
3	ICFO	Antonio Acin	THE
4	UP	Jaromir Fiurasek	THE
5	USTAN	Natalia Korolkova	THE
6	POTSDAM	Jens Eisert	THE
7	CNRS/IO CNRS/ENS	Philippe Grangier Elisabeth Giacobino	EXP EXP
8	NBI	Eugene S. Polzik	EXP
9	DTU	Ulrik L. Andersen	EXP
10	FAU	Gerd Leuchs	EXP

List of participants in COMPAS, including the names of team leaders and the nature of the proposed work (THEory or EXPeriments).

[14] The CNRS partner is actually composed of two distinct groups, denoted as CNRS/IO and CNRS/ENS in the following, so that five experimental teams compose the consortium. (IO=Institut d'Optique; ENS=Ecole Normale Supérieure)

B.1.2 Progress beyond the state of the art

There is a very important and well established research effort worldwide in an attempt to realize quantum computers able to solve hard computational problems. Several technologies are envisaged, but the common philosophy is generally to seek for ways to control a register consisting of quantum bits. This can be viewed as a *top-down approach* in the sense that the informational and/or computational tasks that could be achieved are already identified, at least in part, while the core problem lies in the physical implementation of the quantum computer. The planned research within COMPAS breaks this paradigm: it is oriented towards the specific goal of investigating and designing *small-scale CV quantum processors*, where several photonic and/or atomic modes would interact in a controlled manner. Such small processors could for instance form the nodes of advanced quantum communication networks, or achieve quantum error correction. In this respect, the current proposal rather pursues a *bottom-up approach*, starting from a CV toolbox that has already shown a remarkable success in the laboratory and then building on it to achieve a more modest but realistic goal.

The innovative content of our proposed research is twofold. Firstly, the recent experimental progresses enabling the generation and manipulation of non-Gaussian states have drastically enhanced the promises of CV information processing. Non-Gaussian states (with negative Wigner functions) happen to be compulsory for universal quantum computing with CV states because Gaussian operations can be efficiently simulated on a classical computer, so they are useless in this respect[15]. As a consequence of the *Gaussian no-go theorem*, the de-Gaussification operation is equally necessary for CV entanglement purification[16], which itself is required to reduce the noise arising due to losses and decoherence during the distribution of entangled CV states between the nodes of a communication network. Interestingly, the realm of non-Gaussian states and operations for atomic ensembles and freely propagating light beams has remained almost unexplored until today, as it has opened only very recently. Secondly, the innovation of our proposal lies in the investigation of CV computing, while essentially all studies on CV quantum carriers to date (including those of partners of the present proposal) have been concerned with quantum communication issues. It is fair to say that *CV quantum computing* is, in contrast, almost a virgin territory today, with extremely few things known for example about CV quantum algorithms. This more “foundational” theme is certainly the part of the present project associated with the highest risk, but surely also that with the highest pay-off. It justifies the submission of the present proposal within FET-Open instead of the mainstream QIPC proactive research programme (see Section 3).

It should be noted that COMPAS displays at the same time a more “mature” component, aiming at exploiting the existing state of knowledge and toolbox of experimental results on CV information carriers and, more specifically, on the interfacing between photonic and atomic CV carriers. In particular, several steps on the way to the *CV quantum repeater* have already been demonstrated by members of the present consortium, such as the quantum memory for light, so that the development of this particular instance of a mesoscopic CV processor has now become a very realistic challenge. If successful, this more “maturing-type”

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[15] S. D. Bartlett and Barry C. Sanders, *Efficient Classical Simulation of Optical Quantum Information Circuits*, Phys. Rev. Lett. **89**, 207903 (2002).

[16] J. Eisert, S. Scheel, and M.B. Plenio, Phys. Rev. Lett. **89**, 137903 (2002); G. Giedke and J.I. Cirac, Phys. Rev. A **66**, 032316 (2002).

research will nevertheless produce a breakthrough in quantum information science as it would imply that the CV paradigm is a realistic solution to long-distance quantum communication.

B.1.3 S/T methodology and associated work plan

B.1.3.1 Overall strategy and general description

Our project is structured into 3 scientific workpackages (WP1-3), which are organized in a "star-shaped" structure and will be carried out by specific subgroups of the consortium. In a nutshell, WP1 will be centered on the *design of photonic building blocks* while WP2 will focus on the *design of atomic building blocks*, both with the specific perspective of realizing continuous-variable information processing. Then, WP3 will integrate the outcomes of WP1 and WP2 towards the goal of *experimentally demonstrating mesoscopic CV quantum processors or algorithms*. Each of these 3 workpackages will be directed by one "leading" (L) partner, who will be responsible for its progress and be assisted in such a task by several "supporting" (S) partners. The share of the budget given to each partner depends, of course, on the corresponding work load in the project; hence L partners request larger budgets than S partners. Note that the 3 subgroups of partners associated with the 3 workpackages are mutually exclusive. This structure will of course not prevent L or S partners associated with one workpackage to act also as "auxiliary" partners in other workpackages, although the associated resources will be significantly smaller. This "auxiliary" role will actually guarantee an efficient cooperation within the project. In particular, the outcomes of WP1 and WP2 will be transferred towards WP3, where they will often be exploited by the same partners as those having initiated the research in WP1 or WP2, even though these partners will then play an "auxiliary" role with a lower staff effort and budget in WP3. Finally, a last workpackage WP4, led by the coordinator, will be devoted to the consortium management.

The following table summarizes the themes of the 4 workpackages of COMPAS, with the short names of the leading and supporting partners that are involved, as well as the corresponding shares of the budget (requested EC contribution). Note that this is only an approximate breakdown of the total budget since it does not take into account the involvement of "auxiliary" partners in some tasks. This, however, illustrates the good balance of the requested resources for each of the workpackages, as well as the complementarity between theory and experiments.

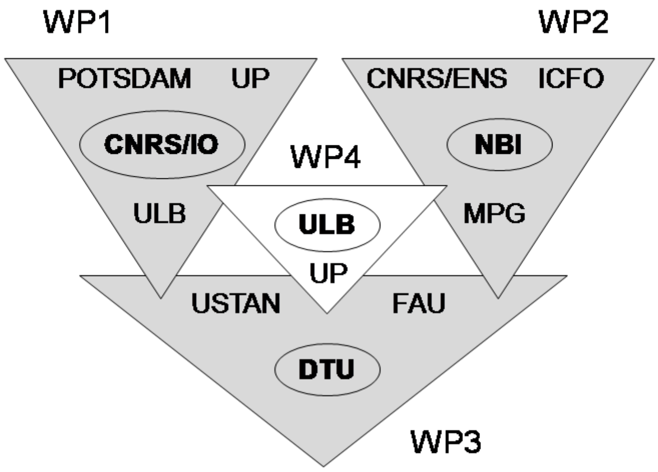
WP 1	**Design of photonic components of CV quantum computing** **L:** CNRS/IO (201 k€) **S:** ULB (138 k€), UP (120 k€), POTSDAM (84 k€)	543 k€
WP2	**Design of atomic components of CV quantum computing** **L:** NBI (201 k€) **S:** CNRS/ENS (135.5 k€), MPG (120 k€), ICFO (84 k€)	540.5 k€
WP3	**Demonstration of mesoscopic CV quantum processors** **L:** DTU (201 k€) **S:** FAU (135.5 k€), USTAN (84 k€)	420.5 k€
WP4	**Project management and knowledge dissemination** **L:** ULB (80 k€) **S:** UP (8 k€)	88 k€
TOTAL		1,592 k€

Structure of the project divided into 4 workpackages (WP1-4). The names of the leading (L) and supporting (S) partners are indicated, as well as the associated shares of the budget (requested EC contributions).

A key specificity of the COMPAS project is indeed that each of the scientific workpackages WP1-3 contains both a theoretical and an experimental component, which warrants that both activities will be developed in parallel and that the arising of any frontier between theory and experiments will be avoided. An experimental team is nevertheless the leading partner of each workpackage (see underlined names below), given that the ultimate objective of the project is an experimental proof-of-principle demonstration.

- **WP1**, whose experimental part is centered on photonic CV information tools, also contains a large theoretical component, aiming at assessing the new promising avenues for CV quantum computing. Several of the techniques that will be investigated (e.g., cat-state computing, one-way computing) involve light, which is the rationale for carrying out this research theme within this workpackage. *Experimental partner*: CNRS/IO. *Theory partners*: ULB, UP, POTSDAM.
- **WP2** also has a significant theoretical component, related to the fundamental physics of the interface between atoms and photons. Better harnessing this light-matter-interaction indeed happens to be indispensable to realize efficient atomic quantum memories for light, which is one of the main experimental research focuses of WP2. This research also extends to the design of quantum repeaters, which requires efficient quantum memories with long storage time. The investigation of new geometries for quantum networks also falls into WP2. *Experimental partners*: NBI, CNRS/ENS. *Theory partners*: MPG, ICFO.
- **WP3** will build upon these two rather "component-oriented" workpackages and be more "system-oriented", focusing on the demonstration of CV protocols, algorithms, and devices. WP3 is thus mainly an experimental workpackage, although it will also be supplemented with a theoretical component devoted to CV entanglement distillation, noise filtering, and error correction protocols. *Experimental partners*: DTU, FAU. *Theory partners*: USTAN.

The overall "star-shaped" organizational structure of COMPAS can be schematically visualized in the following chart (solely the leading and supporting partners are shown here, and the short names of leading partners are circled):



Organizational structure of COMPAS. For clarity, the involvement of "auxiliary" partners in the different workpackages is not shown (the full list of partners is specified in the detailed description of tasks).

B.1.3.2 Timing of work packages and their components

The COMPAS project is intended to last 36 months. We envisage two main layers of activities within the project, of an increasing level of integration. This first one, comprising WP1 and WP2, is "component-oriented" and will target the development of (theoretical and experimental; photonic and atomic) building blocks necessary to develop CV solutions to quantum computing. The second layer, comprising WP3, is "system-oriented" in the sense that it will aim at demonstrating CV computational devices or algorithms. The expected timing of the project follows this strategy (i.e., WP3 extends further in time than WP1-2).

More precisely, each of the 3 scientific workpackages WP1-3 comprises 4 tasks (see detailed work plan below), corresponding to the main pieces of work that need to be achieved in order to attain the overall objective of the workpackage. Each of these tasks is associated with one (or a few) deliverable(s), which will be used to assess the achievement of the corresponding task. Note that a report on the status of all 3 scientific workpackages WP1-3 will be provided in the first periodic activity report, in particular concerning the tasks which have not yet led to a deliverable at that time (in WP2 and WP3). In addition, a reflection paper will be written by all project members by month 12, following the brainstorming session on the potential "medium-term scientific spin-offs" of this research direction that will be organized at the occasion of the CV-QIP workshops (see Sect. B3.2 *i*).

Finally, a few (2 or 3) milestones are expected during the course of each of the 3 scientific workpackages WP1-3, which will witness the successful attainment of a major result required to further pursue the workpackage or the fulfillment of a central goal of the project. All milestones are associated with experimental achievements, since this is the ultimate objective of the project. The timing of the tasks and deliverables can be visualized in the following GANTT chart (see next page).

GANTT chart of the COMPAS project

<table>
<tr><td colspan="3"></td><td colspan="12">YEAR 1</td><td colspan="12">YEAR 2</td><td colspan="12">YEAR 3</td></tr>
<tr><td colspan="3"></td><td>01</td><td>02</td><td>03</td><td>04</td><td>05</td><td>06</td><td>07</td><td>08</td><td>09</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td><td>24</td><td>25</td><td>26</td><td>27</td><td>28</td><td>29</td><td>30</td><td>31</td><td>32</td><td>33</td><td>34</td><td>35</td><td>36</td></tr>
<tr><td rowspan="6">WP1</td><td>T1.1</td><td>D1.1</td><td colspan="12">Characterization of CV entanglement.</td><td colspan="24"></td></tr>
<tr><td>T1.2</td><td>D1.2</td><td colspan="24">Exploration of CV quantum computing with non-Gaussian quantum states.</td><td colspan="12"></td></tr>
<tr><td rowspan="2">T1.3</td><td>D1.3</td><td colspan="24">Generation of high photon number Fock states.</td><td colspan="12"></td></tr>
<tr><td>D1.4</td><td colspan="6"></td><td colspan="18">Generation of monomode and multimode cat states.</td><td colspan="12"></td></tr>
<tr><td rowspan="2">T1.4</td><td>D1.5</td><td colspan="36">Measurement-induced nonlinear operations.</td></tr>
<tr><td>D1.6</td><td colspan="24">Detector process tomography.</td><td colspan="12"></td></tr>
<tr><td rowspan="5">WP2</td><td>T2.1</td><td>D2.1</td><td colspan="36">Engineering and manipulating states in atomic quantum memory.</td></tr>
<tr><td>T2.2</td><td>D2.2</td><td colspan="24">Light-atoms quantum interface for quantum information processing.</td><td colspan="12"></td></tr>
<tr><td rowspan="2">T2.3</td><td>D2.3</td><td colspan="24">Interfacing light with atoms in optical lattices and trapped ions.</td><td colspan="12"></td></tr>
<tr><td>D2.4</td><td colspan="24">Alternative methods for generating non-Gaussian states using Kerr nonlinearity.</td><td colspan="12"></td></tr>
<tr><td>T2.4</td><td>D2.5</td><td colspan="24">CV quantum repeaters based on complex quantum network geometries.</td><td colspan="12"></td></tr>
<tr><td rowspan="5">WP3</td><td rowspan="2">T3.1</td><td>D3.1</td><td colspan="12"></td><td colspan="24">Cat states implementation of the sign-flip operation.</td></tr>
<tr><td>D3.2</td><td colspan="17"></td><td colspan="19">Assessment of the implementation of the C-NOT and Hadamard gates.</td></tr>
<tr><td>T3.2</td><td>D3.3</td><td colspan="24">Demonstration of CV quantum error correction.</td><td colspan="12"></td></tr>
<tr><td>T3.3</td><td>D3.4</td><td colspan="6"></td><td colspan="18">Filtering of noise in CV systems.</td><td colspan="12"></td></tr>
<tr><td>T3.4</td><td>D3.5</td><td colspan="6"></td><td colspan="30">Distillation or concentration of CV entanglement.</td></tr>
<tr><td rowspan="6">WP4</td><td rowspan="6"></td><td>D4.1</td><td colspan="6">Project website</td><td colspan="30"></td></tr>
<tr><td>D4.2</td><td colspan="11"></td><td>AR</td><td colspan="24"></td></tr>
<tr><td>D4.3</td><td colspan="23"></td><td>AR</td><td colspan="12"></td></tr>
<tr><td>D4.4</td><td colspan="35"></td><td>AR</td></tr>
<tr><td>D4.5</td><td colspan="35"></td><td>FR</td></tr>
<tr><td>D4.6</td><td colspan="35"></td><td>DP</td></tr>
</table>

