INFORMATION SOCIETY TECHNOLOGIES (IST)

PROGRAMME

Contract for: **Shared-cost RTD**

Annex 1 - "Description of Work"

PROJECT ACRONYM: **EDIQIP**

PROJECT FULL TITLE:

Effects of Decoherence and Imperfections for Quantum Information Processing

CONTRACT NO.: **IST-2001-38869**

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1. Project summary

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Project Acronym (2)	EDIQIP	Project No (3)	IST–2001–38869

A2. Project Summary (20)

Objectives (maximum 1000 characters)

The aim of this project is the investigation of decoherence and error correction in quantum processors solving physical problems for which new and useful results may be achievable using 40−−60 qubits. New algorithms will be developed for these problems, which will include complex quantum dynamics, nonlinear classical evolution, electron transport in disordered materials and metal−insulator transitions. A numerical code package will be developed to simulate these new algorithms and to model decoherence and imperfection effects for realistic quantum computers with up to 30 qubits. Using this code package, decoherence time scales and critical thresholds for multi−qubit residual imperfections will be determined. Quantum error−correcting codes will be tested with this package to reduce these decoherence effects in the specific algorithms developed within this project.

Description of work (maximum 2000 characters)

We will investigate the effects of various decoherence sources on existing and newly developed efficient quantum algorithms simulating important physical problems, considering decoherence produced by noisy gates modeled by random unitary rotations as well as more general environment−induced noise processes. In parallel the effects of internal static imperfections, including residual couplings between qubits and static level spacing fluctuations for individual qubits, will be investigated. We will develop a numerical code package capable of modeling these imperfections and decoherence effects for a given experimental realization of a quantum processor and thereby determine the bounds for reliable quantum computation. We will develop new efficient quantum algorithms for computationally hard physical problems such as simulation of many−body quantum systems, Anderson transition, electron transport and chaotic classical dynamics. Our numerical code package will model the realistic effects of decoherence and imperfections in the new quantum algorithms developed. We plan to be able to handle up to 30 qubits for noisy gates and quantum trajectory methods and up to 15 qubits for density matrix methods. Using our code, it will be possible to model the static imperfections typical for a given experimental implementation of a quantum processor. Quantum eror correction codes will be numerically tested to stabilize newly developed quantum algorithms against decoherence and static residual couplings between qubits. We will use methods from quantum information theory, the theory of complex classical and quantum dynamical systems, random matrix theory, mesoscopic physics and many−body quantum physics combined with our broad experience in numerical simulations of these systems.

Milestones and expected results (maximum 500 characters)

− Decoherence time scales for noisy gates and dissipative coupling to environment
− Universal laws for many−body chaos and fidelity drop induced by static imperfections
− Efficient quantum algorithms for computationally hard physical problems
− Numerical code package simulating new algorithms with up to 30 qubits
− Numerical tests of quantum error correction codes
− Stability bounds for the operability of realistic quantum processors

2. Project objectives

Recent technological progress in the field of quantum information processing has led to the realization of quantum computers with a small number of qubits, which are able to execute basic quantum logic operations and to perform certain quantum algorithms. A physical realization with up to seven qubits was achieved with nuclear spins in molecules by Nuclear Magnetic Resonance (NMR) and experimental progress in ion-trap technology suggests that, within one or two years, there will be a working ion-trap quantum computer with three or more qubits. Solid state realizations with two and more qubits are also under way in several experimental groups working with SQUIDs and other solid state devices. This suggests that on the scale of two or three years a quantum computer operating with up to ten qubits will be available for the experimental implementation of simple algorithms. The main problem for the operability of such a computer with ten or an even larger numbers of qubits is related to effects of decoherence and imperfections appearing during quantum information processing. Hence it is of primary importance to be able to handle these decoherence effects and to test their manifestation in quantum computers performing exponentially efficient quantum algorithms. If such algorithms are implemented on a first generation of scalable quantum computers with up to ten qubits, then a future generation with 40–60 qubits may be capable of providing information inaccessible to current supercomputers running known classical algorithms.

An efficient way to test these decoherence effects is to create numerical codes capable of modeling various kinds of imperfections in quantum information processing and to simulate a range of quantum algorithms with a few tens of qubits. We propose to study these decoherence effects for new algorithms which can solve important physical and computational problems efficiently and for which quantum computers with 40–60 qubits can provide currently inaccessible information. A package of numerical codes that can simulate quantum algorithms, including error correcting codes, in the presence of decoherence will allow to determine optimal regimes for the operability of the next generation of quantum computers.

Recently the groups participating in the project have developed new exponentially efficient algorithms for physical problems of classical and quantum chaos and new types of error correcting codes. First numerical simulations of these algorithms have already been reported by these groups. First results demonstrate that effects of decoherence and imperfection can be tested numerically in such algorithms for up to about 30 qubits. Such numerical simulations will play an important role for future experiments. Indeed, one of the algorithms, the quantum baker's map, has recently been implemented by D. Cory *et al.* at MIT with a three qubit NMR-based quantum computer

On that basis the main objectives of this project are the following: It is planned to develop models of decoherence which will describe the coupling between a quantum computer and the environment. These models take into account unitary errors originating from noise in the quantum gates as well as dissipative effects which originate from radiatively induced spontaneous decay processes, for example. In parallel, this project aims to investigate effects of residual interactions between qubits and imperfections of individual qubits. These static imperfections lead to the appearance of quantum chaos which induces "melting" of the quantum computer hardware, even in the absence of couplings

with the environment. Here, "melting" means that even in the absence of any coupling to an environment the eigenstates of a quantum computer become ergodic and are characterized by a large entropy. First results obtained by the consortium members indicate the importance of internal many-body chaos which should be studied in combination with effects of external decoherence. Many-body chaos introduces intricate correlations which cause decoherence and which must be taken into account for the development of optimal error correcting codes.

It is planned to study these decoherence- and imperfection-effects in the context of new efficient quantum algorithms. Examples of such algorithms were already developed by the consortium members and include quantum computing for dynamical systems, such as the quantum baker's map, the kicked rotator model, the quantum sawtooth map and the classical chaotic dynamics for the Arnold cat map. The new algorithms and those cited above require a relatively small number of qubits and their rich dynamics can be investigated already with about 20 qubits. Already a quantum computer with 40–60 qubits and with a low decoherence rate could provide new information which is inaccessible by present-day classical computers. Because of their rich dynamics, these algorithms are ideal for the investigation of decoherence and imperfections. Such types of algorithms are very well suited for the first generation of quantum computers: in certain cases the number of workspace qubits can be reduced to zero and rich complex dynamics can be investigated already with 6–10 qubits. It is also important to understand how quantum error correcting codes will operate in the framework of the above algorithms. Numerical codes will be developed for modern supercomputers to simulate the effects of decoherence and imperfections.

The final aim is to create a package of numerical codes which will simulate efficient quantum algorithms for the solution of various important physical problems. Examples are Anderson localization for electron transport in disordered materials, classical nonlinear dynamics, quantum tunneling, and molecular magnets. This will allow us to understand the physics of decoherence in the direct context of these algorithms, to determine the decoherence time scales and the accuracy of algorithms in realistic conditions close to experimental setups. Also this will allow to test some quantum error correcting codes in numerical simulations. Such tests will become of vital importance for the coming generation of quantum computers with ten and more qubits. Instead of just implementing possibly noisy gate sequences, the planned package will perform a simulation of a realistic quantum computer, taking into account experimental imperfections, residual many-body couplings between qubits and other physical decoherence mechanisms. The numerical simulations performed with this package will allow us to develop a deeper understanding of decoherence and imperfection effects during quantum information processing. They will provide clear recipes for experimentalists on how to improve the reliability of quantum information processing and how to improve the accuracy of quantum computation.

3. Participant list

Part. role	**Part. no.**	**Participant name**	**Participant short name**	**Country**	**Date enter proj.**	**Date exit proj.**
C	1	Université Paul Sabatier Toulouse	UPS	F	0	36
P	2	Technische Universität Darmstadt	TUD	D	0	36
P	3	Istituto Nazionale per la Fisica della Materia-Como	INFM	I	0	36
P	4	Royal Holloway University of London	RHUL	UK	0	36

4. Contribution to programme/key action objectives

The project meets the general objectives of the proactive initiative Quantum Information Processing and Communication (QIPC) within the Future and Emerging Technologies (FET). Indeed, the QIPC initiative requires to develop "new quantum algorithms that tackle problems of practical significance, simulators of quantum systems as well as the development of novel few qubit applications of quantum systems, including the control of decoherence".

