EDIQIP
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Effects of Decoherence and Imperfections for Quantum Information Processing

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Partners:

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Technische Universität Darmstadt
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Contents

1. Executive Summary

EDIQIP is a research project which aims to advance European competitiveness in the future emerging technologies of quantum information processing and communication (QIPC).

EDIQIP project investigates decoherence and imperfection effects for quantum information processing. It determines the accuracy bounds and the time scales for reliable computations on realistic quantum processors, develops new efficient quantum algorithms for important physical problems including electron transport in disordered materials, metal-insulator transitions and complex problems of nonlinear classical dynamics.

Research is done in the frame of interdisciplinary and transnational European network of 4 participating organizations, including universities and public research centers. Work is conducted in close link with other projects in the IST-FET cluster QIPC. This network operated in a close collaboration with the US national research on quantum computation in the frame of ARO-NSA-ARDA program since UPS and INFM nodes participated in the US quantum computing program.

In the period of the project 01 Jan 2003 - 31 Dec 2005 a total amount of 67 papers (including 7 Phys. Rev. Lett.) has been prepared, most of which have already been published in leading international journals or have been posted in the public domain (see the list in Appendix B). The results and achievements of this project have been presented in 76 talks, lectures and posters at scientific conferences in different countries, including Europe, USA, Japan, Korea, Mexico, Brasil, Russia and Belarus (total list is given in Appendix C1). This gives high international visibility to the results obtained in the frame of EDIQIP network.

Special emphasis has been given to the dissemination of the knowledge and advances in the field of quantum information to other fields of physics, computer science and mathematics. This dissemination has been especially enhanced by the organization of scientific Events (Conferences, Schools and Workshops listed in the Appendix C2). These events attracted in total nearly 400 participants.

Two PhD theses had been prepared and defended in the frame of EDIQIP project (Appendix D).

Among the highlight results obtained in the frame of this project we stress:

The project developed new quantum algorithms for complex classical and quantum dynamics, for Anderson metal-insulator transition for electrons in disordered metals, delocalization in small-world networks, generic state preparation. Some algorithms have a polynomial gain and in certain cases an exponential gain is expected even if, as for the Shor algorithm, a rigorous mathematical prove is still absent. Numerical tests and analytical theory have been performed and developed for dependence of accuracy of quantum computations on three types of quantum errors: unitary noise errors, errors induced by static imperfections and errors from dissipative decoherence. Universal laws for accuracy decrease characterized by quantum fidelity are obtained and tested in numerical simulations with up to 28 qubits that represents the world record. Quantum numerical recipes for simulation of realistic quantum computations are made available to world public via the project web site. It is shown that most rapid drop of fidelity is produced by static imperfections. To fight this source of errors a new Pauli random error correction method

(PAREC) has been invented. This PAREC method eliminates coherent errors produced by static imperfections and gives a parametric increase of the maximum time over which realistic quantum computations can be performed reliably. This method doesn't require redundancy so that all physical qubits involved can be used for logical purposes. The results obtained by the project stimulated quantum computations of dynamical localization in the quantum sawtooth map recently performed by the group of David Cory (MIT) with a 3-qubit NMR-based quantum computer (quant-ph/0512204). Thus, the results obtained by the project will find further applications with a first generation of quantum computers with up to 10 qubits.

The obtained results allow us to develop a deep understanding of decoherence and imperfection effects during quantum information processing. They provide clear recipes for experimentalists on how to improve the reliability of quantum processors and how to improve the accuracy of quantum computation. The developed quantum algorithms can be used as testing ground for a first generation of quantum computers with up to 10 qubits. The implementation of newly developed efficient quantum algorithms with few tens of qubits would allow to overcome existing classical supercomputers.

2. Work Progress Overview

2.1. Objectives and achievements

Following the contract description of work, the research has been pursued with realization of tasks described in workpackages.

EDIQIP publications are listed in Appendix B, the list of EDIQIP talks and posters is presented in Appendix C1, the list of scientific Events organized by EDIQIP partners is given in Appendix C2, the list of PhD theses is given in Appendex D.

We list the milestones of our results obtained during the report period. They follow the scientific deliverables of the project, listed below (see also Annex 1 - Description of Work for EDIQIP contract):

D4: Quantum Chaos Algorithms (completed after 12 months); results are presented in Refs. [1,2,3,4,5,6,8,11,19,20,21,26,28,32].

D7: Static Imperfection Time Scales for QIP (completed after 24 months); results are presented in Refs. [2,3,6,9,15,21,22,23,24,25,27,37,38,53,59,65].

D8: Decoherence Time Scales for QIP (completed after 24 months); results are presented in Refs. [1,4,5,6,10,12,13,14,20,21,24,25,26,29,31, 34,35,36,37,38,40,41,52,65].

D11: New Quantum Algorithms for Physical Problems (completed after 36 months) ; results are presented in Refs. [3,7,15,16,17,18,25,30,33,39,46,51,56,57,58,60, 62,63,64,65,66].

D12: Numerical Simulator of Decoherence/Imperfection Effects (completed after 36 months); results are presented in Refs. [1,3,10,12,13,14,18,21,23,24,25,29,37,38,40,41, 42,43,44,47,48,49,50,54,55,66,67].