B.1.3.3 Work package list /overview

Project Number [1]	212008	Project Acronym [2]	COMPAS

LIST OF WORK PACKAGES (WP)

WP Number [53]	WP Title	Type of activity [54]	Lead beneficiary number [55]	Person-months [56]	Start month [57]	End month [58]
1	Design of photonic components of CV quantum computing	RTD	7	110	1	36
2	Design of atomic components of CV quantum computing	RTD	8	134	1	36
3	Demonstration of mesoscopic CV quantum processors	RTD	9	136	1	36
4	Project management and knowledge dissemination	MGT	1	18	1	36

In addition to the detailed content of the workpackages, which will be provided below in Sect. B.1.3.5, an overview of the overall work plan and project methodology is given here for clarity and conciseness. First, the topics that will be investigated within the 3 scientific workpackages WP1-3 are summarized hereunder (participating "auxiliary" partners are indicated between parentheses):

WP 1. *Design of photonic components of CV quantum computing.*
EXP: CNRS/IO TH: ULB, UP, POTSDAM, (ICFO)

The "hard core" of this workpackage is primarily devoted to the engineering of mesoscopic quantum states of light, viewed as a central prerequisite to CV quantum processors. This experimental research effort will be supplemented with a main theoretical activity on CV quantum computing, centered on photonic CV information carriers. We will investigate the measurement-induced techniques, where conditioning on single-photon or homodyne detection is used to effect interesting informational operations. We will also explore the prospects of one-way quantum computing with CV cluster states, the simulation of physical systems by CV processors, and even the related foundational issue of the non-locality of CV states (e.g., the classical simulation of CV states with negative Wigner function). This is precisely the point where non-Gaussian states and operations play a central role as it is known that quadratic Hamiltonians (which generate Gaussian states) are insufficient in several applications such as universal computing, entanglement distillation, Bell tests, etc. Thus, a major goal of WP1, on the experimental side, will be the generation of high-purity non-Gaussian mesoscopic states of light with negative Wigner function. This will further lead, in WP3, to the demonstration of quantum gates such as the C-NOT and Hadamard gates, and eventually of cat-state CV computing.

WP 2. *Design of atomic components of CV quantum computing.*
EXP: NBI, CNRS/ENS, (CNRS/IO) TH: MPG, ICFO, (UP), (USTAN)

This workpackage is concerned with the physical implementation of the quantum gates or operations used in protocols where atomic information carriers need to be manipulated (in addition to photonic ones). This will, almost by definition, involve the nonlinear interaction of light with matter (with a higher than 2^{nd} order in the canonical variables for non-Gaussian operations). We will first exploit the available techniques and interactions, such as de-Gaussification, measurement-induced operations, feedforward, and non-resonant interaction of light with atoms in order to design more complex (non-Gaussian) interactions between several modes, while optimizing the fidelity and success rate of these schemes. On the theory side, the physics of the various sources of nonlinear coupling will be investigated in depth, such as the Faraday effect in dense atomic vapors, the coupling of light to a BEC, the cross-Kerr effect in EIT, and even the giant (photon-photon) nonlinearities of single-photon pulses traveling in optical cavities. On the experimental side, new techniques to realize more efficient and longer-lived quantum atomic memories for light will be developed and tested. The engineering of high-purity non-Gaussian mesoscopic states of atoms with negative Wigner function will be still another major goal, paving the way to the experimental demonstration, in WP3, of CV entanglement purification and, ultimately, of CV quantum repeaters. Alternative quantum network geometries will also be analyzed in this perspective.

WP 3. *Demonstration of mesoscopic CV quantum processors.*
EXP: DTU, FAU, (CNRS/IO) TH: USTAN, (ULB), (UP), (POTSDAM)

This workpackage is concerned with the experimental proof-of-principle demonstration of more advanced schemes, parts of the mesoscopic CV quantum processor envisaged in the theoretical tasks of the project. This will require the combination of the experimental procedures developed in WP1-2 into more sophisticated schemes. For example, we intend to demonstrate the generation of multimode entangled states of light and atoms which could be used for teleportation-based implementation of quantum operations as well as the preparation of optical CV cluster states, which could be used in one-way quantum computing. This also includes the theoretical identification of the operations required for computational applications such as entanglement distillation or concentration in the nodes of a CV quantum network. In parallel, the demonstration of CV quantum error correction and CV cat-states quantum computing (using cat states as ancillas and homodyne detection for conditioning) will also be central components of WP3. The role of "auxiliary" partners will be more important in this workpackage since several experimental techniques will need to be transferred from WP1-2. Finally, the ultimate goal of WP3 will be to assess the prospects of mesoscopic CV quantum processors and algorithms.

Second, the breakdown of each of these 3 scientific workpackages into 4 tasks is described below, with a short overview of each task. The theoretical (TH) or experimental (EXP) nature of each task is indicated, as well as the name of the (leading and supporting) partners involved. Participating "auxiliary" partners are again indicated between parentheses.

► **Tasks in WP 1**

T 1.1 *Basic concepts and theoretical tools for CV information processing.*
TH: ULB, POTSDAM, (ICFO)

This task first aims at characterizing and detecting quantum entanglement in multipartite non-Gaussian states. In contrast to the case of Gaussian states, few results exist for non-Gaussian states. In view of the importance of the latter states in this project, we will develop methods to infer (bounds on) the entanglement out of the experimentally available data, requiring fewer data than full quantum state tomography but without making *a priori* assumptions on the state. Another specific objective is the understanding of the minimum "non-Gaussian resources" needed to perform a "useful" computation (which cannot be simulated classically). This will lead us to the issue of the classical simulation of multipartite CV states with non-positive Wigner function, and its implication on computational issues.

T 1.2 *Exploring models of CV quantum computing*
TH: ULB, UP, POTSDAM, (ICFO)

The objective of this task is to explore models of quantum computing with continuous-variable (mainly optical) carriers, in particular circuit-based and one-way quantum computing. The investigation of the latter model in the case of mesoscopic information carriers will lead us to study ways of generating multimode CV cluster states. The potential use of CV processors to simulate quantum systems will also be analyzed. In parallel, another paradigm for CV quantum computing that will be explored relies on "cat states", i.e., multimode superpositions of quasi-classical states with non-positive Wigner functions. Cat-state computing can be viewed as a CV analogue to the celebrated Knill-Laflamme-Milburn (KLM) linear-optics quantum computing scheme[17], where cat states are used instead of Fock states as a resource, and homodyne detection replaces photon counting. Finally, we will assess the approach where an off-line supply of non-Gaussian auxiliary states is used as a resource together with linear optics, measurements, and feedforward, in order to effect highly non-Gaussian operations, potentially useful in the teleportation model of quantum computing.

T 1.3 *Engineering non-Gaussian states of light*
EXP: CNRS/IO

The objective of this task is to address the generation of highly non-Gaussian states of traveling light with negative Wigner function, in particular high-N Fock states and single- or multi-mode "cat states". As already explained, these states are essential elements for CV quantum information processing. The role of measurement-induced techniques (see T1.4) will be established. This task, supplemented with the "breeding"

[17] E. Knill, R. Laflamme, and G. J. Milburn, *A scheme for efficient quantum computation with linear optics*, Nature **409**, 46 (2001).

of cat states, should pave the way to the demonstration of CV cat-states computing, in particular the C-NOT and Hadamard gates that will be realized in WP3 (see T3.1).

T 1.4 *Investigating measurement-induced CV information processes*
EXP: CNRS/IO TH: ULB, UP, POTSDAM

The objective is to analyze the measurement-induced nonlinearity that may be attained by combining linear coupling, single-photon counting, homodyne detection, feedforward or conditioning. Such nonlinear operations are crucial to address universal CV quantum computation and CV entanglement purification. Several CV information protocols will be realized in order to demonstrate this paradigm, which will then be exploited in WP3 for the realization of computing protocols (see, e.g., T3.1). A toolbox for process tomography will also need to be developed, for assessing the fidelity of the measurement-induced processes.

► Tasks in WP 2

T 2.1 *Engineering and manipulating states of an atomic quantum memory*
EXP: NBI TH: MPG, (UP)

The focus of this task is to develop techniques for engineering and/or manipulating the states of an atomic quantum memory[18]. In particular, we will exploit combination of photon counting and homodyne measurement on squeezed light beam interacting with the atomic ensemble, which should allow us to create a large variety of highly non-classical atomic CV states. The state engineering schemes will be generalized to methods for implementing various non-linear transformations of the atomic memory states. In the experiments, we will exploit the Faraday rotation due to the Kerr effect for mesoscopic light pulses traveling in dense atomic vapors, but will also consider alternative approach based on the nonlinear coupling of light with a degenerate quantum gas (Rubidium Bose-Einstein condensate) at low temperatures.

T 2.2 *Realization of high-efficiency long-lived quantum memories*
EXP: NBI, CNRS/ENS TH: MPG

Novel principles for the realization of long-lived quantum memories will be investigated and assessed in the laboratory. We will, in particular, look for the best experimental strategy for mapping light states onto atomic states and *vice versa*. The performance of the proposed mapping protocols for memory storage and retrieval of non-Gaussian states of light will be determined. In parallel, we will develop new schemes for high-efficiency quantum memories based on the off-resonant interaction of light with cold Cesium atoms held in a magneto-optic trap. The generation of entanglement between light and atomic spin in this system will be investigated, and the atomic quantum cloning of a light state will be assessed.

[18] B. Julsgaard, J. Sherson, J. Fiurášek, J.I. Cirac, and E.S. Polzik, *Experimental demonstration of quantum memory for light,* Nature **432**, 482 (2004).

T 2.3 *Investigating alternative schemes for photonic and/or atomic quantum gates*
EXP: CNRS/ENS, (CNRS/IO) TH: MPG, (USTAN)

This task will explore novel effects that may potentially be exploited in order to get a very high nonlinear effect. In particular, we will investigate the cross-Kerr effect that arises in an Electromagnetically Induced Transparency-type interaction of light with an atomic system. It is anticipated that the strength of this nonlinear interaction may be orders of magnitude higher. Another research avenue that will be pursued consists in exploring the possibilities offered by atoms trapped in optical lattices. These lattices could be used to create specific photonic states, useful for CV information processing. Alternatively, the photons could be used to detect atomic states. This may be a clever way to perform highly non-Gaussian operations.

T 2.4 *Developing quantum networks based on CV quantum repeaters*
EXP: NBI TH: ICFO, MPG

We will assess the route towards the CV quantum repeater, exploiting quantum entanglement distillation, entanglement swapping, and quantum memory. We will, in particular, investigate alternatives to the standard DLCZ protocol[19], involving more complex quantum network geometries. The DLCZ protocol has been built for qubit-based networks, where two distant parties are connected by a line of quantum repeaters. CV quantum networks as well as more complex geometries, of dimension larger than one, are largely unexplored and deserve investigation.

► Tasks in WP 3

T 3.1 *Demonstrating CV one-way computing and/or cat-state computing*
EXP: DTU, FAU, (CNRS/IO) TH: USTAN

The first objective of this task is the generation of optical CV cluster states of 4-6-8-modal squeezed beams, on the way to the demonstration of measurement-based one-way computing (investigated in T1.2 for its theoretical aspects). A second research direction will focus on the experimental demonstration of quantum computing with cat states, including the realization of quantum gates (Hadamard and/or C-NOT gates) within this CV paradigm.

T 3.2 *Demonstrating CV quantum error correction*
EXP: DTU TH: USTAN, (ULB), (UP)

We will develop quantum protocols for the correction (or detection) of errors (or erasures) that are suitable to CV information carriers. These protocols, in which information is encoded into a CV multipartite entangled mesoscopic state, should be useful for circumventing the noise in distributed quantum computing networks. This issue is directly linked to the circuit-based model studied in T1.2.

T 3.3 *Demonstrating quantum noise filtering in CV systems*
EXP: DTU, FAU TH: USTAN, (UP)

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[19] L. M. Duan, M. D. Lukin, J. I. Cirac, and P. Zoller, Nature (London) **414**, 413 (2001).

We will develop and demonstrate protocols for filtering the noise that is superimposed on CV quantum states. The filtering will be based on photon counting measurements, and conditioning on the measurement outcomes. Such filtering techniques could suppress discrete noise arising e.g. due to timing-jitter or beam positioning fluctuations. Such noise is likely to be present in any implementation of advanced CV quantum information processing schemes.

T 3.4 *Demonstrating the distillation and/or concentration of CV entanglement*
EXP: FAU TH: USTAN, (UP), (POTSDAM)

The objective of this task is to develop the various ingredients needed to demonstrate entanglement distillation and/or concentration, on the way to the CV quantum repeater. A possibility is that we use CV polarization squeezing to reach this goal.

Finally, a last workpackage (WP4) is dedicated to the project management and knowledge dissemination. Its description will be given in Sect. B2.1. It will be structured into 3 tasks, which are described hereunder:

► Tasks in WP 4

T 4.1 *Project web page and reporting*
TH: ULB, UP

The coordinator (ULB) together with the deputy coordinator (UP) will install and maintain the project web pages. These pages shall contain up-to-date information about the project goals, the scientific activities of the partners and the project results. Major achievements will be highlighted and presented in a way accessible to broad audience and media. A list of all publications with full access to reprints/preprints will be included. A link to web sites of all partners will be provided.