The present project unites groups which have already made significant contributions to the development of new algorithms and error correcting codes. The first investigations of decoherence and imperfection effects were carried out in numerical simulations of these algorithms with few qubits. The project will allow to develop new quantum algorithms which can efficiently solve problems of quantum and classical chaos. These algorithms will allow to simulate efficiently models of quantum chaos with rich dynamics (e.g. quantum baker's map, kicked rotator, sawtooth map, etc.) and to study the quantum-classical correspondence on very small quantum scales. The first generation of quantum computers with up to 10 qubits will provide interesting information. An important task is to

develop efficient quantum algorithms capable of simulating classical dynamics. This will open new perspectives for applications of quantum computers to problems of plasma physics, meteorology and the simulation of molecular dynamics in biophysical systems (indeed, in these fields the simulations are very computation-intensive and involve mainly classical dynamics). Models of decoherence and imperfections in quantum information processing will be developed and tested in numerical simulations. These simulations will be performed by a code package able to model quantum computers with up to 30 qubits, which is directly related to the initiative objectives. This package will allow to test the work of certain quantum error correcting codes and to reach significant progress in the control of decoherence. The ensemble of these developments will allow to improve the operational stability and computational accuracy of scalable quantum processors. The developed numerical simulator will be very useful for the development and running of the next generation of quantum processors, since it will allow to make rapid tests of various imperfection effects.

To summarize, our work will contribute to basic research on quantum algorithms, quantum error correcting codes and decoherence control. It will have a strongly interdisciplinary character, involving scientists from physics and mathematics with a high level of experience in numerical simulations. In this way the project will meet the challenges of the QIPC initiative quoted above.

5. Innovation

It is well appreciated that decoherence is the ultimate problem for operability of quantum computers. Therefore it is essential to understand the details of how decoherence affects the stability of quantum algorithms. The main innovative contribution of the project is the study of various decoherence effects in the concrete example of efficient quantum algorithms simulating important physical problems. These decoherence effects will include noisy gates modeled by random unitary rotations as well as more general environment-induced noise processes, including dissipative effects. In parallel the effects of internal static imperfections, including residual couplings between qubits and static level spacing fluctuations for individual qubits, will be investigated. It is important to test all these effects and to assess their significance in efficient quantum algorithms.

In this respects quantum algorithms for the simulation of physical systems play a very important role, since about 40-60 qubits would allow one to make computations inaccessible to present-day supercomputers. However, at present only a few quantum algorithms are known which simulate physical systems with exponential efficiency. A major breakthrough of our project will be the further development of efficient quantum algorithms for physically significant and computationally hard problems, including simulation of many-body quantum systems, metal-insulator transitions, electron transport and chaotic classical dynamics. We stress that quantum processors would become efficient simulators for physical problems much before than large-scale problems like integer factoring could be usefully tackled. In addition, in some algorithms the number of redundant qubits can be reduced to zero, i.e. all the qubits are used to simulate the system dynamics. Thus, interesting physical phenomena can be investigated experimentally al-

ready with 6-10 qubits. Therefore these algorithms will become the most natural testing ground for the first generation of quantum processors.

We will develop a numerical code package capable to model the imperfection and decoherence effects described above for given experimental realizations of quantum processors and thereby determine the bounds for reliable realistic quantum computation. Using this code package, we will model the realistic effects of decoherence and imperfections in the newly developed quantum algorithms. Thanks to modern supercomputers, we plan to be able to handle up to 30 qubits for noisy gates and quantum trajectory methods, and up to 15 qubits for density matrix methods. This numerical code package will be useful for coming experiments, since it will be possible to model the imperfections typical for a given experimental implementation of a quantum processor and to determine optimal regimes for its operability.

We will develop a code package which will also test the efficiency of certain existing quantum error correcting codes in the presence of static couplings and external decoherence and in the framework of the above algorithms. We note that, contrary to the usual models of external decoherence, the effective decoherence due to the inter-qubit residual interaction is characterized by intricate correlations, which need to be taken into account in any practical fault-tolerant implementation of a quantum computation.

The EDIQIP project will make the pioneering step in the developement of quantum software for realistic quantum processors. This software will be capable to treat and model the important physical problems including electron transport in disordered materials, metal-insulator transitions, complex classical and quantum dynamics. The developed numerical code package will operate with up to 30 qubits. It will allow to develop a profound understanding of decoherence and imperfection effects for these physical processes simulated on realistic quantum processors, to test some quantum error correcting codes, and to fight decoherence. Therefore, the project will provide the results of vital importance for the improvement of the accuracy of quantum information processing.

6. Community added value and contribution to EU policies

The scientific and technological progress in the field of Quantum Information Processing and Communication (QIPC) is of enormous importance for the EU. Indeed quantum information science has emerged as a new dynamic interdisciplinary field of research, which benefits from the contributions of physicists, computer scientists, mathematicians, chemists and engineers. While scientists all over the world are just starting to understand the reasons of the power of QIPC, the industrial and social impact that could result from such research is overwhelming. Therefore, it seems necessary to support this direction of research at the European level, in order to be competitive with research projects from outside the EU, notably from the USA and Japan.

The project is characterized by a broad interdisciplinary background of its participants, who already obtained important results in the field of QIPC. This assures a combination of complementary high-level expertise, from the theoretical aspects of classical and quantum mechanics of complex systems and of information science to large

scale numerical simulations. It is of primary importance to bring together these different expertise available Europe-wide to work on important problems in QIPC. Indeed, the most efficient way to tackle the objectives of the project is at European level: in a single institution or at national level, it is impossible to find enough expertise and a sufficient critical mass in human or financial resources to achieve all the scientific objectives of the project. Since these objectives include different but interrelated tasks, we expect that the effectiveness of the work of the various project partners will be amplified by their cooperation.

We point out that the planned deliverables of this project will be useful for European experimental groups working in the field of QIPC. Indeed in the near future a quantum computer operating with ten or more qubits will be available. In this context, it will be very important to develop new quantum algorithms which allow experimentalists to study useful and interesting physical systems with a small number of qubits. In addition, a numerical code package will be developed to simulate these new algorithms and to model decoherence and imperfection effects for realistic quantum computers. A numerical simulator will be built to test certain error correcting schemes in the specific algorithms developed within the project. Therefore the ensemble of the deliverables of the project will be useful for EU experimentalists, since it will be possible to model these algorithms in realistic conditions close to experimental setups. We expect that this will give clear recipes to EU experimentalists on how to improve the reliability of quantum information processing.

7. Contribution to Community social objectives

The nature of the proposed project is basic research, thus it is difficult to predict all its impacts to the society. However, QIPC opens up a completely new branch of information theory, which promises significant industrial and social impact. In the long run, this should have positive effects on employment prospects. We also point out that the enrollment of post-doc fellows by the consortium members will favor the diffusion of QIPC inside Europe. The training of young researchers is essential in this respect.

8. Economic development and scientific and technological prospects

The standard means of scientific publishing will be used for dissemination of the results of this research. The numerical codes developed in the workpackage **WP6** will be public. Therefore it will be possible for experimental groups working in QIPC to check the stability of quantum algorithms in the presence of imperfection/decoherence effects and also to test certain quantum error correcting codes. Furthermore a webpage describing the progress of the project will be installed.

9. Workplan

9.1. General description

In order to achieve the objectives within the duration of this project, we propose a workplan consisting of 6 workpackages. Each workpackage involves several research teams, making joint use of their respective theoretical and computational skills. The objectives of each workpackage can only be achieved by a joint effort of the participating research teams. The proposed program is inherently interdisciplinary.

The workplan is designed to keep the respective research teams focused on the relevant parts of the overall objectives, in order to achieve the maximal benefit from the interdisciplinary and international collaboration. Each workpackage has clearly defined starting points and objectives. Intermediate results will be shared between all participating research teams. A special webpage will be maintained to represent the public results of workpackages and the publications of the network.

The coordinator of the project participates in the quantum computing research program launched by the USA government and NSA/ARDA/ARO and the INFM member has been recently appointed for this program. Thus the present project will reinforce collaborations between American and European researchers in the field of quantum information processing.

The workpackage **WP1** is devoted to the management of the project, organization of the communication flow within the consortium, meetings of consortium members and periodic reports. The reporting to the Commission will cover all aspects of the project, including project management and administration (Management Reports), technical progress and achievements (Periodic Progress Reports at 6th month each year and Annual Progress Reports at 12th month each year).