We classify milestones by Parts (a), (b), (c), (d), and (e) described shortly in the Executive Summary and give their global description below.

The project was directed towards the investigation of the effects of decoherence and imperfections in a realistic quantum computer with many qubits. These effects give a decrease of accuracy of quantum computations and can be generated by i)noisy errors in quantum gates; ii)static imperfections and static interqubit couplings in a completely isolated system; iii) dissipative decoherence induced by couplings with an external world. An isolated quantum computer is characterized by exponentially small energy level spacings between multi-qubit states. Unavoidably a residual interaction between qubits is present being much larger than this spacing even for computers of a few tens of qubits. The results obtained in Toulouse and Como before the beginning of the project showed that two-body interactions between qubits leads to emergence of quantum chaos, characterized by ergodic eigenstates of the quantum computer hardware if the strength of interactions exceeds the quantum chaos border. In this regime each ideal quantum register state disintegrates quickly into exponentially many state. This process destroys the operability of a quantum computer after a characteristic time scale, without any coupling to an external world. It brings an additional source of errors besides imperfections during gate operations in time and external decoherence. The aim of the project was to study the effects of the above three types of imperfections on different quantum algorithms and to determine the accuracy of quantum computations in their presence. In parallel the project aimed to develop new quantum algorithms for simulation of complex dynamics and Anderson metal-insulator transition and test on them the effects of decoherence and imperfections with the help of extensive numerical simulations with up to 30 qubits. Quantum error correction codes adapted to static imperfections induced by residual couplings between qubits were supposed to be developed and tested during the project.

The main results of the project can be classified in the five main areas

(a) The conditions for emergence of quantum chaos, ergodicity and dynamical thermalization are determined for an isolated quantum computer composed of a two – dimensional lattice of qubits with static random energy shifts of individual qubits energies and residual inter-qubit couplings (Refs. [2,3,48,51,58]). It has been shown that quantum chaos sets in for the strength of inter-qubits couplings being larger than the average static one-qubit energy shift divided by the number of qubits in the quantum computer. Above this border the eigenstates are described by the thermodynamical Fermi-Dirac distribution. It was shown that the relaxation rate to this equilibrium is proportional to the square of the coupling strength multiplied by number of qubits and divided by the average energy shift. The theory was tested by numerical simulations with up to 24 qubits. Also, the stable and quantum chaos regimes in the quantum computer hardware were identified as a function of magnetic field gradient and dipole-dipole couplings between qubits on a square lattice for the all-silicon quantum computer proposal of Yamamoto group with a strong magnetic field gradient [48]. It is shown that eigenstates of a quantum computer performing a complex dynamics algorithm are exponentially sensitive to static imperfections [2]. The obtained results determine the global conditions for onset of quantum chaos in a quantum computer hardware in presence of static imperfections.

(b) It is important to investigate how the effects of decoherence and imperfections influence the accuracy of quantum computation while performing a specific quantum algorithm. To this aim, we developed several new algorithms simulating complex classical dynamics and quantum evolution. These quantum algorithms simulate classical symplectic dynamics (e.g. the Arnold cat map) (Ref.[17]), classical strange attractors (Ref.[1]), quantum sawtooth map with dynamical localization (Refs.[2,3,5]), a dynamical model based on the wavelet transform (Ref. [6]), the Anderson metal-insulator transition (Ref. [15]), the quantum tent map (Ref. [21]) and intermittent maps (Ref. [46]), electrons in a magnetic field and the kicked Harper model (Ref. [25]), delocalization in small-world networks (Ref. [45]). In all these algorithms it was shown that the evolution of exponentially large state vectors can be simulated in a number of elementary gates quadratic or qubic in the number of qubits. However, if the extraction of information via quantum measurements is taken into account, then only a quadratic speed up can be reached for the determination of critical point of the Anderson transition [15] and dynamical localization length [3]. At the same time for classical chaotic dynamics we argue that an exponential gain can be obtained for certain characteristics of the Liouville density function [1] and period finding of Poincaré recurrences [17]. The developed algorithms simulate rich nontrivial dynamics and show interesting behaviours already with 5-7 qubits. First experimental realization of the quantum sawtooth algorithm with dynamical localization has been recently reported by the Cory group (MIT) for 3-qubit NMR-based quantum computer (quant-ph/0512204). We also developed a general algorithm for arbitrary initial pure state preparation [61,62] and algorithms for irreversible time evolutions by exploring the similarity to the problem of Bayesian updating [63].