The coordinator and deputy coordinator will be in charge of preparing the annual reports and the final report at the end of the project as well as plan for dissemination and use of the generated knowledge. In this work they will be assisted by the workpackage leaders. In the periodic progress reports, all workpackage leaders will give an update of the status of the work that will allow reviewers to judge progress even in absence of deliverables due

T 4.2 *Project meetings and workshops*
TH: ULB, UP

A Project Coordination meeting will be organized every year, chaired by the coordinator. The research progress will be analyzed, and future directions of investigation will be defined. Issues raised by partners will be discussed and appropriate decisions will be made preferably by seeking a consensus among all partners. In addition, a major knowledge dissemination activity will be the organization of international workshops focused on continuous-variable quantum information processing, in a continuation of the series of "CV-QIP workshops" which has been running yearly since 2002.

T 4.3 *Contribution to activities at the level of FET-Open*
TH: ULB, UP

In order to support scientific cooperation at the FET-Open level and broad public awareness of project achievements, consortium members will ensure within the areas of interest of the project:

- Publication of project results throughout the duration of the project in widely accessible and, where available, openly accessible science and technology journals, as well as through conferences and through other channels, including the Web, which reach audiences beyond the academic community. Publication of a periodic press release, and other means of disseminating project progress to a wider audience, e.g. via video.
- Participation in FET-organised events, for example conferences, dedicated workshops and working groups, consultation meetings, summer schools, online forums, etc.
- International co-operation and contribution to relevant national and international activities (ex. joint workshops, calls, etc., for example with NSF).

The above activities will be reported in the project's Periodic Progress Reports (see T4.1).

In addition, the consortium agrees to include the following reference in all project-related publications, activities and events: "We acknowledge the financial support of the Future and Emerging Technologies (FET) programme within the Seventh Framework Programme for Research of the European Commission, under the FET-Open grant agreement COMPAS, number 212008".

T 4.4 *Reflection paper on the outlook of the research in continuous-variables QIPC*
TH: ULB, UP

By month 12, the coordinator (ULB) and deputy coordinator (UP), helped by all workpackage leaders, will give input to a short report on the outlook of the research in continuous variables (contribution to the area of quantum information, impact on other areas of research, in particular quantum optics). As explained in Sects. B1.3.2 and B3.2 *i*, this short report will follow the brainstorming session on the potential “medium-term scientific spin-offs” of continuous variables that will be organized at the occasion of the CV-QIP workshops.

B.1.3.4 Deliverables list

LIST OF DELIVERABLES - TO BE SUBMITTED FOR REVIEW TO EC							
Deliverable Number 61	Deliverable Title	WP number 53	Lead beneficiary number	Estimated indicative person-months	Nature 62	Dissemination level 63	Delivery date 64
D4.1	Project website	4	1	3	O	PU	6
D4.2	1st Periodic Progress Report	4	1	3	R	RE	12
D4.3	2nd Periodic Progress Report	4	1	3	R	RE	24
D4.4	3rd Periodic Progress Report	4	1	3	R	RE	36
D4.5	Final Report	4	1	3	R	RE	36
D4.6	Final plan for using and disseminating knowledge	4	1	3	R	PU	36
D1.1	Characterization of CV entanglement from experimental data	1	7	20	R	PU	12
D1.2	Exploration of CV quantum computing with non-Gaussian quantum states	1	7	20	R	PU	24
D1.3	Generation of high photon number Fock states	1	7	20	R	PU	24
D1.4	Generation of monomode and multimode cat states	1	7	20	R	PU	24
D1.5	Measurement-induced nonlinear operations	1	7	15	R	PU	36
D1.6	Detector process tomography	1	7	15	R	PU	24
D2.1	Engineering and manipulating states in atomic quantum memory	2	8	30	R	PU	36
D2.2	Light-atoms quantum interface for quantum information processing	2	8	30	R	PU	24
D2.3	Interfacing light with atoms in optical lattices and trapped ions	2	8	25	R	PU	24
D2.4	Alternative methods for generating non-Gaussian states using Kerr	2	8	25	R	PU	24

D2.5	CV quantum repeaters based on complex quantum network geometries	2	8	24	R	PU	24
D3.1	Cat-states implementation of the sign-flip operation	3	9	23	R	PU	36
D3.2	Assessment of the implementation of the C-NOT and Hadamard gates	3	9	23	R	PU	36
D3.3	Demonstration of CV quantum error correction	3	9	30	R	PU	24
D3.4	Filtering of noise in CV systems	3	9	30	R	PU	24
D3.5	Distillation or concentration of CV entanglement	3	9	30	R	PU	36
			Total	398.0			

B.1.3.5 Work package descriptions

ONE FORM PER WORK PACKAGE

Work package number 53	WP1	**Type of activity** 54	RTD
Work package title	Design of photonic components of CV quantum computing		
Start month	1		
End month	36		
Lead beneficiary number 55	7		

OBJECTIVES

A universal quantum processor should be ideally capable of performing an arbitrary transformation of the input quantum state. In the realm of quantum continuous variables, the range of experimentally accessible operations has until recently been restricted to the Gaussian operations, which can be represented by linear transformations of quadrature operators in the Heisenberg picture. Very recently, the experimental demonstration of single-photon subtraction from squeezed vacuum states via single-photon measurement has opened the access to a new domain of highly non-linear quantum optics. The objective of this workpackage is to fully exploit the potential of the photon counting measurements combined with linear optics, homodyne detection and feedforward. These tools will be used to generate highly non-Gaussian CV states and to design schemes for implementation of various non-linear quantum operations on light modes. Several platforms for CV quantum computing exploiting current or near-future experimental techniques will be considered, such as computing with Schrödinger cat states, CV one-way quantum computing, or CV teleportation-based quantum computing. We expect important findings along this way. Methods for estimating the entanglement of non-Gaussian states from experimental data will be developed and employed in the experiments.

DESCRIPTION OF WORK AND ROLE OF PARTNERS

In the following description of work, the names of leading (L) and supporting (S) partners are written in normal font, while those of "auxiliary" partners are written between parentheses.

T 1.1 Basic concepts and theoretical tools for CV information processing.
TH: ULB, POTSDAM, (ICFO)

An important prerequisite for evaluating the quality of multimode non-Gaussian entangled states needed for CV quantum information processing and computing schemes is the ability to verify and quantify the amount of their entanglement. A closely related issue is the question of whether measurements on a given CV entangled state can be simulated with classical resources. It is known that Gaussian measurements on Gaussian states can be simulated by classical correlations. Partners ULB and ICFO will investigate whether there exist states with non-positive Wigner function with a local model, at least for Gaussian measurements. Such states would be useless for communication complexity protocols, for instance. A related problem that will be also addressed consists of the analysis of the possibility to extend some of the recent results on the efficient classical simulation of quantum systems to CV systems. If a system can be efficiently simulated on a classical computer, then it is useless for quantum computation.
Any proof of functioning of a quantum device will clearly rely on its experimental verification. Partner POTSDAM will develop methods to directly estimate entanglement of a continuous-variable state using all of the available data from measurement outcomes, but making no further a-priori assumptions. This is expected to give rise to a powerful tool to directly certifiably estimate entanglement based on knowledge of higher moments, without having to rely on quantum state tomography, which is costly and in particular in the continuous-variable setting typically associated with relatively large errors.

T 1.2 Exploring models of CV quantum computing
TH: ULB, UP, POTSDAM, (ICFO)

A very promising approach to CV quantum computing is based on exploiting the Schrödinger cat states . The qubit can be represented by a superposition of two nearly orthogonal coherent states with sufficiently large amplitude, i.e., a cat state. Quantum gates for universal computing can, in principle, be implemented with linear optics, homodyne detection and off-line generated cat states. Partners ULB and POTSDAM will investigate in detail the potential of this platform for CV quantum computing.
The off-line prepared entangled states can be used to perform quantum operations by teleportation of quantum gates . It has been recently demonstrated that squeezing transformation can be implemented using auxiliary off-line generated squeezed vacuum states, passive linear optics, homodyne detection and deterministic feed-forward . Partner UP will generalize this approach beyond the realm of Gaussian operations and design schemes for applying various non-linear transformations with the use of off-line generated auxiliary Schrödinger cat states or other highly-nonclassical states, homodyne detection and

feed-forward. It is known that the cubic phase gate could, in principle, be implemented in this way , but a systematic study of operations that could be achieved with experimentally accessible resource states is clearly missing.
Another interesting paradigm for CV quantum computing consists of the one-way quantum computer where the computation proceeds by a series of measurements on parts of entangled multimode quantum state. Partner ICFO will study how to map the CV cluster state into a matrix-product-state picture, similarly as it was done in the finite dimensional case . Then, this formalism will be used to derive other examples of CV states allowing universal quantum computation, possibly connecting these states to ground states of local Hamiltonians. It will be also analyzed what are the minimal non-Gaussian resources needed for universal measurement-based quantum computation.
New measurement-based models of CV computing going beyond the one-way computer will be considered by partner POTSDAM. First preparatory work shows that this is indeed feasible for discrete-variable systems and could open up a new way of thinking about measurement-based computation. Further work will be dedicated to simulation of one continuous-variable system with another. This potentially high payoff-work relates to a topic that is hardly addressed in any other European project at the moment, specifically not in projects SCALA nor in QAP.

T 1.3 Engineering non-Gaussian states of light
EXP: CNRS/IO

Partner CNRS/IO will address the engineering of non-Gaussian states of traveling light. The possibility to generate highly non-Gaussian states using measurement-induced nonlinearities and conditioning is well-established now, following the recent demonstration of 2-photon states and Schrödinger kittens , using such methods. These states are basic resources in the CV computing toolbox, and it is of major importance to fully control their preparation. In the present task, we will focus on the generation of monomode and multimode Schrödinger cat states, i.e., superpositions of non-overlapping coherent states (the coherent states involved in the kittens mentioned above are too weak to fulfill this requirement). This goal can involve the production of high photon number Fock states, which can be obtained as a preliminary step using superconducting photon-resolving counters . In all this work, a special attention will be devoted to the purity of the states, in order to envision concrete applications in quantum computing.

T 1.4 Investigating measurement-induced CV information processes
EXP: CNRS/IO TH: ULB, UP, POTSDAM

Partners ULB, UP, and POTSDAM will investigate which basic non-linear transformations can be performed using photon-counting techniques or other nonlinear measurements supplemented with linear optics and squeezers. Any realistic experimental implementation of such transformation will inevitably add some noise, e.g. due to the imperfect detectors with non-unit efficiency. A natural figure of merit in the design of the basic nonlinear quantum gates will therefore be the noise added by the operation to the state, which should be kept at minimum. Subsequently, attention will be paid to maximization of success probability of the operation. The trade-off between the success probability of the nonlinear operations and the added noise will be studied in detail. After identifying the basic non-linear operations that can be implemented with currently available or near-future experimental techniques, methods to combine them into more complex transformations will be studied. On the one hand, the partners will identify which nonlinear operations are necessary for applications in quantum information processing such as quantum repeaters and attempt to design schemes implementing these operations. On the other hand, a complementary approach will be employed and it will be investigated how various quantum information protocols can be realized with the available effective nonlinearities. The ultimate goal of this task is to design a highly versatile device so that partner CNRS/IO may implement a wide range of non-linear operations. The scaling of the success probability of such gates with their complexity will be analyzed and optimized.
It must be stressed that, in order to fully understand the experimental feasibility of the preparation and manipulation of non-Gaussian quantum states, an exact knowledge of detection devices leading to the non-Gaussian character will be required. Therefore, a toolbox for process tomography that is fully characterizing photon counting detectors will be developed. This work will link to theoretical support work for quantum state manipulation with photon counting detectors.

DELIVERABLES AND MONTH OF DELIVERY

Characterization of CV entanglement from experimental data (see T 1.1 : Basic concepts and theoretical tools for CV information processing)

Exploration of CV quantum computing with non-Gaussian quantum states (see : T 1.2 : Exploring models of CV quantum computing)

Generation of high photon number Fock states (see T 1.3 : Engineering non-Gaussian states of light)

Generation of monomode and multimode cat states (see T 1.3 : Engineering non-Gaussian states of light)

Measurement-induced nonlinear operations (see T 1.4 : Investigating measurement-induced CV information processes)

Detector process tomography (see T 1.4 : Investigating measurement-induced CV information processes)

PERSON-MONTHS PER PARTICIPANT

Participation number [10]	Participant short name [11]	Person-months per participant
7	CNRS	24
1	ULB	24
4	UP	32
6	POTSDAM	24
3	ICFO	6
	Total	110.0

SCHEDULE OF MILESTONES

Milestone number [59]	Milestone name	Lead beneficiary number	Delivery date from Annex I [60]	Comments
MS2	Generation of CV cluster states of light	7	24	Towards measurement-based quantum computing
MS3	Generation and breeding of Schrödinger cat states of light	7	24	Towards cat-state quantum computing

DELIVERABLES – TO BE SUBMITTED FOR REVIEW TO EC

Deliverable Number [61]	Deliverable Title	Lead beneficiary number	Estimated indicative person-months	Nature [62]	Dissemination level [63]	Delivery date [64]
D1.1	Characterization of CV entanglement from experimental data	7	20	R	PU	12
D1.2	Exploration of CV quantum computing with non-Gaussian quantum states	7	20	R	PU	24
D1.3	Generation of high photon number Fock states	7	20	R	PU	24
D1.4	Generation of monomode and multimode cat states	7	20	R	PU	24
D1.5	Measurement-induced nonlinear operations	7	15	R	PU	36
D1.6	Detector process tomography	7	15	R	PU	24
		Total	110.0			

Work package number 53	WP2	Type of activity 54	RTD
Work package title	Design of atomic components of CV quantum computing		
Start month	1		
End month	36		
Lead beneficiary number 55	8		

OBJECTIVES

Developing memory registers for quantum signals carried by light is an essential objective for quantum information processing. Presently, while some spectacular results have been obtained in that direction with the demonstration of quantum pulse storage in an atomic vapor with fidelity higher than classical, a system allowing storage and retrieval of quantum variables is still missing. Atomic ensembles are good candidates for such memory registers, since quantum states of light can be stored in long-lived atomic spin states, by way of linear light-matter interaction. The quantum states can then be retrieved at a later stage. This kind of procedure also opens the way to manipulating the quantum state of matter in view of further processing. The present workpackage is thus devoted to development of high-efficiency long-lived quantum memories, design of optimized protocols for transfer of states between memory and light beams and analysis of methods for manipulating the states stored in the memory.
All the present protocols for the storage of the quantum states of traveling light beams in atomic ensembles and their subsequent retrieval can be described by linear Gaussian operations and, so far, only Gaussian states have been utilized in the experiments. It is, however, highly desirable to extend the toolbox of operations that can be performed on the state stored in the memory and to prepare highly non-classical non-Gaussian states in the memory. This is crucial, among other applications, for CV quantum repeaters. Also, the implementation of nonlinear operations considered in T1.2 requires storing off-line prepared highly non-classical states. A central goal of this workpackage is therefore to identify feasible techniques for engineering highly non-classical states of atomic memory and develop procedures for performing various nonlinear operations on the states in the memory. Alternative schemes for atoms-light interface based on the interaction of light with atoms in optical lattices or trapped ions will also be investigated. Finally, advanced quantum networks composed of quantum memory units and exhibiting complex geometrical structure will be studied.