The workpackage **WP2** is devoted to the dissemination of the results of the project. The built up consortium web page will present the up to day progress reached within the project. Partners will take a broad view on dissemination, setting-up web sites with links inside the consortium and with other FET-QIPC participants. This will give easy public access to scientific publications obtained in the frame of EDIQIP project. The consortium members will give courses at their universities on Quantum Information and Computation, which will provide student access to the most recent developments in this rapidly emerging field. The detailed dissemination plan for workpackages **WP3-WP4-WP5-WP6** will be provided by this workpackage. The first meeting of the consortium members will be made in collaboration with american researchers working in the field of quantum information (see Section 9.7). This will strength the information exchange between EU and USA researchers in the QIPC field.

The innovating results of the project will be obtained in workpackages **WP3, WP4, WP5, WP6**. These results will be reached on the basis of long term expertise of consortium members in such fields of physics as: quantum many-body systems with interactions (including atoms, molecules, electrons in quantum dots, quantum spin glass), mesoscopic physics, metal-insulator transitions, random matrix theory, complex dynamics in systems with classical and quantum chaos, dynamical and Anderson localization, electron transport in disordered materials, semiclassical Gutzwiller quantization, Rydberg atoms in

electric, magnetic and microwave fields, dynamics of cold atoms, wavepacket dynamics, information theory. In the field of QIPC the consortium members have expertise in quantum algorithms for complex dynamics, quantum purification and quantum error correction, entanglement properties in NMR quantum computing experiments. They have long term experience in numerical simulations of interacting quantum many-body systems, metal-insulator transitions, quantum chaos models, mesoscopic systems, quantum trajectories dynamics. During last years they performed numerical simulations of quantum algorithms solving some problems of complex classical and quantum dynamics.

The workpackage (**WP3**) investigates the effects of different decoherence models on simple efficient quantum algorithms already developed by consortium members. Numerical code for these algorithms will be constructed for the different decoherence models. These models will include decoherence produced by noisy gates with random unitary rotations by correlated as well as uncorrelated angles, and the more general case of interaction with an external environment including dissipative effects. In the latter case, the numerical code will either solve the density matrix equations directly, or by using quantum trajectory methods, depending on the number of qubits involved. In this way both unitary and non-unitary effects of decoherence are taken into account.

Initially we will use these numerical codes to investigate decoherence time scales for the particularly simple but nevertheless rich algorithms for the quantum baker's map and the sawtooth map. These maps are well known in the field of dynamical chaos and their classical dynamics was deeply investigated by so well known mathematicians as Anosov, Arnold, Kolmogorov, Sinai and others. The algorithmic complexity of their classical dynamics is characterized by a positive Kolmogorov-Sinai entropy and exponentially rapid mixing in the phase space. Due to that, their deterministic dynamics is unpredictable. In the quantum case the advantage of these simple dynamical models is that they do not require any additional workspace qubits, so that the Hilbert space can be used optimally. In the classical limit these maps describe both the chaotic and complex quasi-integrable dynamics depending on the choice of parameters. Since the investigation of time evolution requires iterative application of these maps, the effects of decoherence play a very important role. Indeed, there exists a decoherence time scale after which the dynamics is completely modified by the environment. As essential element these algorithms use the quantum Fourier transform (back/forward), which allows to make transition from momentum to coordinate representation. The total Hilbert space is composed of $N = 2^{n_q}$ quantum states, where n_q is the total number of qubits, and about n_q^2 elementary gates are required to perform one map iteration.

In such systems the effective Planck constant is $\hbar_{\rm eff} \sim 1/N$ and exponentially small scales in the phase space can be resolved for large number of qubits. The package will develop numerical codes which will simulate the effects of decoherence for these dynamical systems. This will allow to determine the decoherence time scales and their dependence on system parameters. The first experimental NMR-based realization of the quantum baker's map were recently reported by the group of D. Cory at MIT. The results obtained in this workpackage can be used for the experimental investigation of quantum chaos models which are characterized by chaotic unpredictable dynamics in the classical limit. This will allow to test the fundamental nature of transition from quantum to classical behavior in the regime when classical errors grow exponentially with time. We

note that, for these systems, quantum computers with 40–60 qubits may be capable of providing information inaccessible to modern supercomputers. The developed numerical codes will be able to perform simulations with up to 30 qubits for noisy gate and quantum trajectory methods, and up to 15 qubits for density matrix methods.

The workpackage (**WP4**) studies the effects of imperfections in a quantum processor which is isolated from the environment. Indeed, the absence of external decoherence does not mean that the quantum processor will operate properly. Static internal imperfections due to inter-qubit residual couplings J can strongly modify the ideal quantum register represented by noninteracting many-body (multi-qubit) states of ideal qubits. A simple estimate shows that the residual interaction J will be unavoidably much larger than the average energy level spacing Δ_n between adjacent eigenstates of a realistic/generic quantum computer. For J being relatively weak comparing to one-qubit level spacing Δ_0, all N eigenenergies are located in the energy band of size $\Delta E \sim n_q \Delta_0$ and the average multi-qubit level spacing is $\Delta_n \approx \Delta E/N \sim \Delta_0 2^{-n_q} \ll \Delta_0$. For the experimental realization of quantum computer proposed by Kane we have $\Delta_0 \sim 1$ K so that for $n = 1000$, when Shor's algorithm becomes useful, the multi-qubit spacing is incredibly small $\Delta_n \sim 10^3 \times 2^{-10^3} \Delta_0 \sim 10^{-298}$ K (Kelvin). This value is definitely much smaller than any physical residual interaction J. For the Kane proposal with a distance between nuclear spins of $r = 200$ Å and an effective Bohr radius of $a_B = 30$ Å, the coupling between qubits (spin-spin interaction) is $J \sim \Delta_0 \sim 1$ K. By changing the electrostatic gate potential, an effective barrier between nuclei can be modified that can be viewed as a change of effective electron mass possibly up to a factor of two. Since $J \propto (r/a_B)^{5/2} \exp(-2r/a_B)/a_B$, and a_B is inversely proportional to the effective mass, this gives a minimal residual spin-spin interaction of $J \sim 10^{-5}$ K $\gg \Delta_n$. At first glance this would lead to a natural/naive conclusion that for such a residual interaction the ideal quantum computer eigenstates are strongly modified and mixed, resulting in melting of the quantum computer hardware in the sense introduced above. In spite of this expectation it has been shown recently by consortium members that the ideal qubit structure is much more robust and in reality the quantum hardware melting and quantum chaos induced by inter-qubit interaction takes place at $J > J_c \sim \Delta_0/n_q$ being exponentially larger than the nearest level spacing Δ_n. For example, at $\Delta_0 \sim 1$ K and $n = 1000$ the critical coupling $J_c \sim 1$ mK is compatible with the Kane experimental proposal. It is an important open question how this many-body chaos can be overcome by error correcting codes and fault-tolerant schemes. Contrary to the usual models of external decoherence, the effective decoherence due to the many-body quantum chaos is characterized by strong correlations, which need to be taken into account in any practical fault-tolerant implementation of a quantum computation. We conjecture that the optimal regime for operating a quantum computer is below the chaos border.

The above result is closely related to the long term research on quantum many-body systems, started by Wigner, interested in "the properties of the wave functions of quantum mechanical systems which are assumed to be so complicated that statistical consideration can be applied to them". As a result, the random matrix theory (RMT) has been developed to explain the generic properties of complex eigenstates and energy spectra of many-body interacting systems such as heavy nuclei, many electron atoms and molecules. The concepts of RMT and quantum chaos will be significantly used to

investigate the extent to which the internal imperfections of quantum processors affect the results of quantum computations.

In the workpackage **WP4** a numerical code will be developed to simulate the algorithms discussed in **WP3** in the presence of static residual coupling between qubits as well as static fluctuations in the energy level spacings for individual qubits. The first results obtained indicate that these imperfections can be more damaging than the decoherence produced by noisy gates. Also the recent experimental results obtained in the group of R. Blatt at Innsbruck indicate that, in quantum processors based on cold trapped ions, static couplings are more important than decoherence due to a finite temperature environment. The developed code will allow to simulate the quantum dynamics of the baker's and sawtooth maps in the presence of static imperfections with up to 30 qubits. It will be able to model static imperfections typical for a given experimental realization of quantum processor.