(c) The effects of static imperfections were tested on the algorithms described in part (b) by analytical methods and numerical simulations with up to 28 qubits (see e.g. Ref [1] which still remains the world record). We compare these effects with the effects of random errors in quantum gates and dissipative decoherence and show that coherent static errors lead to much faster decay of fidelity (Ref. [21]). Indeed, for random errors in quantum gates the fidelity of quantum computation decays exponentially with the number of performed gates for a wide class of algorithms. The decay rate is given by the square of the noise strength with a well defined numerical constant (Refs. [1,4,6,21]). For dissipative decoherence we show analytically and by extensive numerical simulations with quantum trajectories methods that the rate is proportional to the number of qubits and the one-qubit decay rate (Refs. [10,29,42,50]). The effects of static imperfections are investigated for different algorithms in Refs. [2,3,6,15,21]. In this case, the fidelity decay is given by a combination of exponential and gaussian decays with two time scales, one of them is given by the Fermi Golden Rule and is similar to the Thouless time in mesoscopic systems while the other one is the Heisenberg time scale proportional to the size of the Hilbert space of the quantum computer [21]. This decay law is obtained on the basis of the Random Matrix Theory and gives a *universal* decrease of fidelity induced by static imperfections in a quantum computer simulating complex quantum dynamics. The theory has been tested in extensive numerical simulations where the scaled fidelity varied by 10 orders of magnitude. However, if the dynamics is integrable (e.g. inside the Kolmogorov-Arnold-Moser islands of stability in symplectic maps), then the Random Matrix Theory cannot be applied and the decay of fidelity is described by a more complicated law, which deserves further investigations. Also the stability of the Grover algorithm in presence of static imperfections should be analyzed separately. Results of Ref. [23] show the existence of regular and chaotic phases depending on the imperfections strength. The critical border between two phases drops polynomially with the number of qubits being exponentially larger than the frequency of Grover oscillations. In the regular phase the algorithm remains robust against imperfections while in the chaotic phase it is completely destroyed.

The obtained results give a complete physical picture of the accuracy bounds for the effects of decoherence and static imperfections in a large class of algorithms. They show that fidelity remains close to unity on a time scale which depends polynomially on the imperfection strength and drops not faster than polynomially with the number of qubits. At the same time the eigenstates of repetitive quantum algorithms (e.g. sawtooth, tent map) are exponentially sensitive to static imperfections (Refs. [2,3,25]).

The developed numerical methods of quantum trajectories allowed to obtain a number of interesting effects for cold atoms in pulsed optical latticies including quantum ratchets, the Ehrenfest wave packet explosion and quantum synchronization (Refs. [40,44,47]).

(d) To suppress effects of static imperfections we developed the Pauli random error-correction (PAREC) method (Refs. [41,66]). This generic error-correction method is capable of correcting coherent errors originated from static imperfections in a many-qubit system by repeated application of Pauli operators which change the computational basis. This PAREC method eliminates coherent errors produced by static imperfections and gives a parametric increase of the maximum time over which realistic quantum computations can be performed reliably. The method doesn't require redundancy so that all physical qubits involved can be used for logical purposes. The numerical tests of PAREC were done for the quantum tent map algorithm with up to 10 qubits, and it was shown that the method gives improvement of the fidelity by two orders of magnitude with only 5% increase of the number of gates. Thus the PAREC method eliminates coherent correlated errors induced by static imperfections and opens a way for applications of fault-tolerant quantum error correction methods which assume non correlated errors. A suppression of decoherence by jump codes is analysed in Ref. [65].

(e) The Quantware Library is now freely open at the web site: http://www.quantware.ups-tlse.fr/QWLIB/ . It gives Quantum Numerical Recipes (numerical codes) to simulate realistic quantum computations in presence of static imperfections, noisy errors in quantum gates and dissipative decoherence. It may run computations with about 20 - 30 qubits and various quantum algorithms.

2.2. Future perspectives

The obtained results gave a deep physical understanding of decoherence and imperfection effects during quantum information processing. They provide clear recipes for experimentalists on how to improve the reliability of quantum processors and how to improve the accuracy of quantum computation. Now a first generation of quantum computers can perform algorithms studied in the project (e.g. Cory grout and Blatt group). It would be interesting to make more detailed investigation of decoherence and imperfection effects related to concrete experimental realization of a quantum computer (e.g. effects of finite pulse width, temperature effects, and concrete static imperfections).

Appendix B - List of all EDIQIP Publications

Scientific deliverables are marked by D4,D7,D8,D11,D12.

Year 2003:

[1] M.Terraneo, B.Georgeot and D.L.Shepelyansky, *Strange attractor simulated on a quantum computer*, Eur. Phys. J. D **22**, 127 (2003) [quant-ph/0203062] (D4,D8,D12).

[2] G.Benenti, G.Casati, S.Montangero and D.L.Shepelyansky, *Statistical properties of eigenvalues for an operating quantum computer with static imperfections*, Eur. Phys. J. D **22**, 285 (2003) [quant-ph/0206130] (D4,D7).

[3] G.Benenti, G.Casati, S.Montangero and D.L.Shepelyansky, *Dynamical localization simulated on a few qubits quantum computer*, Phys. Rev. A **67**, 052312 (2003) [quant-ph/0210052] (D4,D7,D11,D12).

[4] B.Levi, B.Georgeot and D.L.Shepelyansky, *Quantum computing of quantum chaos in the kicked rotator model*, Phys. Rev. E **67**, 046220 (2003) [quant-ph/0210154] (D4,D8).