DESCRIPTION OF WORK AND ROLE OF PARTNERS

T 2.1 Engineering and manipulating states of an atomic quantum memory
EXP: NBI TH: MPG, (UP)

Partners NBI, MPG and UP will investigate engineering of high purity non-Gaussian states of atoms and manipulation of states stored in the memory. The proposed method is based on generation of entanglement between light and atoms, followed by a quantum measurement on light and quantum feedback. The new paradigm that will be exploited is the combination of the homodyne measurement of light and photon counting. The basic scenario that will be considered is to let the atomic ensemble interact with photon-subtracted squeezed light beam that will be measured by a homodyne detector after passing through the atomic ensemble. Preliminary calculations suggest that this new approach allows for generation of highly non-classical states with negative Wigner function, such as a Schrödinger cat state. Partner NBI will attempt to demonstrate this technique experimentally using a dipole trapped sample of cold Cesium atoms which has recently been shown to provide a promising sample for a quantum interface with light. Another system that will be explored is the interface between light and a degenerate quantum gas (Rubidium Bose-Einstein condensate). Coherently backward scattered photons from a BEC are known to lead to super-radiance and to creation of a moving condensate with the energy equal to twice the photon recoil energy. Partner NBI will study whether this process can be used for generation of number-squeezed or other non-classical states of a quantum gas.
The quantum state engineering techniques will subsequently be extended to methods for applying various non-linear operations and filters to the state stored in a memory using its coupling with auxiliary light beams, linear optics, homodyning, photon counting and feed-forward. Success probability of such operations will be optimized. This part of the project shall strongly benefit from the results obtained in D1.2 and D1.5, and the schemes for the non-linear gates on light beams designed there will be translated to the present heterogeneous atoms-light setting.

T 2.2 Realization of high-efficiency long-lived quantum memories
EXP: NBI, CNRS/ENS TH: MPG

Partner MPG will identify the optimal experimental scheme for mapping between atoms and light. There exist several theoretical proposals to map the quantum state of light into atoms and vice-versa, as well as some few experiments that

display that. Partner MPG will investigate theoretically how to improve those proposals, as well as how to implement them with the new technologies that are being set up in several laboratories around the world. This analysis will be conducted in collaboration with the experimental partners NBI and CNRS/ENS. Partner MPG will then determine how this mapping between light and atoms can work for non-Gaussian states.
Partner CNRS/ENS will pursue the theoretical study of a protocol for the operation of an atomic quantum memory involving simultaneous storage of non-commuting continuous variables. The model predicts the possibility of high fidelity storage of the two quantum quadratures components of a light field at the same time onto two components of a collective atomic spin, using an additional control field. Efficient retrieval of the quantum variables is also expected by means of an adequate control field. In this task, partner CNRS/ENS expects to experimentally demonstrate high fidelity storage and retrieval of the quantum fluctuations of a coherent field and of a squeezed field. The experimental realization will rely on alkali atoms. After preliminary experimental assessments of the capabilities of atomic ensembles for quantum storage, using Cesium vapor (which is easily manipulated), laser cooled and trapped Cesium atoms in a magneto-optic trap (MOT) interacting with light in a cavity will be employed. The absence of Doppler broadening in the MOT is expected to provide optimal efficiency for the process, while the low finesse cavity enhances the effective optical depth of the atomic medium. The storage time and the effect of decoherence in the ground state will be evaluated, in order to fully characterize the quantum memory.
Finally, all the partners of this task will collaborate to use the light-atoms quantum interface for quantum information processing. The light-atom coupling results in a mapping of the state of light onto the atoms. It thus provides a flexible and programmable way to generate quantum states of the atomic collective spin and to manipulate them. Generation of entanglement between light and atomic spin will be investigated theoretically and experimentally. Based on the light atom coupling, atomic quantum cloning of a light state should be feasible and will be assessed. These techniques should provide novel functional elements for quantum information distribution and processing.

T 2.3 Investigating alternative schemes for photonic and/or atomic quantum gates
EXP: CNRS/ENS, (CNRS/IO) TH: MPG, (USTAN)

Partner MPG will consider new applications based on atoms in optical lattices and trapped ions interacting with non-Gaussian light. Most of the experimental results involving CV and atoms use atomic ensembles at room temperature. However, other atomic configurations offer many possibilities to obtain much better performances. For example, atoms in BEC, optical lattices, or trapped ions give us regular structures which will enhance our current capabilities, as well as give rise to new protocols to interface light with atoms. Partner MPG will investigate these new approaches, and relate them to the objectives of the other workpackages. For example, one can perform quantum gates using trapped ions and then map the state into light, thus producing a large variety of entangled states.
Partner USTAN will investigate feasible schemes for generation of strongly non-Gaussian states using the cross-Kerr nonlinearity. The resultant states are expected to be highly nonclassical and exhibit negativity of their Wigner function, sub-Poissonian photon statistics, and amplitude squeezing. Furthermore, the Wigner function will have a distinctly pronounced ``crescent" shape specific for the Kerr-type interactions, which so far was not demonstrated experimentally. It is anticipated that creating and detecting such states should be possible with the present technology using an EIT-based cross-Kerr interaction in a four-level atomic system in N-configuration . Such scheme responds, on the one hand, to the need for an efficient source of non-Gaussian states, and on the other hand can be seen as a test-bench for the strong non-linear coupling using an EIT based system. The first evidence of the large non-linear phase shift in combination with enough coherence to generate and preserve quantum features can be obtained using merely a direct photodetection to verify the photon-number squeezing in one of the output modes.
Partners CNRS/ENS and CNRS/IO will explore similar ideas on the experimental side. This would pave the way for further applications of such non-linear systems since cross-Kerr nonlinear interaction provides a basis for several proposals of quantum information protocols or their elements (e.g. non-demolition photon number detection, C-NOT gate, or continuous-variable entanglement concentration).

T 2.4 Developing quantum networks based on CV quantum repeaters
EXP: NBI TH: ICFO, MPG

Partners MPG and ICFO will investigate new geometries for quantum repeaters. So far, all quantum repeaters proposals are based on a one-dimensional geometry. However, it has been shown that in simple cases other geometries may help. In the present task, it will be investigated how the geometry induces new protocols that may improve the following three figures of merit for quantum repeaters: time, error threshold, and local resources. Furthermore, a connection will be established between the new protocols and the experimental set-ups investigated in WP3. Again this theoretical study will be carried out in close cooperation with the experimental partner NBI.

DELIVERABLES AND MONTH OF DELIVERY

Engineering and manipulating states in atomic quantum memory (see T 2.1 : Engineering and manipulating states of an atomic quantum memory)

Light-atoms quantum interface for quantum information processing (see T 2.2 : Realization of high-efficiency long-lived quantum memories)

Interfacing light with atoms in optical lattices and trapped ions (see T 2.3 : Investigating alternative schemes for photonic and/or atomic quantum gates)

Alternative methods for generating non-Gaussian states using Kerr nonlinearity (see T 2.3 : Investigating alternative schemes for photonic and/or atomic quantum gates)

CV quantum repeaters based on complex quantum network geometries (see T 2.4 : Developing quantum networks based on CV quantum repeaters)

PERSON-MONTHS PER PARTICIPANT

Participation number 10	Participant short name 11	Person-months per participant
8	NBI	36
7	CNRS	30
2	MPG	38
3	ICFO	18
4	UP	8
5	USTAN	4
	Total	**134.0**

SCHEDULE OF MILESTONES

Milestone number 59	Milestone name	Lead beneficiary number	Delivery date from Annex I 60	Comments
MS4	Efficient quantum memory for light based on cold atoms	8	24	Storage or retrieval of light states, towards quantum repeaters
MS6	Demonstration of atomic Schrödinger cat states	8	24	Towards quantum repeater with a cat state distributed between two nodes

DELIVERABLES – TO BE SUBMITTED FOR REVIEW TO EC

Deliverable Number 61	Deliverable Title	Lead beneficiary number	Estimated indicative person-months	Nature 62	Dissemination level 63	Delivery date 64
D2.1	Engineering and manipulating states in atomic quantum memory	8	30	R	PU	36
D2.2	Light-atoms quantum interface for quantum information processing	8	30	R	PU	24
D2.3	Interfacing light with atoms in optical lattices and trapped ions	8	25	R	PU	24
D2.4	Alternative methods for generating non-Gaussian states using Kerr nonlinearity	8	25	R	PU	24
D2.5	CV quantum repeaters based on complex quantum network geometries	8	24	R	PU	24
		Total	**134.0**			

Work package number 53	WP3	**Type of activity** 54	RTD
Work package title	Demonstration of mesoscopic CV quantum processors		
Start month	1		
End month	36		
Lead beneficiary number 55	9		

OBJECTIVES

The elementary optical and atomic components of mesoscopic CV quantum processor developed in WP1 and WP2 will be integrated into more complex devices, which implement advanced protocols for quantum information processing. The emphasis will be put on the experimental proof-of-principle demonstration of such devices envisaged in the theoretical tasks of the project. Several platforms for CV quantum computing will be tested. Multimode CV entangled states will be generated which could be used for one-way quantum computing or for teleportation-based implementation of quantum operations. In parallel, computing with Schrödinger cat states will be tested experimentally, and the possibility to implement basic quantum gates will be assessed.
The theoretical analysis and experimental demonstration of CV quantum error correction and entanglement distillation or concentration will also be central components of this workpackage. These procedures are required for suppression of noise that will inevitably arise in any realistic advanced CV quantum communication or computing scenario that would involve entangled states.

DESCRIPTION OF WORK AND ROLE OF PARTNERS

T 3.1 Demonstrating CV one-way computing and/or cat-state computing
EXP: DTU, FAU, (CNRS/IO) TH: USTAN

Having monomode and multimode Schrödinger cats at our disposal from D1.3 and D1.4, partner CNRS/IO can explore the feasibility of the CV cat-states computing scheme proposed by Ralph, Milburn et al . A first basic operation to be implemented is the sign-flip operation, that can transform an odd photon-number Schrödinger cat to an even one, and conversely. From the results obtained at this preliminary stage, the possibility to implement the C-NOT and Hadamard gates will be considered, towards the demonstration of CV cat-state quantum computing. The implementation of other future protocols may also be considered in the present task.
Another approach to CV quantum computing that will be pursued by partner DTU and FAU within this task is the utilization of entangled quantum states for teleportation-based implementation of quantum gates or for one-way quantum computing studied theoretically in D1.2. Multimode entangled states of light such as CV cluster states will be produced and their suitability for the computing applications will be investigated by partner USTAN.

T 3.2 Demonstrating CV quantum error correction
EXP: DTU TH: USTAN, (ULB), (UP)

The aim of this task is to investigate and implement experimentally schemes of coherent state quantum error correction coding using CW laser light. Quantum error correction is a crucial technique to combat errors in quantum information processing, and it is based on ingenious encoding and decoding strategies. Despite the immense importance of quantum error correction coding, to date there has been only two proposals for error correction coding in continuous variables systems . However, these schemes are only suitable for proving a point of principle and are not concerned with technological feasibility. In this task we will develop new, technically much simpler and more versatile quantum error correction coding schemes. Two possibilities will be explored:
First, partner DTU and UP will analyze a scheme of quantum error correction coding where coherent state information is dispersed into two channels possessing white Gaussian noise. Using a special encoding scheme exploiting squeezed states and a decoding scheme involving conditional homodyne measurements, preliminary theoretical studies have indicated that it is possible to probabilistically correct the corrupted information if the amount of noise in the two channels is different and uncorrelated. The experimental realization of such scheme will be addressed by partner DTU. The non-classical light will be produced using parametric interaction inside a nonlinear periodically poled non-linear crystal which will be placed inside a cavity to increase the effective nonlinearity. A novel method where two non-linear crystals are placed inside the same cavity to produce two orthogonally polarized CW squeezed modes will be pursued. The achievability of such a configuration has recently been confirmed in preliminary experimental studies .
Secondly, partners DTU and ULB will investigate another scheme of quantum error correction codes capable of correcting complete erasure errors. Such erasure-code has been considered for discrete variable systems , demonstrating the

protection of two photons, but to date no CV analogue has been found. Preliminary theoretical studies by partners ULB and DTU have shown that a qubit erasure-code for single photons can be transformed into a CV erasure-code for coherent states, and that the experimental realization relies solely on linear optics, homodyne detection, feedforward and Gaussian entanglement. This protocol will be implemented experimentally by partner DTU using similar technology as mentioned above. Two different approaches will be pursued; a deterministic approach where all data are used and a probabilistic approach where only favorable events are selected. The latter approach allows for multiple erasures as well as ignorance about which channels were affected by erasure.