The workpackage **WP5** is concentrated on the development of new quantum algorithms. One of the main applications of computers is the simulation of physical systems. It is therefore desirable to find quantum algorithms which describe physical models with rich and complex dynamics. During the last decades it has been understood that generally the dynamics of classical nonlinear systems is chaotic. The corresponding quantum dynamics, called quantum chaos, demonstrated a rich and complex behavior even for systems with only a few degrees of freedom and rather simple Hamiltonians. The cornerstone models in the study of quantum chaos are the quantum baker's map, the sawtooth map, and the kicked rotator. The quantum dynamics of these systems displays many phenomena of general importance including quantum ergodicity, spectral statistics as in RMT, quantum Kolmogorov-Arnold-Moser regime and the phenomenon of dynamical localization in which quantum interference suppresses quantum diffusion in momentum leading to exponentially localized eigenstates. The later effect has close analogy with the Anderson localization of electrons in disordered materials. The quantum kicked rotator describes also the properties of microwave ionization of Rydberg atoms, as it was observed in the experiments of Bayfield, Koch and Walther. This model has been realized experimentally with cold atoms (experiments of Raizen and many other groups). The members of the consortium recently developed efficient quantum algorithms which simulate the dynamics of the above three models. The further development of the research in this direction will allow to construct new quantum algorithms which can efficiently simulate the problems of transport of electrons in disordered materials and metal-insulator transition in different dimensions. The later problem is currently under active investigations in mesoscopic physics, where different numerical methods had been developed to simulate it numerically (transfer matrix techniques, Lanczos diagonalization, decimation method, level spacing statistics, etc.). We plan also to generalize these algorithms to be able to simulate with their help the effect of inter-particle interactions in the presence of disorder. The problem of interaction effects on the Anderson localization is under extensive experimental investigations by different experimental groups (Kravchenko at Boston, Sarachik at New York, Pepper at Cambridge, etc.). These problems are very difficult for simulations on classical computers since the size of the numerical basis grows rapidly with system size, dimension and exponentially with the number of electrons. Quantum algorithms making use of quantum parallelism and entanglement have the po-

tential for breakthroughs in their investigation. In this respect the new algorithms will be of primary importance for simulations of transport properties in various materials on quantum computers. We also plan to develop efficient quantum algorithms to simulate the problem of quantum tunneling in deep semiclassical regime. At present the problem of macroscopic quantum tunneling is under active investigation in the experiments with large magnetic momentum molecules. Also the chaos assisted quantum tunneling is studied in the experiments with cold atoms (Raizen at Austin) and Bose-Einstein condensates (Phillips at NIST). These algorithms will also allow to investigate the properties of quantum ergodicity in models of quantum chaos. We note that an investigation of quantum transport on atomic scales is performed at INFM (Como) and UPS (Toulouse) in the framework of the RTN Network contract HPRN-CT-2000-0156. This will allow us to optimize information exchange and research efforts in connection with the present project.

In parallel, the **WP5** package will develop quantum algorithms simulating classical dynamics. Recently the consortium members demonstrated that certain problems of classical dynamical chaos (e.g., generalized Arnold cat map) can be efficiently simulated on quantum processors. The developments in this direction will allow to understand how quantum algorithms can resolve problems of classical Newtonian dynamics. The possible application of such algorithms is enormously broad since the simulation of problems in plasma physics (plasma confinement), meteorology and large molecular dynamics are mainly based on classical equations of motion. Quantum algorithms can provide important new information about correlation functions in the regime of classical chaos and about the hierarchical structure of mixed phase space on very small scales. These algorithms give also access to exponentially high harmonics of Liouville density distributions and allow to study in detail how dynamical motion generates the laws of statistical mechanics. We will test how sensitive these new algorithms are with respect to the decoherence mechanisms and imperfections analysed in workpackages **WP3** and **WP4**.

We should stress that the quantum algorithms of the **WP5** package have certain advantages over, e.g., the Shor algorithm in that they promise to provide information inaccessible for classical simulations already with about 40–60 qubits whereas the Shor algorithm becomes useful only for more than 1000 qubits. This is due the fact that they require only a small number of workspace qubits (in certain cases it can be reduced to zero) and describe important physical processes with rich dynamics. Furthermore they are iterative, representing evolution in time for many iterations, which makes them ideal for tests of decoherence. Due to these reasons the **WP5** algorithms are ideal for experimental tests of the first generations of quantum processors.

The workpackage **WP6** develops the numerical codes which simulate the decoherence and imperfection effects considered in **WP3** and **WP4** and implements them to the new quantum algorithms developed in **WP5**. These codes will allow to carry out extensive numerical simulations of quantum information processing for important physical and mathematical problems with up to 30 qubits using modern supercomputers. The project coordinator has access to a supercomputing center supporting research on many-body interactions and quantum computing. We will thus be able to investigate how decoherence in quantum processors affects quantum computations simulating phenomena such as Anderson localization, metal-insulator transition and charge transport

in disordered materials. The preliminary results obtained by the consortium members indicate that certain characteristics of transport (e.g. diffusion rate or conductivity) can be exponentially sensitive to amplitude of noise in the quantum gates, while other characteristics (e.g. inverse participation ratio, number of populated states) remain stable in respect to imperfections and noise for rather long times. Thus the numerical tests will allow to choose the optimal strategy of measurement of observable characteristics in experimental realizations of quantum processors. This package will allow also to understand how decoherence affects quantum computations simulating the process of quantum tunneling in the deep semiclassical regime, where effects of unstable periodic orbits and chaos assisted tunneling play an important role. The proposed package can be used to model small molecules with magnetic moments going up to 15 in the presence of a noisy environment. It can be also used to investigate quantum simulations of the process of microwave ionization of Rydberg atoms in the presence of decoherence. It furthermore allows to study the sensitivity of eigenstates of a quantum processor which simulates quantum evolutions periodic in time, e.g. the kicked rotator. Indeed, since the evolution simulated by the processor takes place in the regime of quantum chaos, it is possible that the eigenstates of the periodic evolution operator will become exponentially sensitive to internal static imperfections. The preliminary results obtained give such indications. This reminds of the situation for chaotic enhancement of parity violation in the scattering of polarized neutrons on heavy nuclei. In this process, observed experimentally, the weak interaction which is responsible for parity breaking was enhanced by a factor of a million due to the complex chaotic structure of excited states in heavy nuclei. The package will allow to investigate the sensitivity of eigenstates and the change in the level spacing statistics in the presence of static imperfections. In fact the level spacing statistics is a sensitive tool which allows to determine the transition from integrable to chaotic eigenstates and to detect the Anderson transition for electrons in disordered materials. This characteristic was extensively used in the fields of quantum chaos, RMT, nuclei, complex atoms and molecules and quantum dots. The methods developed in these fields, together with the numerical simulator, will allow to detect the regions of stability for operability of quantum processors as a function of imperfection strength and parameters of the model simulated by the quantum algorithm.

This package will be also used to study the effects of decoherence on quantum computing of classical chaotic dynamics. The investigation of decoherence and static imperfection effects for chaotic nonlinear classical dynamics is of fundamental interest. It is important to determine the regions of stability for quantum information processing in this regime. This will open access to quantum computer simulations of such important problems as plasma confinement in magnetic fields, meteorology and dynamics of large molecules. Indeed in these systems the dynamics is primarily determined by the classical Newton equations which generally lead to chaotic behavior. The numerical simulation carried out with the **WP6** code package will determine the tolerance bound for imperfections for operating a quantum processor.

Although the main research of this workpackage will concentrate on the physical algorithms discussed above, the simulator will also be useful for the investigation of decoherence and imperfections in other algorithms such as those of Grover and Shor.

The development of workpackage **WP6** is based on the results obtained in work-

packages **WP3, WP4** and **WP5**. This workpackage will also implement a numerical simulator which can apply some of the existing quantum error correction codes. These codes will be tested for the algorithms developed in **WP5** in the presence of decoherence and imperfections. This simulator will allow to test the efficiency of error correction codes for different sources of errors. The decoherence models developed in **WP3** generate both correlated and uncorrelated errors, while the static imperfections induced by residual inter-qubit couplings (see **WP4**) produce a rather specific type of correlated errors. The planned simulator will handle up to 30 physical qubits. Depending on the error correction codes used, this will allow us to study problems with at least 6–10 logical qubits, which is sufficient to simulate rich physical dynamics, e.g. in the quantum sawtooth map. These numerical tests will enable experimentalists to optimize decoherence suppression and fault tolerant quantum computation in the first generation of quantum processors with up to 10 qubits.

The numerical simulators developed in **WP6** will use the Fortran, C and C++ programming languages. They will allow to perform numerical simulations of important physical processes with up to 30 qubits. They will model accurately imperfections and decoherence in realistic quantum computers and will play an important role for the design of experiments on quantum information processing.

9.2. Workpackage list

Workpackage list with WP titles, total person-months distribution, start/end month and deliverables numbers. For person-months the first number gives the number of post-doc months and the second number gives the number of months for academics (permanent stuff).