[5] S.Bettelli and D.L.Shepelyansky, *Entanglement versus relaxation and decoherence in a quantum algorithm for quantum chaos*, Phys. Rev. A **67**, 054303 (2003) [quant-ph/0301086] (D4,D8).

[6] M.Terraneo and D.L.Shepelyansky, *Imperfection effects for multiple applications of the quantum wavelet transform*, Phys. Rev. Lett. **90**, 257902 (2003) [quant-ph/0303043] (D4,D7,D8).

[7] A.A.Pomeransky, *Strong superadditivity of the entanglement of formation follows from its additivity*, Phys. Rev. A **68**, 032317 (2003) [quant-ph/0305056] (D11).

[8] R.Livi, S.Ruffo and D.L.Shepelyansky, *Le cheminement de Kolmogorov de l'integrabilite au chaos et au-dela*, p.15-45, Eds. R.Livi et A.Vulpiani, in *L'heritage de Kolmogorov en physique* (Belin, Paris, (2003)) (in French); *Kolmogorov pathways from integrability to chaos and beyond*, Eds. R.Livi and A.Vulpiani, in *The Kolmogorov legacy in physics* (Lecture Notes in Physics, Springer, Berlin (2003)) (D4).

[9] S.Montangero, G.Benenti and R.Fazio, *Dynamics of entanglement in quantum computers with imperfections*, Phys. Rev. Lett. **91**, 187901 (2003) [quant-ph/0307036] (D7).

[10] G.G.Carlo, G.Benenti and G.Casati, *Teleportation in a noisy environment: a quantum trajectories approach*, Phys. Rev. Lett. **91**, 257903 (2003) [quant-ph/0307065] (D8,D12).

[11] G.Casati and S.Montangero, *Measurement and information extraction in complex dynamics quantum computation*, in Proceedings of First International Workshop DICE (Decoherence, Information, Complexity and Entropy), Piombino, Italy, 2002, Ed. H.-T. Elze, Lecture Notes in Physics, Vol. 633 (2003), p. 341 Springer-Verlag [quant-ph/0307165] (D4).

[12] G.Alber, Th.Beth, Ch.Charnes, A.Delgado, M.Grassl, M.Mussinger, *Detected-jump-error-correcting quantum codes, quantum error designs, and quantum computation*, Phys. Rev. A **68**, 012316 (2003) [quant-ph/0208140] (D8,D12).

[13] Th.Beth, Ch.Charnes, M.Grassl, G.Alber, A.Delgado, M.Mussinger, *A New Class of Designs Which protect against Quantum Jumps*, Designs, Codes and Cryptography **29**, 51 (2003) (D8,D12).

[14] G.Alber, M.Mussinger, A.Delgado, *Quantum information processing and error correction with jump codes*, in *Quantum Information Processing*, edited by Th. Beth and G. Leuchs (Wiley-VCH, Berlin, 2003) (D8,D12).

Year 2004:

[15] A.A.Pomeransky and D.L.Shepelyansky, *Quantum computation of the Anderson transition in the presence of imperfections*, Phys. Rev. A **69**, 014302 (2004) [quant-ph/0306203] (D11,D7).

[16] B.Georgeot and D.L.Shepelyansky, *Les ordinateurs quantiques affrontent le chaos*, (in French, *Images de la Physique 2003-2004*, CNRS Edition, pp. 17-23) [quant-ph/0307103] (D11).

[17] B.Georgeot, *Quantum computing of Poincare recurrences and periodic orbits*, Phys. Rev. A **69**, 032301 (2004) [quant-ph/0307233] (D11).

[18] J.W.Lee, A.D.Chepelianskii and D.L.Shepelyansky, *Treatment of sound on quantum computers*, Proceedings of ERATO Conference on Quantum Information Science 2004, Tokyo, pp. 91-92 (2004); and *Applications of quantum chaos to realistic quantum computations and sound treatment on quantum computers*, in *Noise and information in nanoelectronics, sensors, and standards II* Proceedings of SPIE Eds. J.M.Smulko, Y.Blanter, M.I.Dykman, L.B.Kish, v.5472, pp.246-251 (2004) [quant-ph/0309018] (D11,D12).

[19] M.Terraneo and D.L.Shepelyansky, *Dynamical localization and repeated measurements in a quantum computation process*, Phys. Rev. Lett. **92**, 037902 (2004) [quant-ph/0309192] (D4).

[20] S.Bettelli, *A quantitative model for the effective decoherence of a quantum computer with imperfect unitary operations*, Phys. Rev. A **69**, 042310 (2004) [quant-ph/0310152] (D4,D8).

[21] K.M.Frahm, R.Fleckinger and D.L.Shepelyansky, *Quantum chaos and random matrix theory for fidelity decay in quantum computations with static imperfections*, Eur. Phys. J. D **29**, 139 (2004) [highlight paper of the issue] [quant-ph/0312120] (D4,D7,D8,D12).

[22] A.Stotland, A.A.Pomeransky, E.Bachmat and D.Cohen, *The information entropy of quantum mechanical states*, Europhys. Lett. **67**, 700 (2004) [quant-ph/0401021] (D7).