T 3.3 Demonstrating quantum noise filtering in CV systems
EXP: DTU, FAU TH: USTAN, (UP)

Partners DTU, FAU, and UP will jointly investigate the filtering of discrete thermal noise from continuous variable states. Some channels exhibit pronounced timing-jitter noise and beam positioning noise, leading to time synchronization and detection problems. As a result, information carried by a coherent state will be randomly disturbed by noise. The partners DTU, FAU, and UP have recently shown that if the introduced noise is the vacuum state, the signal can be optimally recovered by diagnosing the error with a weak photon counting measurement. Partner UP will theoretically investigate the filtering of more complex noise sources such as a discrete mixture of thermal noise and subsequently propose optimal filtering strategies. Preliminary studies indicate that the use of multiple photon counters might be necessary. Partner FAU in collaboration with DTU will experimentally investigate the proposed filtering protocols and compare them with non-optimal strategies based on homodyne detection.

T 3.4 Demonstrating the distillation and/or concentration of CV entanglement
EXP: FAU TH: USTAN, (UP), (POTSDAM)

Partner FAU will lead the present task, devoted to the CV entanglement distillation. Distillation of entangled resources is a major issue in quantum information processing, in particular for the development of quantum repeaters that allow for fault tolerant communication between different information processors. It has been found that the distillation of Gaussian entangled states requires the usage of highly nonlinear Gaussian operations which are difficult to realize. The distillation of non-Gaussian quantum states can however be carried out using linear optics and conditional homodyne detection, which has recently been realized for a statistical mixture of squeezed states . Building on this scheme, the partners FAU, UP, DTU and POTSDAM will investigate the distillation of non-Gaussian mixtures of entangled states. A particular kind of non-Gaussian attenuation noise (fading noise) in which the attenuation factor varies in time will be investigated. The entangled states will be formed in the polarization degrees of freedom by exploiting the optical Kerr effect in two polarization maintaining fibers pumped with femtosecond pulses at the telecommunication wavelength. The partner FAU has recently demonstrated highly efficient squeezing employing such an approach. In collaboration with USTAN, self-induced transparency (SIT) and electromagnetically induced transparency (EIT) in gas filled hollow core fibers will be explored as an alternative nonlinearity. The degree of polarization entanglement before and after distillation will be estimated using high efficiency polarization detectors. This activity will be complemented by work bringing together continuous-variable schemes and those using techniques exploiting finite-dimensional polarization entanglement.
A second activity within this task will concern proposals for entanglement concentration protocols for Gaussian continuous-variable entangled states. Partner USTAN will focus on a family of such protocols that involve mixing the entangled state with the ancilla state via a non-linear media before subjecting the ancilla to a measurement . In general, such protocols have the capacity to produce entangled non-Gaussian states, whose entanglement content cannot be calculated analytically. In addition, its relationship with the measurement result on the ancilla is non-trivial and cannot be used as an indicator of success of the protocol. However, in a recent work, USTAN has shown that if the non-linearity is particularly weak then both of these problems are solved. Indeed, the weakness of the non-linearity allows a Gaussian preservation effect whilst correlating the measurement result to the entanglement content of the output state. One can take this further by exploiting the weak value formalism, which provides new insight to such protocols. Indeed, one can regard these weak non-linear protocols as the encoding of a weak value onto the entangled state. Furthermore, USTAN has derived conditions on the weak value for entanglement concentration to occur. The benefits of this model are two-fold. Firstly, the weak value formalism explains the need for a weak non-linearity. Secondly, the conditions on the weak value constrain the possible initial ancilla states and the subsequent measurement strategies employed that will allow Gaussian preserving entanglement concentration. The success of the weak value paradigm for entanglement concentration protocols of this kind, naturally suggests to investigating whether weak values can provide insight into other CV protocols including the recently experimentally confirmed protocol using photon-subtraction measurements.

DELIVERABLES AND MONTH OF DELIVERY

Cat-states implementation of the sign-flip operation (see T 3.1 : Demonstrating CV one-way computing and/or cat-state computing)

Assessment of the implementation of the C-NOT and Hadamard gates (see T 3.1 : Demonstrating CV one-way computing and/or cat-state computing)

Demonstration of CV quantum error correction (see T 3.2 : Demonstrating CV quantum error correction)

Filtering of noise in CV systems (see T 3.3 : Demonstrating quantum noise filtering in CV systems)

Distillation or concentration of CV entanglement (see T 3.4 : Demonstrating the distillation and/or concentration of CV entanglement)

PERSON-MONTHS PER PARTICIPANT

Participation number 10	Participant short name 11	Person-months per participant
9	DTU	48
10	FAU	48
5	USTAN	8
7	CNRS	6
1	ULB	6
4	UP	8
6	POTSDAM	12
	Total	136.0

SCHEDULE OF MILESTONES

Milestone number 59	Milestone name	Lead beneficiary number	Delivery date from Annex I 60	Comments
MS1	Experimental quantum error/erasure correction	9	12	Quantum communication with enhanced tolerance to noise/losses
MS5	Experimental entanglement distillation/purification	9	24	Entanglement transmission with enhanced tolerance to fading noise
MS7	Experimental small-scale few-modes CV quantum processor	9	36	Demonstration of the advantage of CV quantum information processing

DELIVERABLES – TO BE SUBMITTED FOR REVIEW TO EC

Deliverable Number 61	Deliverable Title	Lead beneficiary number	Estimated indicative person-months	Nature 62	Dissemination level 63	Delivery date 64
D3.1	Cat-states implementation of the sign-flip operation	9	23	R	PU	36
D3.2	Assessment of the implementation of the C-NOT and Hadamard gates	9	23	R	PU	36
D3.3	Demonstration of CV quantum error correction	9	30	R	PU	24
D3.4	Filtering of noise in CV systems	9	30	R	PU	24
D3.5	Distillation or concentration of CV entanglement	9	30	R	PU	36
		Total	136.0			

Work package number 53	WP4	**Type of activity** 54	MGT
Work package title	Project management and knowledge dissemination		
Start month	1		
End month	36		
Lead beneficiary number 55	1		

OBJECTIVES

The project management shall ensure a smooth and efficient implementation of the project and a wide dissemination of the knowledge generated during the project. Besides the daily coordination of the project and communication with the European Commission and the partners, the coordinator and deputy coordinator will maintain the project website, prepare the annual and final reports, and organize the Annual Coordination meetings.

DESCRIPTION OF WORK AND ROLE OF PARTNERS

T 4.1 Project web page and reporting
TH: ULB, UP

The coordinator (ULB) together with the deputy coordinator (UP) will install and maintain the project web pages. These pages shall contain up-to-date information about the project goals, the scientific activities of the partners and the project results. Major achievements will be highlighted and presented in a way accessible to broad audience and media. A list of all publications with full access to reprints/preprints will be included. A link to web sites of all partners will be provided.

The coordinator and deputy coordinator will be in charge of preparing the annual reports and the final report at the end of the project as well as plan for dissemination and use of the generated knowledge. In this work they will be assisted by the workpackage leaders.

T 4.2 Project meetings and workshops
TH: ULB, UP

A Project Coordination meeting will be organized every year, chaired by the coordinator. The research progress will be analyzed, and future directions of investigation will be defined. Issues raised by partners will be discussed and appropriate decisions will be made preferably by seeking a consensus among all partners. In addition, a major knowledge dissemination activity will be the organization of international workshops focused on continuous-variable quantum information processing, in a continuation of the series of "CV-QIP workshops" which has been running yearly since 2002.

T 4.3 Contribution to activities at the level of FET-Open
TH: ULB, UP

In order to support scientific cooperation at the FET-Open level and broad public awareness of project achievements, consortium members will ensure within the areas of interest of the project:
- Publication of project results throughout the duration of the project in widely accessible and, where available, openly accessible science and technology journals, as well as through conferences and through other channels, including the Web, that reach audiences beyond the academic community. Publication of a periodic press release, and other means of disseminating project progress to a wider audience, e.g. via video.
- Participation in FET-organised events, for example conferences, dedicated workshops and working groups, consultation meetings, summer schools, online forums, etc.
- International co-operation and contribution to relevant national and international activities (ex. joint workshops, calls, etc., for example with NSF).

The above activities will be reported in the project's Periodic Progress Reports (see T4.1).

In addition, the consortium agrees to include the following reference in all project-related publications, activities and events: "We acknowledge the financial support of the Future and Emerging Technologies (FET) programme within the Seventh Framework Programme for Research of the European Commission, under the FET-Open grant agreement COMPAS, number 212008".

DELIVERABLES AND MONTH OF DELIVERY

Project website 1st Annual Report 2nd Annual Report 3rd Annual Report Final Report Final plan for the use and dissemination of foreground' and report on horizontal issues

PERSON-MONTHS PER PARTICIPANT

Participation number 10	Participant short name 11	Person-months per participant
1	ULB	18
	Total	**18.0**

SCHEDULE OF MILESTONES

Milestone number 59	Milestone name	Lead beneficiary number	Delivery date from Annex I 60	Comments

DELIVERABLES – TO BE SUBMITTED FOR REVIEW TO EC

Deliverable Number 61	Deliverable Title	Lead beneficiary number	Estimated indicative person-months	Nature 62	Dissemination level 63	Delivery date 64
D4.1	Project website	1	3	O	PU	6
D4.2	1st Periodic Progress Report	1	3	R	RE	12
D4.3	2nd Periodic Progress Report	1	3	R	RE	24
D4.4	3rd Periodic Progress Report	1	3	R	RE	36
D4.5	Final Report	1	3	R	RE	36
D4.6	Final plan for using and disseminating knowledge	1	3	R	PU	36
		Total	**18.0**			

B.1.3.6 Efforts for the full duration of the project

B3.3:
Project Effort by Beneficiary and Work Package

Project Number 1	212008	Project Acronym 2	COMPAS

Indicative efforts (man-months) per Beneficiary per Work Package

Beneficiary number	WP1	WP2	WP3	WP4	Total per Beneficiary
1 - ULB	24.0	0.0	6.0	18.0	48.0
2 - MPG	0.0	38.0	0.0	0.0	38.0
3 - ICFO	6.0	18.0	0.0	0.0	24.0
4 - UP	32.0	8.0	8.0	0.0	48.0
5 - USTAN	0.0	4.0	8.0	0.0	12.0
6 - POTSDAM	24.0	0.0	12.0	0.0	36.0
7 - CNRS	24.0	30.0	6.0	0.0	60.0
8 - NBI	0.0	36.0	0.0	0.0	36.0
9 - DTU	0.0	0.0	48.0	0.0	48.0
10 - FAU	0.0	0.0	48.0	0.0	48.0
Total	110.0	134.0	136.0	18.0	398.0

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B.1.3.7 List of milestones

LIST AND SCHEDULE OF MILESTONES					
Milestone number 59	Milestone name	WP number 53	Lead beneficiary number	Delivery date from Annex I 60	Comments
MS1	Experimental quantum error/erasure correction	WP3	9	12	Quantum communication with enhanced tolerance to noise/losses
MS2	Generation of CV cluster states of light	WP1	7	24	Towards measurement-based quantum computing
MS3	Generation and breeding of Schrödinger cat states of light	WP1	7	24	Towards cat-state quantum computing
MS4	Efficient quantum memory for light based on cold atoms	WP2	8	24	Storage or retrieval of light states, towards quantum repeaters
MS5	Experimental entanglement distillation/purification	WP3	9	24	Entanglement transmission with enhanced tolerance to fading noise
MS6	Demonstration of atomic Schrödinger cat states	WP2	8	24	Towards quantum repeater with a cat state distributed between two nodes
MS7	Experimental small-scale few-modes CV quantum processor	WP3	9	36	Demonstration of the advantage of CV quantum information processing

B2. Implementation

B.2.1 Management structure and procedures

i) Management structure

Coordinator	Nicolas J. Cerf
Deputy coordinator	Jaromir Fiurasek
WP1 leader	Philippe Grangier
WP2 leader	Eugene S. Polzik
WP3 leader	Ulrik L. Andersen
WP4 leader	Nicolas J. Cerf

Role of project coordinator and deputy coordinator
Besides chairing an annual Project Coordination Meeting (see below), the project coordinator (Nicolas Cerf) will be responsible for the day-to-day management of the project, reporting, liaison with the European Commission, checking the quality of the deliverables, dissemination activities, and project evaluation. He will be assisted in this task by the deputy coordinator (Jaromir Fiurasek).

Role of workpackage leaders
Each of the three scientific workpackages will be led by a senior scientist heading one of the participating sites (Philippe Grangier for WP 1, Eugene Polzik for WP 2, and Ulrik Andersen for WP 3). They will be responsible for the management and work coordination within the workpackage, and will also be members of the Project Coordination Committee (see below). The management workpackage, WP4, will be led by the coordinator (Nicolas Cerf).

ii) Management procedures

Project Coordination Meetings
Given the reasonable scale of the consortium, its management will be kept light, focusing on the main objective, i.e. to ensure optimum synergy between the various groups. In addition to regular scientific meetings between the partners, which will take place on an informal basis following the evolution of the research, a Project Coordination Meeting will be organized every year, chaired by the project coordinator. A Project Coordination Committee consisting of the coordinator, deputy coordinator, and the three scientific workpackage leaders will steer these project coordination meetings. These meetings will be attended by all the project participants and, possibly, by invited experts. The research progress will be analyzed in details, and future directions of investigation will be defined.

Overall management
The Project Coordination Committee will deal, in its annual Project Coordination Meetings, with all issues tabled by the participating sites, the European Commission, or any other relevant party. Agenda and minutes will be distributed to all project participants.

Decision making
Decisions will normally be made by seeking a consensus. However, to avoid deadlock positions in the operational progress of the project, a majority (3 persons) within the Project Coordination Committee will be sufficient to proceed after enough time has allowed for the defense of the conflicting positions.