Work-package No	**Workpackage title**	**Lead contractor No**	**Person-months**	**Start month**	**End month**	**Deliv-erable No**
WP1	Project Management	1	0+4	0	36	D3, D5-6 D9-10 D14-15
WP2	Dissemination	1	0+4	0	36	D1-2 D13
WP3	Decoherence Models for QIP	1	27+25	0	24	D8
WP4	Effects of Residual Inter-Qubit Interactions for QIP	3	22+24	0	24	D6
WP5	New Quantum Algorithms for Physical Systems	4	23+29	0	36	D4, D11
WP6	Numerical Simulator of Decoherence and Imperfection Effects	1	30+32	6	36	D12
	TOTAL		102+120			

Person-months distribution for each workpackage and each node (first number gives the number of months for post-docs, second number gives the number of months for academics):

Work-package No	**UPS**	**TUD**	**INFM**	**RHUL**
WP1	0+1	0+1	0+1	0+1
WP2	0+1	0+1	0+1	0+1
WP3	10+8	0+4	8+6	9+7
WP4	6+6	0+4	12+12	4+4
WP5	6+6	0+6	5+5	12+12
WP6	14+14	0+2	11+11	5+5

9.3. Workpackage descriptions

WP1: Project Management

Workpackage number: WP1
Start date or starting event: month 0
Participant number: 1 (3,4,2)
Person-months per participant: post-doc 0 (0,0,0) [academics 1 (1,1,1)]

Objectives

The workpackage **WP1** is devoted to the management of the project, organization of the communication flow within the consortium, meetings of consortium members and periodic reports. The reporting to the Commission will cover all aspects of the project, including project management and administration (Management Reports), technical progress and achievements (Periodic Progress Reports at 6th month each year and Annual Progress Reports at 12th month each year).

Description of work

This workpackage organizes the scientific researches described in workpackages **WP3-WP4-WP5-WP6**. This will include the follow-up of workpackages, the possible synchronization of different tasks, the building and maintenance of progress reviews.

Deliverables

Deliverables are Periodic Progress Reports (D3-D5-D6-D9-D10-D14) and Final Report (D15).

Milestones and expected results

1. Periodic progress reports at 6th month of each year.
2. Annual progress reports at 12th month of each year.
3. Final report.

WP2: Dissemination of scientific results

Workpackage number: WP2
Start date or starting event: month 0
Participant number: 1 (3,4,2)
Person-months per participant: post-doc 0 (0,0,0) [academics 1 (1,1,1)]

Objectives

The objective is to provide easy public access to the scientific results obtained within the project and establish collaborations with other researchers in the QIPC field.

Description of work

The workpackage **WP2** is devoted to the dissemination of the results of the project. The built up consortium web page will present the up to day progress reached within the project. Partners will take a broad view on dissemination, setting-up web sites with links inside the consortium and with other FET-QIPC participants. This will give easy public access to scientific publications obtained in the frame of EDIQIP project. The consortium members will give courses at their universities on Quantum Information and Computation, which will provide student access to the most recent developments in this rapidly emerging field. The detailed dissemination plan for workpackages **WP3-WP4-WP5-WP6** will be provided by this workpackage.

Deliverables

Deliverables are Project Presentation (D1), Dissemination and Use Plan (D2), and Technical Implementation Plan (D13).

Milestones and expected results

1. Project presentation and creation of interconnected web-sites.
2. Publications of obtained results in international scientific journals.
3. Presentation of obtained results in scientific conferences and meetings.

WP3: Decoherence Models for QIP

Workpackage number: WP3
Start date or starting event: month 0
Participant number: 1 (4,3,2)
Person-months per participant: post-doc 10 (9,8,0) [academics 8 (7,6,4)]

Objectives

The main objective is to determine the decoherence time scales and their dependence on system parameters, for quantum computers simulating simple efficient quantum algorithms already developed by consortium members (quantum baker's map, quantum sawtooth map). These maps are particularly interesting for the first generation of quantum computers, since their rich dynamics can be explored with less than ten qubits. The first experimental NMR-based realization of the quantum baker's map was recently reported by the group of D. Cory at MIT.

Description of work

This workpackage investigates the effects of different decoherence models on simple efficient quantum algorithms. Numerical code for these algorithms will be constructed for the different decoherence models. These models will include decoherence produced by noisy gates with random unitary rotations by correlated as well as uncorrelated angles, and the more general case of interaction with an external environment including dissipative effects. In the latter case, the numerical code will either solve the density matrix equations directly, or by using quantum trajectory methods, depending on the number of qubits involved. In this way both unitary and non-unitary effects of decoherence will be taken into account.

Deliverables

Deliverable D8 are decoherence time scales and dissipative rates for an operating quantum computer, which is simulating efficient quantum algorithms. The results are tested in numerical simulations. All results will be published in international journals and posted to the electronic archive quant-ph.

Milestones and expected results

1. Stability of simple quantum algorithms in the presence of decoherence effects.
2. Decoherence time scales for noisy gates.
3. Dissipative rates for non-unitary noise.
4. Numerical simulations of quantum algorithms for simple maps.

WP4: Effects of Residual Inter-Qubit Interactions for QIP

Workpackage number: WP4
Start date or starting event: month 0
Participant number: 3 (1,4,2)
Person-months per participant: post-doc 12 (6,4,0) [academics 12 (6,4,4)]

Objectives

The main objective of this workpackage is to study the effects of imperfections inside a quantum processor which is isolated from the environment. Indeed, the absence of external decoherence does not mean that the quantum processor will operate properly. Static internal imperfections due to inter-qubit residual couplings can strongly modify the ideal quantum register represented by noninteracting many-body (multi-qubit) states of ideal qubits. The first results obtained by consortium members indicate that these imperfections can be more damaging than the decoherence produced by noisy gates. Also the recent experimental results obtained in the group of R. Blatt at Innsbruck indicate that, in quantum processors based on cold trapped ions, static couplings are more important than decoherence due to a finite temperature environment.

Description of work

In this workpackage a numerical code will be developed to simulate the algorithms discussed in WP3 in the presence of static residual couplings between qubits as well as static fluctuations in the energy level spacings for individual qubits. The developed code will allow to simulate the quantum dynamics of the baker's and sawtooth maps in the presence of static imperfections with up to 30 qubits. It will be able to model static imperfections typical for a given experimental realization of a quantum processor. Methods from quantum information and many-body quantum chaos (e.g., quantum eigenstates entropy and level spacing statistics) will be used.

Deliverables

Deliverable D7 are fidelity bounds for quantum simulation of efficient algorithms as a function of residual inter-qubit coupling strength and static imperfections; numerical tests for these bounds. All results will be published in international journals and posted to the electronic archives quant-ph.

Milestones and expected results

1. Quantum chaos border for an operating quantum computer: mixing of quantum eigenstates and phase transition for level spacing statistics.
2. Universal laws for fidelity drop induced by static imperfections.
3. Numerical simulation of static imperfection effects.

WP5: New Quantum Algorithms for Physical Systems

Workpackage number: WP5
Start date or starting event: month 0
Participant number: 4 (1,3,2)
Person-months per participant: post-doc 12 (6,5,0) [academics 12 (6,5,6)]

Objectives

The simulation of physical phenomena is a key area in which quantum computers are expected to become useful long before they will become capable to solve large-scale factorization problems. The main objective of this workpackage is the development of new efficient quantum algorithms for the simulation of important physical models, both quantum and classical. It is expected that the experimental implementation of these algorithms will become feasible with 6-10 qubits while quantum computers with 40–60 qubits will provide new information inaccessible to classical computers.

Description of work

The work will focus on finding efficient quantum algorithms suitable for a quantum computer solving computationally hard problems such as simulation of many-body quantum systems, electron transport in disordered materials, detection of metal-insulator transitions, and complex problems of classical Newtonian dynamics. Methods from the theory of quantum algorithms and of classical and quantum dynamical systems will be used.

Deliverables

Deliverable D4 represents the algorithms for problems of quantum chaos and deliverable D10 is an ensemble of efficient quantum algorithms capable of simulating important physical problems including problems of classical chaos. All results will be published in international journals and posted to the electronic archive quant-ph. They will be directly accessible via the web site of the consortium.

Milestones and expected results

1. Efficient quantum algorithm for the simulation of electron transport in disordered materials.
2. Quantum algorithms for the study of metal-insulator transitions in interacting systems.
3. Quantum algorithms simulating quantum tunneling in a deep semiclassical regime.
4. Efficient quantum algorithms for solution of problems of classical nonlinear dynamics.