[23] A.A.Pomeransky, O.V.Zhirov and D.L.Shepelyansky, *Phase diagram for the Grover algorithm with static imperfections*, Eur. Phys. J. D **31**, 131 (2004) [quant-ph/0403138] (D7,D12).

[24] A.A.Pomeransky, O.V.Zhirov and D.L.Shepelyansky, *Effects of decoherence and imperfections for quantum algorithms*, Proceedings of ERATO Conference on Quantum Information Science 2004, Tokyo, pp. 171-172 (2004) [quant-ph/0407264] (D7,D8,D12).

[25] B.Levi and B.Georgeot, *Quantum computation of a complex system: the kicked Harper model*, Phys. Rev. E **70**, 056218 (2004) [quant-ph/0409028] (D7,D8,D11,D12).

[26] D. Rossini, G. Benenti and G. Casati, *Entanglement Echoes in Quantum Computation* Phys. Rev. A **69**, 052317 (2004) [quant-ph/0309146] (D4,D8).

[27] W.-G. Wang, G. Casati and B. Li *Stability of Quantum Motion: Beyond Fermi-golden-rule and Lyapunov decay*, Phys. Rev. E **69**, 025201 (2004) [quant-ph/0309154] (D7).

[28] G. Casati and S.Montangero, *Measurement and Information Extraction in Complex Dynamics Quantum Computation* in *Decoherence and Entropy in complex Systems*, H.-T. Elze Ed., Lectures Notes in Physics Vol. 633, Springer-Verlag, Berlin 2004 [quant-

ph/0307165] (D4).
[29] G.G. Carlo, G. Benenti, G. Casati and C. Mejía-Monasterio, *Simulating noisy quantum protocols with quantum trajectories*, Phys. Rev. A **69**, 062317 (2004) [quant-ph/0402102] (D8,D12).
[30] G. Benenti, G. Casati and S. Montangero, *Quantum computing and information extraction for dynamical quantum systems*, Quantum Information Processing **3**, 273 (2004) [quant-ph/0402010] (D11).
[31] D. Rossini, G. Benenti and G. Casati, *Classical versus quantum errors in quantum computation of dynamical systems*, Phys. Rev. E **70**, 056216 (2004) [quant-ph/0405189] (D8).
[32] G. Benenti, G. Casati and G. Strini, *Principles of quantum computation and information*, Volume I: Basic concepts (World Scientific, Singapore, 2004) (D4).
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(available at http://www.quantware.ups-tlse.fr/theses.html) (D7,D8,D11,D12).
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[42] J.W.Lee and D.L.Shepelyansky, *Quantum chaos algorithms and dissipative decoherence with quantum trajectories*, Phys. Rev. E **71**, 056202 (2005) [quant-ph/0501120] (D12).
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ph/0503081] (D12).
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[46] O.Giraud and B.Georgeot, *Intermediate quantum maps for quantum computation* , Phys. Rev. A **72**, 042312 (2005) [quant-ph/0504230] (D11).
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[49] D.Braun and B.Georgeot, *A quantitative measure of interference*, to appear in Phys. Rev. A [quant-ph/0510159] (D12).
[50] O.V.Zhirov and D.L.Shepelyansky, *Dissipative decoherence in the Grover algorithm*, Eur. Phys. J. D (to appear) [quant-ph/0511010] (D12).
[51] B.Georgeot, *Quantum algorithms and quantum chaos*, to be published in the Proceedings of the "Enrico Fermi" School on *Quantum Computers, Algorithms and Chaos*, Varenna, Italy, 5-15 July, 2005 (D11).
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[54] V.V. Sokolov, G. Benenti and G. Casati, *Quantum dephasing and decay of classical correlation functions in chaotic systems*, preprint quant-ph/0504141, submitted to Phys. Rev. Lett. (D12).
[55] G. Benenti, S. Felloni and G. Strini, *Effects of single-qubit quantum noise on entanglement purification*, preprint quant-ph/0505177, to be published in Eur. Phys. J. D (D12).
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[62] A. N. Soklakov and R. Schack, *Efficient state preparation for a register of quantum bits*, (quant-ph/0408045 expanded version), to appear in Phys. Rev. A (D11).
[63] A.N. Soklakov and R. Schack, *Bayesian updating of a probability distribution encoded on a quantum register*, submitted to Phys. Rev. A (quant-ph/0511216) (D11).

[64] A. Scherer, A. N. Soklakov and R. Schack, *Classical predictability and coarse-grained evolution of the quantum baker's map*, submitted to Phys. Rev. D (quant-ph/0511215) (D11).
[65] O. Kern, G. Alber, *Suppressing decoherence of quantum algorithms by jump codes*, Eur. Phys. J. D **36**, 241 (2005) (D7,D8,D11).
[66] O. Kern, G. Alber, *Controlling quantum systems by embedded dynamical decoupling schemes* Phys. Rev. Lett. **95**, 250501 (2005) (quant-ph/0506038) (D11,D12).
[67] Quantware Library: *Quantum numerical recipes* (numerical codes for realistic quantum simulations created in the frame of EDIQIP project), publicly available at the EDIQIP web site http://www.quantware.ups-tlse.fr/QWLIB/ (D12)