Reporting
Each scientific workpackage leader will submit input for the progress reports at the end of the reporting period. Input from the workpackage leaders will be compiled by the project coordinator and deputy coordinator, and included in the progress reports. All participants to the project will duly report any encountered problem that might affect the course of the project.

B.2.2 Beneficiaries

A brief description of the organization and the short profile of the key personnel is provided for each of the 10 partners of COMPAS in the following pages.

Participant 1	**ULB**	**Université Libre de Bruxelles** **Brussels, Belgium**

The Université Libre de Bruxelles was founded in 1834, with its charter being based on a declaration of intellectual freedom from any kind of religious or philosophical dogma, prejudice or polemic. It consists of 18 Faculties and Schools distributed over 8 campuses and an academic hospital. The faculty body and staff total up 5,000 persons, and about 18,000 students are registered every year. Over its 150-year history, the University has acquired a leading position in the world's academic community. It has many distinguished alumni, including three Nobel Prize winners, several Francqui Prize winners, and a Fields Medal.

The Centre for Quantum Information and Communication (QuIC), led by Prof. N. J. Cerf, has been working on quantum information sciences for several years, with research contributions ranging from fundamental questions such as quantum measurement, quantum entanglement, or quantum nonlocality, to more information-flavored issues such as quantum cloning, quantum cryptography, or quantum computation. A large fraction of its recent research has focused on continuous-variable quantum information, in particular continuous-variable quantum key distribution. It also has started recently an experimental quantum information activity together with the ULB optics laboratory. It currently holds two provisional patents, and has published numerous scientific papers among which two in the journal *Nature*.

The QuIC Center has been involved in many European projects, QUIPROCONE (FP5), EQUIP (FP5), CHIC (FP5), RESQ (FP5), SECOQC (FP6), QAP (FP6), QUROPE (FP6), and has coordinated the project COVAQIAL (FP6). In 2002, it has initiated a series of conferences especially devoted to continuous-variable quantum information processing, which now runs on an annual basis.

Prof. Nicolas J. Cerf earned an Engineering Degree (1987), a M.Sc. in Physics (1988), and a Ph.D. in Physics (1993) at the ULB. He was then awarded a Marie Curie fellowship from the European Commission, and worked for two years as a postdoctoral research associate at the Division of Theoretical Physics, University of Paris, in Orsay. His research mainly concerned quantum many-body systems and quantum Monte Carlo methods, but also extended to the statistical physics of combinatorial problems. In 1995, he joined the research faculty of the California Institute of Technology to work on quantum computation and information theory, which then became his main research interest. In 1998, he was appointed as an associate professor at the ULB, where he now heads the QuIC Center. He earned the Caltech President's Fund award in 1997, the Alcatel-Bell prize (awarded by the Belgian National Fund for Scientific Research) in 1999, a Marie Curie Excellence Award in 2006, and was also promoted to professor in 2006. He authors around 100 publications.

Dr. Serge Massar graduated in Physics in 1991, and defended a Ph.D. thesis on quantum black hole physics in 1995 at the ULB. He then held a 2 year postdoctoral position at Tel Aviv University (Israel), followed by a 1 year postdoctoral position at Utrecht University (The Netherlands). He is at present permanent Research Fellow of the Belgian National Fund for Scientific Research at the ULB. His original domain of research was quantum gravity and in particular black hole radiation and quantum cosmology. His research interests have since shifted towards quantum information theory, and, for the past years, he has been working actively on subjects such as quantum measurement, quantum copying and entanglement purification. He also has started an experimental activity in quantum optics and information.

Participant 2	MPG	Max-Planck-Gesellschaft Garching, Germany

The Max-Planck Institute for Quantum Optics is a non-profit organization fully devoted to research. It is formed by around 150 scientists, most of them PhD students and postdocs. It is divided into four divisions: three experimental (led by Prof. Hänsch, Krausz, and Rempe) and one theoretical (Prof. Cirac). In addition, there are four experimental Junior Research Groups (led by Dr. Schätz, Kippenberg, Kienberger, and Kling). The theory division is composed of about 20 scientists, half of them PhD students, 6 postdocs, 3 senior researchers, and 2 master thesis students. The research topics range from Quantum Information Theory, to strongly correlation behavior, and includes investigations of many quantum optical systems (trapped ions, atoms in lattices, atomic ensembles, quantum dots, etc).

Prof. J. Ignacio Cirac: Head of the theory group, has authored around 190 papers in Quantum Optics and Quantum Information. He has directed 7 Ph.D. thesis. His present interests include many-body entanglement theory, simulation of quantum systems, and quantum optical implementations of quantum information processors.

Dr. Michael Wolf: postdoc/assistant, leading the subgroup 'Quantum Information' in the MPQ theory division. He authors 50 publications (18 in Physical Review Letters). His interests include quantum information, mathematical physics, and quantum many-body theory.

Participant 3	ICFO	Institut de Ciencies Fotoniques Barcelona, Spain

The ICFO-Institute of Photonic Sciences is a non profit agency founded in 2002 in Barcelona that aims at advancing the limits of scientific and technological knowledge in optical sciences including quantum optics, nonlinear optics, bio-photonics and nano-optics. ICFO hosts 15 research groups that use some 45 laboratories and one nanophotonics fabrication facility in a 9000 sq.m. dedicated building. The centre is engaged in both, research and education and training of M.Sc. and Ph.D. students and post-doctoral researchers. Also, ICFO collaborates actively with many leading European research centers and Universities, as well as with leading institutes worldwide.

The Quantum Information Theory group at ICFO is led by Antonio Acín. At the moment, the group consists of 2 post-doctoral researchers and 4 Ph.D. students. The research activity is mainly focused on Quantum Information Theory, but also covers Quantum Optics and Many-Body physics problems. The ICFO contribution to this project will mainly focus on WP 2, in particular with the study of entanglement distribution through quantum networks, in the Gaussian and non-Gaussian regime.

Dr. Antonio Acín got his PhD degree in Theoretical Physics from the University of Barcelona in 2001. From October 2001 to March 2003, he was a post-doctoral researcher in the group of Prof. Nicolas Gisin at the University of Geneva. Since April 2003, he leads the Quantum Information Theory group at ICFO, where he became Assistant Professor in January 2005. He has published more than 55 articles, including 1 Nature Physics, 1 Review of Modern Physics and 24 Physical Review Letters.

Note: ICFO researchers have different affiliations and some of the Group Leaders, such as Dr. Antonio Acín, are officially appointed as full-time "ICREA Research Professors". The ICREA (Catalan Institution for Research and Advanced Studies) is a non-profit foundation supported by the Regional Government of Catalonia, Ministry of Innovation, Universities and Enterprise. ICREA researchers are not bound to any specific project, but are freely available for the research center that hosts them. ICFO is free to allocate ICREA professors to different projects.

Participant 4	UP	Palacky University Olomouc, Czech Republic

Palacky University is the second oldest university in the Czech Republic founded in 1566. The quantum information group at the Department of Optics is led by Dr. Jaromir Fiurasek and includes two additional permanent members (Dr. Radim Filip and Dr. Miloslav Dusek), three post-docs and three graduate students. The research activities cover a broad range of topics in quantum optics, quantum information theory and control of quantum noise. The group actively participates in many national and European research projects including two projects of the 6th Framework Programme of the EC: COVAQIAL (Continuous Variable Quantum Information with Atoms and Light) and SECOQC (Development of a Global Network for Secure Communication based on Quantum Cryptography).

Dr. Jaromir Fiurasek received his Ph.D. degree in Optics and Optoelectronics at Palacky University in 2002. In the years 2003-2004 he was a post-doctoral researcher in the group of Professor Nicolas Cerf, Ecole Polytechnique, Université Libre de Bruxelles, Belgium. In 2003, Jaromir Fiurasek received the Czech Head prize (Doctorandus category) for his research in the field of quantum information theory. Jaromir Fiurasek is now an Associate Professor at the Department of Optics, Palacky University, and he is also the head of the Centre of Modern Optics established there. His main research interests include quantum optics and quantum information processing.

Dr. Radim Filip received his Ph.D. degree in Optics and Optoelectronics at Palacky University in 2002. In the years 2005-2007 he stayed as a Alexander von Humboldt fellow in group of Professor Gerd Leuchs, Institut of Optics, Information und Photonics (Max Planck Research-group), University of Erlangen-Nürnberg, Germany. In 2007, Radim Filip was awarded by the Special Prize of Czech Grant Agency for his works in the control of decoherence and quantum noise of light. Radim Filip is now Associate Professor at the Department of Optics, Palacky University. His main research interests are quantum optics and quantum noise control.

Participant 5	USTAN	University of St. Andrews St. Andrews, UK

The University of St Andrews, founded 1411 is the oldest university in Scotland. Its research excellence, combined with a large increase in the number of student applications in almost all subjects, resulted in The Sunday Times declaring St Andrews the UK University of the year 2002. We are therefore both an ancient seat of learning and certainly one of Britain's most dynamic universities. The School of Physics and Astronomy has an internationally recognized set of research programmes in astrophysics, condensed-matter physics, and photonics. The University plays an active role in the Scottish Universities' Physics Alliance, which aims to place Scotland at the forefront of international research in Physics through a coordinated promotion and pursuit of excellence in research. The School undertakes active research in both theoretical and experimental areas of photonics, including quantum and atom optics and quantum information. The Theoretical quantum optics group led by U. Leonhardt focuses on several exciting and imaginative quantum-optical phenomena, such as optical black holes, slow light and invisibility devices. There are two experimental groups: Quantum optics (F. Koenig) and Quantum non-degenerate gases (D. Cassettari). Theoretical quantum information group led by N. Korolkova consists currently of 2 post-doctoral fellows and 2 PhD students and focuses on quantum information protocols using infinite-dimensional quantum systems, quantum structure of short optical pulses, and effects of light-matter interactions. The group has actively participated in national and European research projects including COVAQIAL of the 6th EU Framework Programme.

Dr. Natalia Korolkova has received her Ph.D. in theoretical quantum optics in 1996 from Moscow State University. In 1996/97, she was appointed as a postdoctoral researcher at the Department of Optics, Palacky University in Olomouc, Czech Republic. In 1997, she joined the Quantum Metrology group at Erlangen University, Germany, as a Humboldt Fellow. In 1999-2003 she was a group leader of the Quantum Information group, Center of Modern Optics at Erlangen University, Germany. In 2002, Natalia Korolkova has completed her habilitation. Since 2003 she is appointed as a Lecturer at the School of Physics and Astronomy, University of St. Andrews, UK and leads there the Theoretical Quantum Information group. Her current research interests are in the field of quantum optics of ultrashort light pulses and quantum information using continuous variables of light.

Participant 6	POTSDAM	University of Potsdam Potsdam, Germany

Although it is only a few years old, the University of Postdam nevertheless has its own history. In 1948 the Brandenburg Landeshochschule (school of higher education of the Land Brandenburg) was founded in Potsdam. Out of this institution developed later the Karl Liebknecht Pedagogical College, the largest teacher training institution in the GDR. After the social and political changes of the year 1989, the University of Potsdam was founded on the grounds of the previous institutions on July 15, 1991. Today, it is the largest university in Brandenburg. Presently, approximately 16,000 students study in its various departments, including about 1,300 foreign students from more than 85 countries.

The quality of the research carried out at Potsdam University is witnessed by the steadily increasing funding through industry and other third parties and the financing of two research groups and two graduate seminars by the German Research Society (DFG). These have been established in the fields of Linguistics, Psychology and Jewish Studies. The achievements in these fields is indicated by the admission of the university into the German Research Society (DFG) in the summer of 1998. Moreover, the university is responsible for further academic education, for example in the area of in-service teacher training and additional qualification courses.

Prof. Jens Eisert is Professor at the University of Potsdam. He was until very recently a Lecturer at Imperial College, London, heading a subgroup within Quantum Optics and Laser Science and the IMS. He received his PhD in Potsdam in Germany in 2001, which was awarded the Michelson Prize. In 2004 he received the Prestigious European Young Research Award. He has authored about 70 publications in quantum information science, 21 of which in the Physical Review Letters (including work in press). He has also supervised 5 Diploma and PhD thesis. His interests are in quantum information science and the study of quantum many-body systems. He has a strong research background in the study of manipulation of continuous-variable entanglement, distillation of states of light, quantum channels and their capacities, detection and estimation of properties of states of light, as well as in research on simulation and quantum computation.

Participant 7	CNRS	Centre National de la Recherche Scientifique Paris, France

CNRS/IO : Laboratoire Charles Fabry de l'Institut d'Optique

During the 1990's, the Quantum Optics group of the Laboratoire Charles Fabry of the Institut d'Optique, led by Dr. Philippe Grangier, has performed key experiments in the field of quantum non-demolition (QND) measurements. Theoretical papers on QND measurements include a set of quantitative criteria for QND measurements, which is now widely used in the quantum optics community. The group has also been working on quantum noise in laser diodes, demonstrating the crucial importance of longitudinal and transverse modes in the noise properties of laser diodes. Since 2000, it has realized several experiments directly related to quantum information processing: trapping individual neutral atoms in microscopic dipole traps, producing single photons from the pulsed fluorescence of single NV centers in diamond nanocrystals, developing novel quantum cryptography protocols based upon continuous variables, and generating non-Gaussian states by conditioning. The Institut d'Optique has very good mechanical, optical and electronics facilities.

The group has also a great deal of experience in European projects. It has been involved in the European ESPRIT projects NOROS (FP2), QUINTEC (FP3), ACQUIRE (FP4), and then in the FET / QIPC projects QUBITS, QGATES, S4P, QUICOV, COVAQIAL, SECOQC, and SCALA. Dr. Philippe Grangier has been the coordinator of the RTN "Non Classical Light" (1993-96) and "QUEST" (Quantum Entangled States of Trapped particles) (2000-2004), and he is now coordinating the Integrated Project "SCALA".