WP6: Numerical Simulator of Decoherence and Imperfection Effects

Workpackage number: WP6
Start date or starting event: month 6
Participant number: 1 (3,4,2)
Person-months per participant: post-doc 14 (11,5,0) [academics 14 (11,5,2)]

Objectives

The main objective of this workpackage is to develop a package of numerical codes which simulate the decoherence and imperfection effects considered in WP3 and WP4 and implement them to the new quantum algorithms developed in WP5. Using these codes, it will be possible to carry out extensive numerical simulations of quantum information processing for important physical and mathematical problems with up to 30 qubits using modern supercomputers. This will allow us to detect the regions of stability for operability of quantum processors as a function of imperfection strength and parameters of the models simulated by quantum algorithms. Quantum error correction codes will be tested with these algorithms. We expect that this will give clear recipes for experimentalists on how to improve the accuracy of quantum computations.

Description of work

The starting points for this work are the quantum algorithms developed in WP5 and the insights about decoherence/imperfection effects obtained from the simple algorithms considered in WP3-WP4. The numerical codes will be developed in standard programming languages (Fortran, C, C++) and will include realistic decoherence and imperfection models. Suppression of decoherence by quantum error correction codes will be tested numerically. Since the project coordinator has access to a supercomputing center, we expect to be able to deal with up to 30 qubits for noisy gates and quantum trajectories methods and up to 15 qubits for density matrix methods.

Deliverables

The deliverable D12 will be a package of numerical codes for the simulation of the algorithms developed in WP5 in the presence of realistic decoherence/imperfection effects.

Milestones and expected results

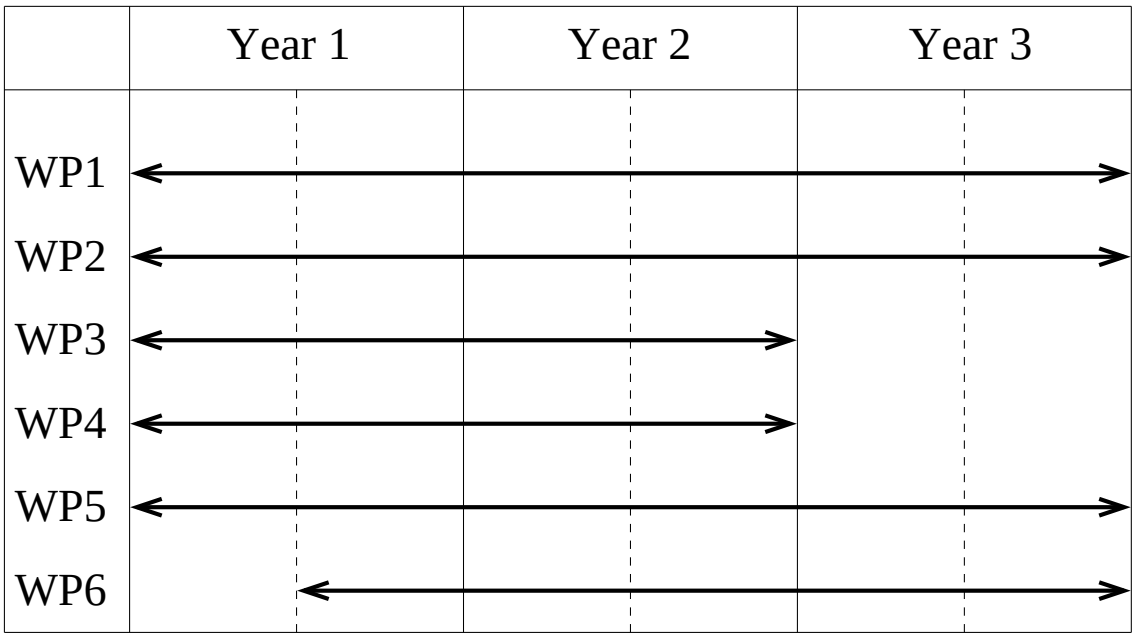
1. Package of numerical codes.
2. Stability of physical characteristics (e.g. transport conductivity,
number of populated states) with respect to decoherence/imperfections.
3. Numerical tests of quantum error correction codes.
4. Assessment of the stability regions for operability of quantum processors.
5. Accuracy bounds for new quantum algorithms from WP5.

9.4. Deliverables list

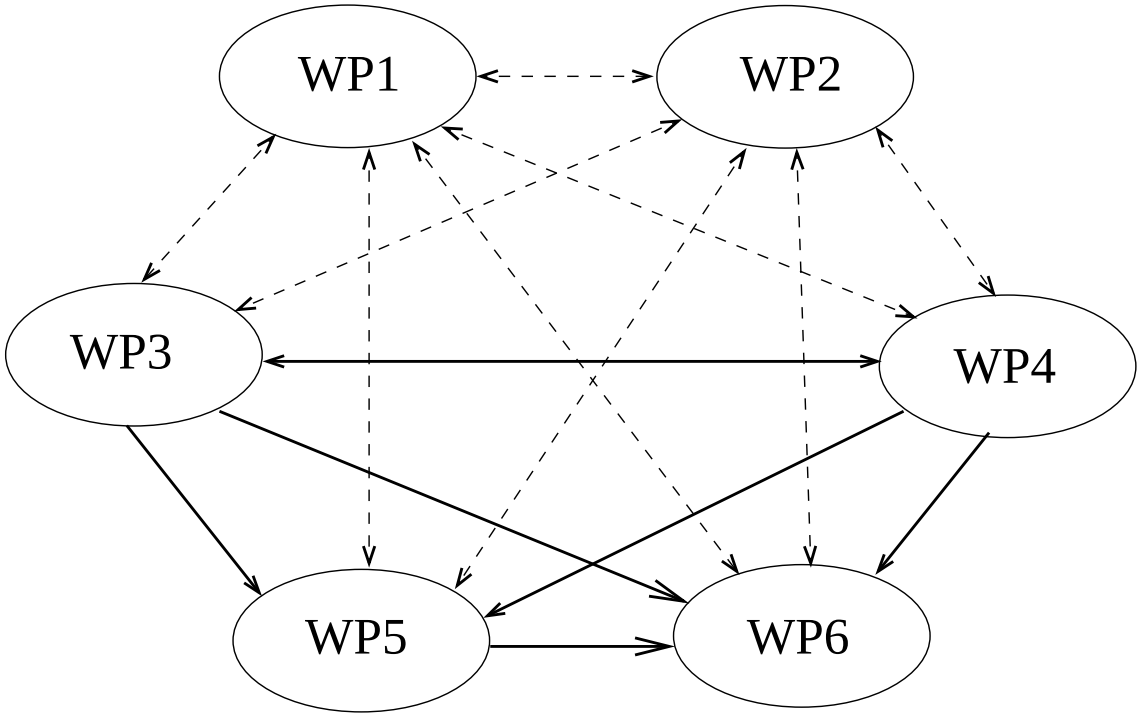
(person-months are given for post-docs + academics)

Del. no.	**Deliverable name**	**WP**	**Lead part.**	**Est. pers. -months**	**Del. type**	**Secur.**	**Deliv. (month)**
D1	Project Presentation	WP2	1	0+1	power point	Pub.	6
D2	Dissemination/Use Plan	WP2	1	0+1	report	Int.	6
D3	Periodic Report	WP1	1	-	report	Int.	6
D4	Quantum Chaos Algorithms	WP5	4	6+6	papers	Pub.	12
D5	Annual Report	WP1	1	0+1	report	Int.	12
D6	Periodic Report	WP1	1	-	report	Int.	18
D7	Static Imperfections Time Scales for QIP	WP4	3	22+24	papers	Pub.	24
D8	Decoherence Time Scales for QIP	WP3	1	27+25	papers	Pub.	24
D9	Annual Report	WP1	1	0+1	report	Int.	24
D10	Periodic Report	WP1	1	0+1	report	Int.	30
D11	New Quantum Algorithms for Physical Problems	WP5	4	17+23	papers	Pub.	36
D12	Numerical Simulator of Decoherence/Imperfection Effects	WP6	1	30+32	codes	Pub.	36
D13	Tech. Implem. Plan	WP2	1	0+1	report	Int.	36
D14	Annual Report	WP1	1	0+1	report	Int.	36
D15	Final Report	WP1	1	0+1	report	Int.	36

9.5. Project planning and timing



9.6. Graphical representation of project components



9.7. Project Management

The coordinator of the project is responsible for planning, organizing, and directing in a clear and transparent way the integrated efforts of the consortium members, in order to efficiently achieve all the objectives within the time schedule and budget. In particular, he is responsible for:

- scientific and administrative coordination of the whole project;
- identification of deliverables and corresponding actions;
- compilation of reports and supporting documents.