Appendix C1 - List of all EDIQIP Talks and Posters

Year 2003
[1] Invited lecture D.L.Shepelyasnky: *Quantum algorithms for complex dynamics*, at Euroworkshop *Quantum computers: nanoscopic implementation*, 10-21 February, 2003, ISI, Villa Gualino, Torino, Italy.
[2] Invited talk D.L.Shepelyansky: *Les ordinateurs quantiques affrontent le chaos*, Journée de Physique pour l'Istitut de Mathématiques, Calcul et conrôle quantiques, 25 April 2003, Paris.
[3] Invited talk D.L.Shepelyansky: *Quantum computation: entanglement, chaos and decoherence*, Workshop on Quantum Chaos and Localisation, 24-25 May 2003, Warsaw, Poland.
[4] Invited talk D.L.Shepelyansky: *Quantum algorithms in presence of imperfections*, ARO/NSA/ARDA meeting *Theory in Quantum Computing*, Harper's Ferry, West Virginia, 9-10 June 2003.
[5] Invited talk D.L.Shepelyansky: *Quantum computation: entanglement and chaos*, NATO Advanced Research Workshop *Quantum chaos: theory and applications*, Como, Italy, 17-21 June 2003.
[6] Invited talk D.L.Shepelyansky: *Imperfection effects in quantum computation*, at Quantum computing program review organized by ARO/NSA/ARDA, 18-23 August 2003, Nashville, TN, USA.
[7] Invited talk D.L.Shepelyasnky: *Chaos and quantum computation*, at the Conference *Kolmogorov's legacy in physics: one century of chaos, turbulence and complexity*, ICTP, Trieste, Italy, 15-17 September 2003.
[8] Invited talk D.L.Shepelyansky: *Chaos and realistic quantum computation*, at *Fundamentals of solid state quantum information processing*, Lorentz Center, Leiden, The Netherlands, 8-12 December 2003.
[9] Invited talk B.Georgeot: *Quantum computation and quantum chaos*, at International Conference *Inhomogeneous Random Systems*, Université de Cergy Pontoise, France, 28-29 January, 2003.
[10] Poster S.Bettelli: *Quantum algorithms for complex dynamics in presence of imperfections*, 4th European QIPC Workshop, Oxford, UK, 13-17 July, 2003.

[11] Invited talk G.Casati: *Fidelity decay and correlation functions in classical and quantum systems*, at International conference on *Dynamical Chaos in Classical and Quantum Physics*, Budker Institute of Nuclear Physics, Novosibirsk, Russia 4-9 August, 2003.
[12] Invited talk G.Casati: *Quantum chaos and quantum computers*, at Quantum computing program review organized by ARO/NSA/ARDA, 18-23 August 2003, Nashville, TN, USA.
[13] Invited talk G.Casati: *Quantum Computing of Complex Systems: Dynamical Localization*, at Int. conference on *Quantum information, quantum computation and nanotechnology*, Waseda University, Tokyo, Japan, 29-31 October 2003.
[14] Invited talk G.Casati: *Decay of fidelity in classically chaotic and integrable systems*, at International Conference *Quantum Information*, Tokyo University of Science, Tokyo, Japan, 1-3 November, 2003.
[15] Invited talk G.Casati: *On the stability of quantum motion under system's perturbations*, at International Conference *Quantum Information*, International Institute for Advanced Studies, Kyoto, Japan, 5-7 November, 2003.
[16] Invited talk G.Casati: *Fidelity decay and entanglement echo*, at Pan American Advanced Institute on "The Physics of Information" Buzios, Brasil, 4-9 december, 2003.
[17] Invited talk G.Benenti: *Localization and entanglement in quantum computing of complex systems*, at International Conference *Quantum Information*, Tokyo University of Science, Tokyo, Japan, 1-3 November, 2003.
[18] Invited talk G.Benenti: *Stability of quantum computation in a noisy environment: a quantum trajectories approach*, at International Conference *Quantum Information*, International Institute for Advanced Studies, Kyoto, Japan, 5-7 November, 2003.
[19] Poster G.G.Carlo: *Quantum trajectories and quantum information: teleportation in a noisy environment*, 4th European QIPC Workshop, Oxford, UK, 13-17 July, 2003.
[20] Contributed talk A.A.Pomeransky: *Strong superadditivity of the entanglement of formation follows from its additivity*, Madeira Math Encounters XXV "Quantum information, Control and Computing", Madeira, Spain, 1-11 October 2003.
[21] Invited talk R.Schack: *Unknown quantum operations*, at International Conference on *Quantum Theory: Reconsideration of Foundations 2*, Växjö University, Sweden, June 2003.
[22] Invited talk R.Schack: *Unknown quantum operations: A de Finetti representation theorem*, at Workshop on *Quantum Information Processing (QIP 2003)*, Mathematical Sciences Research Institute (MSRI), Berkeley, USA.
[23] Contributed talk G.Alber: *Dynamics of Nonlinear Maps for Quantum Information Processing*, at Annual Meeting of the German Physical Society (DPG), 25 March 2003.