Dr. Philippe Grangier: Group leader (Directeur de Recherche au CNRS, Professeur à l'Ecole Polytechnique). His research activities began in 1980 with the realization of experimental tests of Bell's inequalities, under the supervision of Alain Aspect. He obtained a position at the CNRS in 1982 in the field of quantum optics, and carried out experimental studies of non-classical properties of light, such as the conditional preparation of a single photon state (PhD thesis, 1986). Other experimental works were devoted to spectroscopic measurements, and to studies of soliton effects and propagation in femtosecond lasers. Then he demonstrated the use of a squeezed-light-enhanced interferometer, and he realized the first observation of pulsed squeezed light (AT&T Bell Laboratories, Murray Hill, USA, postdoctoral position with R.E. Shusher). Since 1988, he has been heading the "Quantum Optics" department at the Institut d'Optique in Orsay. Until 1998 he worked on the realization of "Quantum Non-Demolition" (QND) measurements in optics, using atomic non-linear systems, and on reducing the intensity noise of laser diodes below the standard shot noise limit. Since 1999, he became involved in several experiments directly related to quantum information processing.

Dr. Rosa Tualle-Brouri: Assistant Professor**.** She completed her PhD at Université de Villetaneuse, France, about the realization of several atom optics experiments. Then she had a Temporary Assistant Professor position in Ecole Normale Supérieure de Cachan, and started to work on the implementation of a single photon source for quantum cryptography, using the fluorescence of individual NV centers in diamond. This work resulted in the first quantum cryptography set-up using a "true" single photon source. She has also been working on various quantum communication schemes involving continuous variables, before focusing during last 4 years on the generation of non-Gaussian states by conditioning.

CNRS/ENS : Ecole Normale Supérieure (Laboratoire Kastler Brossel)

The Laboratoire Kastler-Brossel, Ecole normale Supérieure and Université Paris 6, associated with CNRS is a large research unit with 50 permanent scientists, 25 administrative and technical staff, and over 40 PhD students and 40 visiting scientists and postdocs. The quantum optics group led by Elisabeth Giacobino focuses on the study and manipulation of quantum fluctuations of light in various systems, aiming to demonstrate new tools for quantum information. They have shown the first evidence for quantum correlations in the parametric oscillator in the continuous regime. They have demonstrated for the first time entanglement generation in cold atomic ensembles. They have also been working on the origin of quantum noise in laser diodes together with the Institut d'Optique group. In recent years, they have been working on quantum fluctuation processing in optical parametric oscillators, semiconductor lasers, semiconductor microcavities, and atomic ensembles. These techniques are applied to ultra-high sensitivity measurements and quantum information processing.

Dr. Elisabeth Giacobino, group leader, Directeur de Recherche at CNRS, has a broad experience in the fields of laser spectroscopy, laser physics, nonlinear optics, quantum optics, squeezed states of radiation, optical parametric oscillators, nonlinear and quantum effects in laser cooled atoms and in semiconductor microcavities, quantum noise in lasers transmission, and storage of quantum information. She is author of 180 publications in scientific journals and books, and gave 70 invited talks in international conferences. She trained 25 PhD students, and held several high-level management responsibilities.

Dr. Alberto Bramati is Maître de Conférences at the University P. et M. Curie, Paris 6. He is graduated from the University of Milan in 1993 in the group of Prof. Lugiato. He prepared and received the PhD degree in 1998 at the Laboratoire Kastler Brossel with a dissertation on the generation of squeezed states in semiconductor lasers. In 2000-2001, he held a post-doctoral position at the University of Como in the group of Prof. Di Trapani. In 2004 he received the Habilitation degree at the university P. et M. Curie. Since 2006, he is member of the Institut Universitaire de France (IUF). His fields of interest are laser physics, non linear and quantum optics and he is an expert in squeezed light and entangled beam generation in various media, including crystals, semiconductors and atoms. He is author of 45 publications in international journals.

Note: Two CNRS Joint Research Units (clause 10 of the Grant Agreement) are involved in the Project, namely UMR 8501 and UMR 8552. Consequently, the CNRS also represents:

- IO (Institut d'Optique), UPS (Université Paris-Sud) for the UMR 8501 (CNRS/IO);
- ENS (Ecole Normale Supérieure), and UPMC (Université Pierre et Marie Curie) for the UMR 8552 (CNRS/ENS).

Participant 8	NBI	Niels Bohr Institute Copenhagen, Denmark

The Niels Bohr Institute in Copenhagen is one of the institutions where foundations of quantum mechanics have been laid down. The Institute is part of the Department of Physics of Copenhagen University with strong traditions of research in various fields of theoretical physics. The Quantum Optics Laboratory is a part of the Danish National Research Foundation Center for Quantum Optics (QUANTOP). The Laboratory has recently moved to the Niels Bohr Institute as a whole from the University of Aarhus where it was operating since 1994. The group works at the forefront of the research in quantum information processing with continuous variables. In 1998, in collaboration with the Caltech team, the quantum teleportation of a continuous variable state of light has been experimentally demonstrated. Since 1997, the group has been developing a new approach to the quantum interface between light and atoms using optically thick atomic ensembles. In 1999, the group reported first experimental demonstration of spin squeezing of a macroscopic atomic ensemble. In 2001, the group reported experimental observation of entanglement generated between two separate atomic ensembles – a corner stone for teleportation and other quantum protocols with atomic ensembles and light. In 2004, the group demonstrated the first quantum memory for continuous variables of light and in 2006 it realized the first inter-species quantum teleportation from a light beam onto an atomic ensemble.

Prof. Eugene Polzik: Group leader. Eugene Polzik has earned his Master and PhD degrees in experimental atomic physics from the University of St. Petersburg (Leningrad University) in 1976 and 1980 respectively. He has then become interested in theoretical quantum optics, specifically in the generation of squeezed light by lasers and by atomic spin systems. From 1990 to 1995, he resumed experimental research at Caltech in the group of Jeff Kimble. From 1993 to 2002, E. Polzik has been a head of the Quantum Optics Laboratory at the University of Aarhus in Denmark. Eugene Polzik received the Danish Physical Society Prize in 1999. He is now Director of the Danish Quantum Optics Center (QUANTOP). Since January 2003, his Laboratory moved to the Niels Bohr Institute.

Participant 9	DTU	Technical University of Denmark Copenhagen, Denmark

The main focus of the Technical University of Denmark (DTU) is research in technical and natural sciences that contributes to the development of society. Some of the current profile areas are nano, information and communication technology. The Department of Physics (FYS) at DTU has significant and internationally recognized activities in atomic scale material science, surface physics, nanostructured materials, bio-optics, and quantum optics.

The Quantum Information group at FYS is a newly established group led by the associate professor Ulrik L. Andersen, who until recently was leading the “Quantum Information Processing” group at the Max-Planck research center in Erlangen, Germany. The Quantum Information group at FYS-DTU comprises 1 faculty member, 2 PhD students and 2 postdocs, and is conducting experiments in continuous-variable quantum information processing, quantum plasmonics and quantum imaging. Despite the young age of the laboratory, it is fully functioning with new high-tech equipment.

Dr. Ulrik L. Andersen studied Applied Physics at the Technical University of Denmark (DTU) where he received the Ph.D. degree in 2002. As part of his dissertation he worked 8 months at the Australian National University. In 2003 he was awarded an Alexander von Humboldt Fellowship which he used to join the Institute of Optics, Information and Photonics of the University of Erlangen-Nürnberg. From 2004 to 2006 he was leading the quantum communication group at this Institute. In 2006 he was appointed an associate professorship at the technical university of Denmark. His fields of interest are nonlinear optics, generation and application of non-classical and entangled light as well as the development and implementation of quantum information processing protocols. In 2005 he won the DOPS prize of the Danish Optical Society.

Participant 10	FAU	Friedrich-Alexander-Universität Erlangen-Nürnberg Erlangen, Germany

The Chair of Optics at the Physikalisches Institut of the Friedrich-Alexander-Universität Erlangen-Nürnberg was founded in 1973. It consists of three groups and of 50 scientists, Ph.D. and Diploma students. The spectrum of the work spans the whole range from technical optics to quantum optics. The available infrastructure includes a laser pattern generator for generating diffractive optical elements and computer generated holograms, various pieces of interferometric test equipment, optical fibre tools, and 2 ultrashort pulsed laser laboratories. The projects range from optics in medicine and advanced distance sensors to the study of resolution limits e.g. in microscopy to quantum measurements and optical communication. The newly founded Institute for Optics, Information and Photonics is operated jointly by the University and the Max-Planck Society. The Chair of Optics is a part of this new Institute. The FAU group is involved in the Focused Research Program "Quantum Information Processing" of Deutsche Forschungsgemeinschaft (DFG). It has received grants from the Federal Ministry for Education and Research, the Bavarian Science Agency, and the European Commission. It was involved in the EC QIPC projects QUIPROCONE (*Quantum Information Processing and Communications Network of Excellence*), QUICOV (*Quantum Information with Continuous Variables*) and it currently participates in the project COVAQIAL *(Continuous VAriable Quantum Information with Atoms and Light*).

Prof. Dr. Gerd Leuchs studied Physics and Mathematics at the Universität zu Köln until 1975 and received the Ph.D. in 1978 and the Habilitation degree in 1982 both from the Ludwig-Maximilians Universität in München. In 1979, he received a Feodor-Lynen Stipend from the Alexander-von-Humboldt Foundation and, from 1983 to 1985, a Heisenberg-Fellowship of the Deutsche Forschungs-Gemeinschaft. In 1980/81, he was Visiting Fellow at the Joint Institute for Laboratory Astrophysics at Boulder, Colorado. At the time his scientific work concentrated on laser spectroscopy and multi-photon processes. From 1985 to 1989, he was leading the gravitational-wave-detection group at the Max-Planck-Institut für Quantenoptik in Garching. From 1990 to 1994, he was Technical Director of Nanomach AG, Switzerland and, in 1994, he was given the Chair of Optics at Erlangen University. So far, he participated in four Esprit/STREP projects. Since April 2003, he is director of the Max-Planck Research Group Optics, Information and Photonics. In 2004 he was appointed Fellow of the Optical Society of America and Fellow of the Institute of Physics, UK. In 2005 he won the Quantum Electronics Prize of the European Physical Society and was appointed member of the German Academy of Science Leopoldina.

Dr. Christine Silberhorn studied physics and mathematics at the University of Erlangen where she received the Ph.D. in 2002 for a thesis on intense entangled light beams and quantum cryptography. In the following two years, she was Junior Research Fellow of the Wolfson College Oxford, working in the Clarendon Laboratory with Ian A. Walmsley. In 2005, she won a prestigious independent junior research group of the Max-Planck Society which she is heading since then. She won several prizes and was elected member of the "Junge Akademie". Her research topics are quantum state characterization, preparation and manipulation of ultra fast multi-photon wave packets in linear optical networks, fundamental aspects of quantum measurement and the application of optical quantum technology.

B.2.3 Consortium as a whole

The consortium is composed of 6 theoretical and 4 – effectively 5 – experimental teams, each having a leading expertise in this field. The agreed-upon working principle is to have them work "*hand-in-hand*" towards the final objective, keeping a constant contact between the theoretical concepts and experimental issues. This complementarity will ensure that new ideas are always developed in close collaboration between at least one theoretical and one experimental team. Also, given the wide perspectives of the envisaged research, it is crucial to join the expertise of various teams. In particular, the range of potential CV quantum computing schemes that will be investigated in WP1 as well as the diversity of the sources of nonlinearity that will be explored in WP2 to effect non-Gaussian operations motivates the size of our consortium.

The consortium includes leading experimental teams in the fields of generation and manipulation of squeezed and entangled states of light (CNRS/IO, FAU, DTU) and interfacing light with atomic ensembles (NBI, CNRS/ENS). Two experimental teams demonstrated the worldwide first generation of Schrödinger kitten states of traveling light beams via single photon subtraction (CNRS/IO, NBI), which is the starting point for a good fraction of the research planned within the present project. The experimental teams have a strong experience with the implementation of basic CV quantum information processing protocols such as quantum state teleportation, quantum cloning, the purification and distillation of squeezed states, and quantum cryptography.

The planned experimental activities will be strongly supported by the some of the leading theoretical groups in the field of CV quantum information processing which, together, cover all areas of expertise that are required for the project. The theoretical know-how includes the distillation, purification, and concentration of CV entanglement (POTSDAM, UP, USTAN), the characterization of entanglement properties of CV states (MPG, POTSDAM, ULB, ICFO, UP), the generation of highly non-classical states of light via photon subtraction (ULB, UP, USTAN), the measurement-induced CV operations (UP, POTSDAM), the theory of the interface between light and atomic ensembles (MPG, UP), and continuous-variable quantum key distribution and non-locality (ULB, ICFO).

Our well-balanced consortium is thus fully prepared and capable to pursue the envisaged research on advanced quantum computing and information processing with continuous quantum variables. Such pan-European collaboration ensures the necessary synergy between the experimental and theory partners and the accumulation of critical mass required for the successful achievement of the ambitious goals of the present proposal.