The project coordinator will use the workplan and its breakdown into workpackages as a basis for coordination. The workpackages WP1 and WP2 are devoted to the management and presentation of the scientific results obtained in the workpackages WP3, WP4, WP5, WP6. Each workpackage will be managed by a workpackage manager. The workpackage manager is responsible for:

- the follow-up of the workpackage;
- the possible synchronization of different tasks;
- the use of synergy effects and information exchanges with other project workpackages;
- the building and maintenance of progress reviews.

Reporting
The workpackage managers are responsible for reports to the coordinator when appropriate, e.g. after completion of a milestone or deliverable, and for submitting management/progress reports. The coordinator is responsible for periodic progress reports.

Meetings
The communication flow between consortium members is necessary to efficiently achieve the scientific objectives of the project. It is a coordinator's task to assure clear and complete information-flow between the consortium members. He will assure the organization of an annual meeting between consortium members. In addition, each workpackage manager can call for special meetings whenever appropriate.

First meeting
The first meeting of the consortium is fixed for 7 - 14 July, 2002 during the international Quantware workshop organized in Toulouse in the frame of collaboration of coordinator (UPS) with the american research program in quantum computing supported by NSA/ARDA/ARO. The workshop will take place in Toulouse during 1 - 14 July, 2002. It will attract about 10 american and 20 european participants, and will be supported by funds available at UPS independently from this project.

Information management
Documents, data, reports, and programs will be continuously exchanged between the partners. The project coordinator is responsible for the installation of a web page describing the progress of the project. The dissemination of the scientific results will be assured by the standard means of scientific publishing.

10. Clustering

This project is part of the action line Quantum Information Processing and Communication (QIPC) within Future and Emerging Technologies (FET) in the IST program and is therefore clustered with a number of theoretical and experimental projects. Since this project deals with the stability of existing and newly developed quantum algorithms in the presence of decoherence and imperfection effects, it is theoretical in nature. However, it will be important to follow closely the experimental developments in this sector. Indeed, we plan to investigate decoherence and imperfection effects in realistic models close to experimental conditions. In addition, the numerical codes that we will develop to study these effects will be useful for experimentalists. At the same time, the developed quantum algorithms for the simulation of physical systems will become interesting for the first generation of quantum processors operating with a limited number of qubits. We also plan to discuss and exchange our results with the other theoretical groups within QIPC.

All papers and publications produced by this project shall acknowledge the funding source even in case op partial support. The following sentence should be added in the acknowledgement section: "this research was (partially) funded by project EDIQIP of the IST-FET programme of the EC".

A reference to all published papers and publications should be sent to Sarah Hulbert, Quiprocone administrator (e-mail Sarah_Hulbert@hplb.hpl.hp.com) for uploading to the appropriate section of the Quiprocone web site.

11. Other contractual conditions

It is important to follow closely the development of research on quantum information processing in the USA and Japan. Indeed, many important results in QIPC were obtained there. Therefore, the consortium members plan to use up to 15% of their travel budget for travels to QIPC conferences in USA and Japan. If there will be no scientific need for such travels this part of the budget will be used for travel inside the EU member states.

The budget of other specific costs is planed to use in the following way:

UPS will pay the publication charges of color figures (2250 euro), a usual charge for a paper with color figure is around 700 - 1000 euro.

RHUL will use this budget to cover expenses of visits of US researchers to RHUL: a 1-week visit to Royal Holloway by Dr Todd Brun from Institute for Advanced Studies, Princeton, in YEAR 1 and a 1-week visit to Royal Holloway by Professor Carlton M.

Caves, University of New Mexico, in YEAR 2 (1000 euro). These visits will be useful for realisation of workpackages WP3 and WP5.

A. Consortium description

The coordination of the project will be done by UPS, Toulouse. The project is characterized by a broad interdisciplinary background of its participants, who already obtained important results related to the objectives of the project. The coordinator of the project participates in the quantum computing research program launched by the USA government and NSA and ARDA under ARO contract No. DAAD19-01-1-0553. INFM member has been recently appointed under a contract following ARO solicitation DAAD19-01-R-008. This will reinforce collaboration between American and European researchers in the field of quantum information processing. Presently, the consortium members participate in EU programs IST-1999-10596 (RHUL) and RTN network contract HPRN-CT-2000-0156 (UPS and INFM).

The consortium consists of four research groups who already obtained significant results in the field of QIPC. They complement each other with respect to their knowledge about quantum computing, quantum error correcting codes, decoherence/imperfection effects in complex quantum systems and large-scale numerical simulation. The project partners are:

- Université Paul Sabatier, Toulouse, France (UPS).
  Key persons: Dr. Dima Shepelyansky (project coordinator),
  Dr. Bertrand Georgeot.

- Technische Universität Darmstadt, Germany (TUD).
  Key person: Prof. Gernot Alber (responsible for TUD).

- Istituto Nazionale per la Fisica della Materia, Como, Italy (INFM).
  Key persons: Prof. Giulio Casati (responsible for INFM), Dr. Giuliano Benenti.

- Royal Holloway, University of London, United Kingdom (RHUL).
  Key person: Dr. Rüdiger Schack (responsible for RHUL).

We emphasize that the consortium members bring different and complementary expertise. UPS and INFM members have a long tradition and obtained outstanding results in the study of complex classical and quantum systems, with a strong background in large scale numerical simulations, RHUL member has since long worked on topics in chaos, quantum optics, and classical and quantum information theory, TUD member has a long expertise in the fields of theoretical atomic, molecular and optical physics. Recently efficient quantum algorithms were developed in RHUL, UPS and INFM, first studies of decoherence and imperfection effects on the stability of quantum computations were performed in UPS, RHUL and INFM, new efficient error correcting codes and methods for quantum state purification were developed in TUD.

The association between project partners and workpackages is described in detail in the Annex A of this proposal (see above). Workpackage managers have been chosen

taking into account the complementary expertise of consortium members: UPS will be responsible for **WP1, WP2, WP3** and **WP6**, INFM for **WP4**, RHUL for **WP5**. However, it should be understood that it will be possible to efficiently achieve all the project objectives and workpackages deliverables within the time schedule and budget only by the coordinate effort of all the consortium members.

A1. UPS, Toulouse, France

The research group in Toulouse has developped an internationally recognized expertise in the fields of classical and quantum chaos, mesoscopic physics, Rydberg atoms in external fields, quantum transport, and interactions and disorder in many-body quantum systems. This expertise has been used in the recent contributions the group has made in the study of quantum computers, both in assessing the effects of imperfections and decoherence in quantum computation, and in the conception of new efficient algorithms simulating physical systems. The group has long term experience in numerical simulations of complex quantum systems on modern supercomputers.

The scientific staff includes as permanent members Dima Shepelyansky (group leader), Bertrand Georgeot (chargé de recherche) Robert Fleckinger (associate professor), and Klaus Frahm (associate professor). It includes two post-doc fellows (S.Bettelli and M.Terraneo), two Ph.D. students (B.Lévi and A.Pomeransky) and one undergraduate student (A.Chepelianskii).

The group participates in RTN "Quantum transport on an atomic scale", contract HPRN-CT-2000-0156. The results obtained in [7,11] have been singled out by two press coverages in the internet version of " Nature". They have been presented in an invited talk at the Nobel symposium "Quantum chaos" (Sweden, 2000) [9]. The group has been awarded a grant by the US government (NSA and ARDA under ARO contract No. DAAD19-01-1-0553 on quantum computing) (principal investigator: D. Shepelyansky; senior investigator: B. Georgeot).
The group web page is at http://www.quantware.ups-tlse.fr

Key persons:

Dima Shepelyansky (http://w3-phystheo.ups-tlse.fr/∼dima)
Born 1956 in Novosibirsk, Russia. Citizenship: Russia, France
PhD at Inst. of Nuclear Physics, Novosibirsk (1981, supervisor Boris Chirikov)
Current position: Directeur de recherche (group leader) at CNRS and Univ. P. Sabatier, Toulouse, France. In 1981–1991: researcher, senior and leading senior researcher at Inst. of Nuclear Physics, Novosibirsk. Since 1991 till present he works in the Toulouse group.