Year 2004

[24] Contributed talk D.L. Shepelyansky: *Quantum computation in presence of imperfections and decoherence*, EU IST-FET QIPC Program Review, Bratislava, SK, 16 - 18 February 2005.
[25] Invited talk D.L. Shepelyansky: *Quantum algorithms in presence of imperfections* at the International workshop *Quantum entanglement - from error correction to secure key distribution*, Waldemar-Peterson Haus, Hirschegg, Austria, 30 March - 2 April 2004.
[26] Invited talk D.L. Shepelyansky: *Quantum computation of complex dynamics in presence of imperfections* at NATO Advanced Research Workshop *Decoherence, entan-*

glement and information protection in complex quantum systems, Ecole de Physique Les Houches, France, 25 - 30 April 2004.
[27] Invited talk D.L. Shepelyansky: *Applications of quantum chaos to realistic quantum computations and sound treatment on quantum computers*, SPIE Conference 5472 *Noise and information in nanoelectronics*, Maspalamos, Gran Canaria, Spain, 25 - 28 May 2004.
[28] Poster presentation D.L. Shepelyansky: *Effects of decoherence and imperfections for quantum algorithms* at ERATO Conference on Quantum Information Science 2004, Tokyo, Japan, 4 September 2004.
[29] Poster presentation D.L.Shepelyansky and B.Georgeot: *Quantum computation in presence of imperfections*, ARO Quantum Computing Program Review (Orlando (FL, USA)), August 16-20, 2004.
[30] Contributed talk K. Frahm: *Universal regime of fidelity decay in realistic quantum computations*, Quantum information and Decoherence in Nanosystems (39th Rencontres de Moriond, La Thuile, Italy), January 25 - February 1, 2004.
[31] Invited talk B. Georgeot: *Quantum chaos and quantum computing* at *Quantum Chaos and its applications to mesoscopic physics*, Focus Program, APCTP, Pohang, Korea, July.
[32] Poster presentation J.W. Lee: *Quantum algorithms and decoherence with quantum trajectory methods*, 5th European QIPC Workshop, Rome, Italy, 20th-22th September 2004.
[33] Contributed talk B. Georgeot: *Quantum computation of chaotic systems*, Conference GdR *Quantum information and communication*, Orsay, France, 1-3 december, 2004.
[34] Contributed talk D. Braun: *Entanglement from coupling to a common heat bath*, Conference GdR *Quantum information and communication*, Orsay, France, 1-3 December, 2004.
[35] Contributed talk J. Lages: *Decoherence by a chaotic many-spin bath*, Conference GdR *Quantum information and communication*, Orsay, France, 1-3 December, 2004.
[36] Contributed talk J. Lages: *Decoherence by a chaotic many-spin bath*, GDR 2426 *Physique Quantique Mésoscopique*, Aussois, France, 6-9 December, 2004.
[37] Invited talk K. Frahm: *Quantum computation and quantum chaos with random matrix theory*, GDR 2426 *Physique Quantique Mésoscopique*, Aussois, France, 6-9 December, 2004.
[38] Invited talk G. Casati: *Quantum computation of dynamical systems*, at the conference *Problemi Attuali di Fisica Teorica*, Vietri sul Mare, Italy, 2-7 April, 2004.
[39] Invited talk G. Casati: *On the stability of quantum motion*, *International Conference in Quantum Optics*, Institute of Physics National Academy of Science of Belarus, Minsk, Belarus, may 29-june 3, 2004.
[40] Invited talk G. Casati: *Classical and quantum fidelity decay and correlation functions in dynamical systems*, *Complexity in science and society*, Education Center of Ancient, Olympia, Greece, July 19-26, 2004.
[41] Contributed talk G. Casati: *Quantum computing and quantum chaos*, ARO Quantum Computing Program Review (Orlando (FL, USA)), August 16-20, 2004.
[42] Invited talk G. Casati: *On the stability of quantum motion*, *Quantum Chaos in the 21st century*, Cuernavaca, Mexico, august 18-25, 2004.