B.2.4 Resources to be committed

Project Number 1	212008	Project Acronym 2	COMPAS

One Form per Project

Participant number in this project 3	Participant short name	Estimated eligible costs (whole duration of the project)					Total receipts	Requested EC contribution
		RTD / Innovation (A)	Demonstration (B)	Management (C)	Other (D)	Total A+B+C+D		
1	ULB	184,000.00	0.00	80,000.00	0.00	264,000.00	0.00	218,000.00
2	MPG	160,000.00	0.00	0.00	0.00	160,000.00	0.00	120,000.00
3	ICFO	112,000.00	0.00	0.00	0.00	112,000.00	0.00	84,000.00
4	UP	160,000.00	0.00	8,000.00	0.00	168,000.00	0.00	128,000.00
5	USTAN	112,000.00	0.00	0.00	0.00	112,000.00	0.00	84,000.00
6	POTSDAM	112,000.00	0.00	0.00	0.00	112,000.00	0.00	84,000.00
7	CNRS	448,664.00	0.00	0.00	0.00	448,664.00	0.00	336,498.00
8	UCPH	268,000.00	0.00	0.00	0.00	268,000.00	0.00	201,000.00
9	DTU	268,000.00	0.00	0.00	0.00	268,000.00	0.00	201,000.00
10	FAU	180,664.00	0.00	0.00	0.00	180,664.00	0.00	135,498.00
TOTAL		2,005,328.00	0.00	88,000.00	0.00	2,093,328.00	0.00	1,591,996.00

ONE FORM PER PROJECT

Partici-pant number	Participant short name	Estimated eligible costs (whole duration of the project)						Total receipts (€)	Requested EC contribution (€)
		Effort (PM)	Personnel costs (€)	Subcontracting (€)	Other Direct costs (€)	Indirect costs OR lump sum, flat-rate or scale-of-unit (€)	TOTAL costs		
1	ULB	48.0	160,000.00	0.00	5,000.00	99,000.00	264,000.00	0.00	218,000.00
2	MPG	38.0	75,000.00	0.00	8,000.00	77,000.00	160,000.00	0.00	120,000.00
3	ICFO	24.0	65,000.00	0.00	5,000.00	42,000.00	112,000.00	0.00	84,000.00
4	UP	48.0	95,000.00	0.00	10,000.00	63,000.00	168,000.00	0.00	128,000.00
5	USTAN	12.0	60,000.00	0.00	10,000.00	42,000.00	112,000.00	0.00	84,000.00
6	POTSDAM	36.0	63,000.00	0.00	7,000.00	42,000.00	112,000.00	0.00	84,000.00
7	CNRS	60.0	280,415.00	0.00	0.00	168,249.00	448,664.00	0.00	336,498.00
8	NBI	36.0	152,500.00	0.00	15,000.00	100,500.00	268,000.00	0.00	201,000.00
9	DTU	48.0	152,500.00	0.00	15,000.00	100,500.00	268,000.00	0.00	201,000.00
10	FAU	48.0	107,915.00	0.00	5,000.00	67,749.00	180,664.00	0.00	135,498.00
	Total	398.0	1,211,330.00	0.00	80,000.00	801,998.00	2,093,328.00	0.00	1,591,996.00

The total budget for Research and Technological Development is given in the budget breakdown form. The budget mainly comprises the personnel costs. In total, the manpower needed to achieve our goals is estimated to be about 380 person-months (an extra 18 person-months being used for management), as indicated in the staff effort forms. The detail is given in the table below.

Participant	Personnel to be hired on the project	Total PM
ULB	one post-doctoral fellow (12 PM), one Ph.D. student (18 PM), and one part-time administrative staff member (18 PM)	48
MPG	one post-doctoral fellow (12 PM), one Ph.D. student (18 PM), and two senior researchers (8 PM)	38
ICFO	one junior post-doc for 2 years (24 PM)	24
UP	one post-doctoral fellow for 3 years (36 PM) and one senior researcher (12 PM)	48
USTAN	one post-doctoral fellow for 1 year (12 PM)	12
POTSDAM	one postdoctoral fellow for 3 years (36 PM)	36
CNRS IO & ENS	two post-doctoral fellows (24 PM), two Ph.D. students (24 PM), and one senior researcher (12 PM)	60

NBI	one post-doctoral fellow for 3 years (36 PM)	36
DTU	one post-doctoral fellow for 3 years (36 PM) and one Ph.D. student (12 PM)	48
FAU	one post-doctoral fellow for 1 year (12 PM) and one Ph.D. student for 3 years (36 PM)	48

COMPAS requested manpower in person-months (PM)

As indicated, the personnel costs will mainly cover the hiring of researchers, such as postdocs and Ph.D. students, working on the project. Frequent travels within the consortium will ensure a coordinated coherent work on the project goals. Therefore, the rest of the budget will mainly serve to cover travels within the consortium (or the attendance to conferences). The requested EU contribution represents 75% of the total eligible costs, while each participating institution will cover 25% of the corresponding costs.

The groups have at their disposal the equipment and resources required for a successful achievement of the project, which will complement the EC requested contribution. This includes the necessary office space, laboratories and laboratory equipment, mechanical and electronics workshops, computer facilities including computer clusters, and access to scientific journals and databases. The major experimental equipment that will be mobilized for the work on COMPAS is listed hereunder:

CNRS/IO: VERDI doubled YAG lasers (5W and 15W); femtosecond titanium-sapphire lasers, pulsed OPAs, detection equipment, spectrum analyzers, photon counters and homodyne detections, cryostats.

CNRS/ENS: CW doubled YAG lasers; titanium-sapphire lasers, CW OPO in the near infrared, detection equipment, CCD cameras, spectrum analyzers, photon counters and homodyne detections.

NBI: experimental setup for cooling and dipole trapping of Cesium; optical setup for quantum interface of light with Cesium atoms; experimental setup for Bose-Einstein condensate in Rubidium; optical setup for quantum interface of light with the BEC; experimental setup for generation of entangled and Fock states of light, and experimental setup for quantum memory with room temperature Cesium gasses.

DTU: Dual frequency CW laser (532nm (700mW) and 1064nm (400mW)), Homodyne detectors, Standard characterization equipment (oscilloscopes, spectrum analyzers, power meters etc.).

FAU: CW 10W pump lasers at 532 nm, 400 mW femtosecond laser at 1500nm, CW 200mW diode laser at 800nm, gated Si APD detectors, homodyne detectors, electro-optics modulators, standard polarization maintaining fibers, high speed electronics, standard characterization equipment (oscilloscopes, spectrum analyzers, autocorrelators), hollow core photonic crystal fibers.

The recently established experimental group DTU will need some additional laboratory equipment for the successful realization of the planned project. The following equipment is requested (included in the "other direct costs" category):

- Electro-optical modulators for signal encoding
- Standard consumable equipment (mechanical and optical components, wave plates and electronics).

Total estimated cost: 10,000 €

The management part of the budget is kept to a minimum (88,000 €), and will be mainly used to cover the organization of international workshops on continuous-variable quantum information processing (one per year). This will be a main opportunity for the consortium to meet annually as well as to interact with the entire continuous-variable community worldwide.

B3. Potential impact

B.3.1 Strategic impact

The planned research within COMPAS addresses one of the main challenges of the work programme for ICT within FET, namely “rethinking the nature of computing” and its physical implementation, especially in connection with quantum information technologies. We foresee that by addressing the issue of quantum information processing following a non-traditional but highly promising road, COMPAS will have a strong impact on the future of ICT-related technologies. It significantly departs from the mainstream QIPC research in that it assumes a *paradigm shift*, from qubits to continuous information carriers, which radically changes both the tools and prospects. There is, of course, cross-fertilization between these two research paradigms, but the issues of interest are sufficiently distinct so that the present theme requires a specific expertise and treatment. The planned research direction within COMPAS is therefore complementary to that of the QIPC proactive initiative within FET. This specialization level also clearly justifies the need for an international collaboration at the European scale, since a critical mass cannot be reached at the national level.

The project comes at a relatively early stage in the development of continuous-variable quantum information science, where no European country alone possesses the critical mass necessary to create an effective interdisciplinary research community in this specific area. It will therefore provide a real chance to make progress on the current outstanding issues, whose answers will greatly impact on the perspectives of the CV quantum computing. Such a pan-European research effort on continuous-variable quantum information science has been initiated in 2004 – though to a smaller extent – via the exploratory research project COVAQIAL, funded within FP6. The present project, while being centered on the same core partners, involves several other main actors in the field and is specifically focused on computational goals. It should thereby largely strengthen the European research effort in this field, which has undergone a remarkable expansion since 2004. Besides several breakthroughs such as the first quantum memory of light or the first interspecies quantum teleportation, both having been demonstrated with CV quantum information carriers within the COVAQIAL project, the raising interest for continuous variables is also witnessed by the great success met by a recent series of international workshops solely devoted to this topic, which has been organized yearly by several COVAQIAL members (see Section 3.3).

The objectives of the COMPAS project are complementary to those of the three Integrated Projects currently funded in the QIPC proactive initiative, namely SCALA, QAP, and EuroSQIP. Both SCALA and QAP have only a marginal theoretical activity and no experimental activity at all on CV quantum information processing. The focus of QAP is on “qubit applications” (as indicated by the title!), and SCALA does not address atomic ensembles, for example, or any other CV experimental platform. Furthermore, the overlap of the present project with EuroSQIP is strictly zero, given the very specific focus of the latter proposal on solid state quantum computers and superconducting devices. The present project also goes much beyond the earlier project COVAQIAL, whose central theme was to reach a proof-of-principle of the potential of CV quantum communication. By combining expertise from experimental and theoretical quantum optics as well as information theory, the COMPAS consortium has indeed laid down the foundation for a work that is exploratory and theoretical on the one hand, but also firmly grounded in today’s experimental possibilities on the other hand. The success of the COMPAS project should undoubtedly contribute to a European lead in this field, with the associated benefits for European competitiveness.

B.3.2 Plan for the use and dissemination of foreground

i) Dissemination measures

The results obtained by the participants will be made accessible to a wide scientific community mainly by their publication in the top international peer-reviewed scientific journals such as Nature, Science, Physical Review Letters and Physical Review A. A website of the project will be established and maintained. It shall include an up-to date information about the project goals, the achieved scientific results and a database of all publications that will be thus made freely available to the public. The members of COMPAS consortium will also present their results at the major international scientific conferences and workshops in the fields of quantum information science and quantum optics.

A major dissemination measure within COMPAS will be the organization of a series of international workshops focused on continuous-variable quantum information processing (CV-QIP workshops). This series was initiated by a few members of the present consortium (ULB, CNRS, and NBI) in 2002, when the first such meeting (CV-QIP'02) was held in Brussels. The great success of this workshop triggered the interest in continuous-variable quantum information processing and was an incentive for starting this workshop series. The second workshop in this series was organized by CNRS and ULB (CV-QIP'03, Aix-en-Provence), while the third workshop took place in Veilbronn, organized by FAU and ULB. The fourth workshop was organized in April 2005 in Prague by partners UP and ULB. The fifth workshop (CV-QIP'06), organized by partners NBI and ULB, was held in Copenhagen, in May 2006. Finally, the sixth workshop in this series (CV-QIP'07) was organized by partners USTAN and ULB in St. Andrews, April 2007. These workshops turned out to be extremely successful and popular, and have attracted the attention of a broader audience of the top world researchers in the field of continuous-variable quantum information processing. Each workshop was attended by about 40-50 scientists from Europe as well as from the overseas (USA, Australia, Japan). These workshops contribute to define the boundaries of – and give a specific identity to – this new field.

At the occasion of the CV-QIP workshops that will be organized during the course of the project, a work group will be set up and meet with the objective of brainstorming on the perspectives of the CV paradigm. The main mission of this work group will be to evaluate the potential "medium-term scientific spin-offs" of the field, which are anticipated to emerge on the route to – but before – quantum computers. It is indeed important to investigate the competitive advantage of the CV paradigm in terms of spin-offs, which may be applicable in a closer future and would not require the ability to implement a complete quantum computer. Possible candidates of such promising spin-offs are the protocols that usually require many qubits before the advantage of quantum information can be taken (e.g., bit string commitment), but may become immediately efficient using CV quantum information carriers.

The COMPAS members will also actively present their results to a wide audience. The project website will contain a section with popular description of the results achieved and the underlying physical principles. Another contribution to the promotion of quantum information research to the general public will be made by publishing articles in popularizing science magazines and newspapers. In particular, it is expected that the announcements of the major achievements will attract the attention of popular media.

ii) Exploitation of project results

Given its fundamental nature, it is not anticipated that the present project will directly produce exploitable results defined as knowledge having a potential for industrial or commercial application in research activities or for developing, creating or marketing a product or process or for creating or providing a service. Most of the results obtained by the COMPAS consortium will be made freely accessible to all experts as well as to the public. It is expected that these results will form a basis for future applied research leading to patentable quantum communication technologies. However, if the situation arises that results having potential for further commercial exploitation will be achieved already during this project, then appropriate measures such as patent applications will be taken to protect this intellectual property. The access rights and detailed conditions of protection of knowledge will be defined in the consortium agreement.

iii) Positioning with respect to the realization of a long term vision in the ECT domain

One of the main challenges of the coming decade – and probably of more decades to come – for Europe is to remain competitive in a global market place. The Lisbon European Council in March 2000 puts it even stronger in stating that Europe “has to become the most competitive and dynamic knowledge-based economy in the world.” In this context, Information and Communication Technologies (ICT) are at the heart of the knowledge-based economy, and have profound effects on the way we work and live. Apart from the ICT sector itself, information technologies dramatically influence other areas such as healthcare, education, environment, business, government, and entertainment. Being competitive in ICT is very clearly a prerequisite to staying competitive in all affected areas.

The challenges addressed within COMPAS meet the broader vision of our future ICT-based society, and therefore are very well positioned within the FP7 work programme for Information and Communication Technologies. If successful, COMPAS will indeed open novel directions to the physical realization of ICT-related technologies, which should, in the long term, induce a qualitative boost in the computing and communication capabilities of computer networks. Its expected societal impact will result from the transfer of the basic science results towards new schemes and/or devices for quantum computing. This may lead to a considerable progress in information technologies since advanced scientific results will be used for the development of new practical devices. It is in the interest of the future international competitiveness of the European industry to take advantage of the leading position that the quantum optics community in Europe has achieved, and transfer those accomplishments to the progress in quantum optical communication technology.

In conclusion, considering that the main ingredients of the CV toolbox are now being demonstrated or are becoming viable, we believe that it is the “right time” to start this radically new, high pay-off, exploratory project aiming at building a small-scale mesoscopic quantum processor, away from the traditional qubit paradigm. Asides from being one of its core specificities, the bottom-up philosophy of our project also ensures that any incremental progress achieved on mesoscopic CV processors will contribute towards the “big picture” of quantum computation. The interdisciplinary consortium that we have formed is composed of leading European research teams, so that we hope that it will help strengthen the cooperation in this particular research area, where Europe has started to establish itself at the leading edge.