His main results include the theory of diffusive photoelectric effect in Rydberg atoms, which predictions were later observed in experiments of Bayfield, Koch and Walther; chaos of color dynamics of classical Yang-Mills fields; conditions for chaotic Landau level mixing in the resonant tunneling diode[2]; emergence of quantum ergodicity and thermalization in finite interacting Fermi systems [3]; first prediction of the two interacting particles effect, due to which two repulsive particles propagate coherently in a disordered material with Anderson localization [1]; theory of quantum chaos for quantum computers [7,8,9]; new quantum algorithms [11,12,13]; imperfections effects on quantum

computation [10,12,13,14]. He is author or co-author of 130 papers in scientific journals, including 36 in Phys. Rev. Lett. and 1 in Physics Reports.

Bertrand Georgeot
Born 1967 in Saint-Mandé (94), France. PhD in Orsay in 1994.
Current position: Chargé de recherche (permanent position) at CNRS and Univ. P. Sabatier, Toulouse, France.

Dr Georgeot was postdoctoral researcher in the Univ. of Maryland and the Niels Bohr Institute, Copenhagen, and moved to Toulouse in 1996. His main results include the theory of arithmetical chaos, which explained anomalous level statistics found in systems of constant negative curvature [5]; the construction of the Fredholm method to resum semiclassical series for chaotic systems [4]; quantum chaos for systems with ray-splitting; quantum chaos in many-body systems such as finite fermionic systems or spin glass clusters [6]; theory of inertial waves in rotating fluids; theory of quantum chaos in quantum computation [7,8]; new efficient quantum algorithms [11,12,13]. He is author or co-author of 23 papers in scientific journals, including 10 in Phys. Rev. Lett. and 1 in Physics Reports.

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A2. TUD, Darmstadt, Germany

The TUD member has a long tradition and expertise in the fields of quantum optics, atomic physics and nonlinear dynamics. Major research areas in which he has obtained significant research results include wave packet dynamics, open quantum systems and QIPC. Recently, he has obtained important research results on Rydberg systems interacting with intense half-cycle pulses [1], on decoherence and wave packet dynamics [2], on critical properties of confined interacting quantum gases [3], and on quantum error correction [4].

During the recent few years he has been involved actively in the field of QIPC [5]. He has been part of the Ulm-team headed by Prof. W.P.Schleich and participating as a contractor in the IST-project QUBITS (IST-1999-13021). Besides developing new strategies for quantum error correction the TUD member also obtained significant results related to universal quantum processes [6] and to quantum state purification [7]. Currently, he is building up a new research group at the TUD. The scientific staff will include two newly appointed assistant professors, a post-doc fellow (Georgios Metikas) and a Ph.D. student (Michael Mussinger).

Key person:

Gernot Alber
Born 1957 in Innsbruck, Austria.
Current position: Full Professor of Theoretical Physics (starting April 2002), Institut für Angewandte Physik, Technische Universität Darmstadt, Germany.
Expertise: Since 1986 he has been working on problems of wave packet dynamics in atomic and molecular systems. On the basis of multidimensional semiclassical methods he made pioneering contributions concerning the understanding of the relation between quantum and classical dynamics. He developed new methods for describing decoherence and dissipation in open quantum systems by stochastic Schrödinger equations. In the field of QIPC he recently developed a basic understanding of bipartite universal quantum processes and developed new methods for quantum state purification and quantum error correction. He is author and co-author of more than 60 papers in scientific journals and of 1 book on QIPC.

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A3. INFM, Como, Italy

The research group for the study of dynamical systems at INFM and Università degli Studi dell'Insubria, Como, has a long tradition and expertise in the fields of classical and quantum chaos, with a number of fundamental results of theoretical and practical relevance obtained since the seventies. More recently the group has obtained important results about open quantum systems [1,2], dynamical localization in Rydberg atoms [3], anomalous quantum transport [4,5], classical transport in nonlinear models for biomolecules [6], and the interplay of disorder and interactions in many-body quantum systems [7,8,9].

The scientific staff includes as permanent members Giulio Casati (full professor, leader of the group), Italo Guarneri (full professor), Roberto Artuso (associate professor) and Giorgio Mantica (associate professor). The scientific team also includes two researchers (Giuliano Benenti and Gregor Veble) and two Ph.D. students (Simone Montangero and Sandro Wimberger).

The group participates in RTN "Quantum transport on an atomic scale", contract HPRN-CT-2000-0156. G. Veble (from Slovenia) and S. Wimberger (from Germany) are in Como in the frame of this RTN project.

Recently the group has been actively involved in the field of QIPC, obtaining important results related to the stability of quantum computer hardware [10], the proposal o a new efficient quantum algorithm for the simulation of a quantum mechanical system [11], the properties of the eigenfunctions of an operating quantum computer [12], the fidelity of quantum motion [13]. An international scientific conference on "Quantum Computers and Quantum Chaos" was organized by G.Casati, D.L.Shepelyansky and P.Zoller in Como (28-30 June 2001). The conference attracted about 100 participants from all over the world. The group has been recently appointed by the USA government and NSA and ARDA under a contract following the ARO solicitation DAAD19-01-R-0008 "Experimental and Theoretical Developments of Quantum Computers" (principal investigator Giulio Casati).

Key persons:

Giulio Casati
Born 1942 in Brenno (CO), Italy.
Current position: Full Professor in Theoretical Physics, Univ. degli Studi dell'Insubria, Sede di Como, Italy; director of the International Center for the Study of Dynamical Systems.
Expertise: Since 1972 he is working in problems of classical and quantum chaos and he has made pioneering contributions to both fields. Important achievements are the discovery of quantum dynamical localization and the understanding of chaotic excitation and ionization of hydrogen atoms in microwave fields. Author or co-author of more than 170 papers on scientific journals.

Giuliano Benenti
Born 1969 in Voghera (PV), Italy; Ph.D. in Theoretical Physics, Milano Univ. (1997).
1998-2000: Postdoctoral position at the CEA, Centre d'Etudes de Saclay, France, within the TMR network "Phase Coherent Dynamics in Hybrid Nanostructures".
From 2000: researcher at the INFM, Como, within the project "Quantum Transport and Classical Chaos".
Expertise: Classical and quantum chaos, open quantum systems, Anderson localization, mesoscopic physics, many-body interacting disordered systems, metal-insulator transitions. Present research is concentrated on quantum information theory. Co-author of more than 20 papers on scientific journals.

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A4. RHUL, London, United Kingdom

The Department of Mathematics at Royal Holloway, University of London, includes the Quantum Dynamics Group with three faculty members, and the world-leading Information Security Group with eleven faculty members. There is a large number of postdoctoral research assistants and research students. The department regularly hosts international visitors and has close links with many international institutions, including the California Institute of Technology, the University of New Mexico, the University of Queensland and the Max-Planck-Institute for Quantum Optics.

The department's areas of expertise include classical cryptography, the design and evaluation of cryptographic algorithms and protocols, theoretical atomic physics, the physics of atoms in strong magnetic and electric fields, the three-body Coulomb problem, quantum chaos, quantum trajectory methods and quantum state diffusion, quantum control theory, quantum information theory and quantum computing.

Key person:

Rüdiger Schack
Born 1960 in Düsseldorf, Germany.
1991: Ph.D. in Theoretical Physics, Universität München.
1991: Postdoctoral position at the Max-Planck-Institut für Quantenoptik.
1991–1994: Postdoctoral positions with Prof. Carlton M. Caves at the University of Southern California in Los Angeles, then at the Center for Advanced Studies at the University of New Mexico in Albuquerque.
1994–1995: Postdoctoral position with Prof. Ian C. Percival at Queen Mary and Westfield College in London.
Since 1995: Lecturer in Applied Mathematics at Royal Holloway, University of London.
2000: Promoted to Reader in Applied Mathematics.

Expertise: Classical and quantum chaos, open quantum systems, quantum information theory. Author or co-author of more than 35 papers in scientific journals. He presented more than 10 invited talks at international conferences and workshops.

Past work relevant to the current proposal includes results in classical information theory [1]; an information-theoretical approach to quantum chaos [2–4]; the development of an efficient numerical method for the solution of quantum master equations using localization of quantum trajectories [5,6]; the creation of a publicly available C++ library for quantum trajectory simulations [7]; an early investigation of quantum error correction [8]; the first proposal for the investigation of a chaotic quantum map on a quantum

computer [9]; a detailed analysis of a simulation of the quantum baker's map on an NMR quantum computer [10] (a similar experiment has been performed recently at MIT); the proof that there is no entanglement in current NMR quantum computing experiments [11]; a detailed analysis of the role of entangling quantum operations in NMR quantum computing [12]; results on entanglement and entanglement purification [13,14]; the application of quantum information-theoretical methods to the analysis of the quantum baker's map. He is a participant in the FET project Q-ACTA (IST-1999-10596).

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