[43] Invited talk G. Casati: *Quantum-classical correspondence in perturbed chaotic systems*, Second International Workshop DICE 2004, Piombino, Italy September 1-4, 2004.
[44] Invited talk G. Casati: *Quantum-classical correspondence in perturbed chaotic systems*, School and Workshop on Quantum Entanglement, Decoherence, Information, and Geometrical Phases in Complex Systems, Abdus Salam International Centre for theoretical Physics, Trieste, Italy November 1-5, 2004.
[45] Invited talk G. Benenti: *Quantum computing of dynamical quantum systems: Information extraction and noise effects*, at the conference *Problemi Attuali di Fisica Teorica*, Vietri sul Mare, Italy, 2-7 April, 2004.
[46] Invited talk G. Benenti: *Quantum computing of dynamical quantum systems: Information extraction and noise effects*, at the annual meeting of the Italian Physical Society, Brescia, Italy, 20-25 September, 2004.
[47] Contributed talk G. Benenti: *Quantum ratchets in dissipative chaotic systems*, at the annual meeting of the MIUR project *Fault tolerance, control and stability in quantum information processing*, Torino, Italy, 11-12 November, 2004.
[48] Invited talk R. Schack: *From Degrees of Belief to Quantum Process Tomography*, One-day conference on "Probability in Quantum Mechanics", Centre for Philosophy of Natural and Social Science, LSE, London, UK, February 2004.
[49] Invited talk R. Schack: *The frequency operator in quantum mechanics*, *International Conference in Quantum Optics*, Institute of Physics National Academy of Science of Belarus, Minsk, Belarus, may 29-june 3, 2004.
[50] Invited talk R. Schack: *A de Finetti Representation Theorem for Quantum Process Tomography*, nternational Symposium on Entanglement, Information and Noise, Krzyzowa/Kreisau, Poland, June 2004.
[51] Invited talk R. Schack: *Bayesian Approach to Quantum Probability*, Twentyfourth International Workshop on Bayesian Inference and Maximum Entropy Methods in Science and Engineering (MaxEnt'04), Max Planck Institute for Plasma Physics (IPP), Garching, Germany, July 2004.
[52] Invited talk A. Soklakov: *Algorithm for encoding probability distributions in quantum states*, *International Conference in Quantum Optics*, Institute of Physics National Academy of Science of Belarus, Minsk, Belarus, may 29-june 3, 2004.
[53] Poster presentation A. Soklakov: *Encoding probability distributions in quantum states*, 7th International Conference on Quantum Communication, Measurement, and Computing (QCMC), University of Strathclyde, UK, July 2004.
[54] Poster presentation A. Soklakov: *Quantum state preparation via Grover iterations*, 5th European QIPC Workshop, Rome, Italy, 20th-22th September 2004.
[55] Contributed talk G. Alber and O. Kern: *Quantum computation with jump codes under non-ideal conditions*, Annual meeting of the German Physica Society (DPG) in Munich, 22-26 March 2004.
[56] Contributed talk B. Georgeot: *Quantum computation of chaotic systems*, Second Feynman Festival, Maryland, USA, August 20-25, 2004.

Year 2005

[57] Contributed talk D.L. Shepelyansky: *Quantum computation in presence of imperfections and decoherence*, EU IST-FET QIPC Program Review, Innsbruck, AU, 14 - 16 February 2005.

[58] Invited talk D.L. Shepelyansky: *Quantum chaos and realistic quantum computations* at the International KIAS-KAIST Workshop *Quantum information science*, Seoul, South Kirea, August 22 - 24, 2005.
[59] Invited talk G. Benenti: *Quantum simulation of dissipative chaotic systems: Quantum ratchets and Ehrenfest explosion*, at the conference *Quantum Mechanics and Quantum Computation*, Vietri sul Mare, Italy, 18-20 March, 2005.
[60] Invited lectures G. Benenti: *Quantum chaos, decoherence and quantum computation*, at the "Enrico Fermi" School on *Quantum Computers, Algorithms and Chaos*, Varenna, Italy, 5-15 July, 2005.
[61] Invited talk G.G. Carlo: *Quantum noise in algorithms and transport*, at the Workshop on *Noise and Instabilities in Quantum Mechanics*, Trieste, Italy, 3-7 October, 2005.
[62] Invited talk V.V. Sokolov: *Dephasing and quantum-classical correspondence in the decay of the Loschmidt echo*, at the Workshop on *Noise and Instabilities in Quantum Mechanics*, Trieste, Italy, 3-7 October, 2005.
[63] Invited talk G. Casati: *Quantum chaotic dissipative ratchets*, at the International Conference on *Aspect of quantum chaotic scattering*, Max Planck Institute, Dresden, Germany, 8-11 March 2005.
[64] Invited talk G. Casati: *Chaos and Fourier law in classical and quantum mechanics*, at the 2nd workshop on *Quantum Chaos*, Varsaw, Poland, 19-22 May 2005.
[65] Invited talk G. Casati: *Fidelity decay and quantum dephasing*, at Max Planck Institute for Complex Systems, Dresden, Germany, 26-29 September 2005.
[66] Invited talk G. Casati: *Classical dynamical chaos and quantum dephasing*, at the International Conference *Are there quantum jumps?*, Losinij, Slovenia, 5-10 September 2005.
[67] Invited talk G. Casati: *Quantum chaos, fidelity decay and decoherence*, at the International Conference on *New Trends in Quantum Mechanics: Fundamental Aspects and Applications*, Palermo, Italy, 11-13 November 2005.
[68] Poster presentation O. Kernand G.Alber: *Quantum algorithms and quantum maps – implementation and error correction* at *Quantum physics of nature*, Workshop in Vienna, Austria, 20 - 26 May 2005.
[69] Poster presentation O. Kern and G.Alber: *Quantum algorithms and quantum maps – implementation and error correction* at *Quantum information processing*, Workshop of the Deutsche Forschungsgemeinschaft, Bad Honnef, Germany, 2 - 3 June 2005.
[70] Oral presentation O. Kern: *Combinating random and cyclic decoupling technique* at *Quantum Computers, Algorithms and Chaos*, International "Enrico Fermi" School, Varenna, Italy 5 - 15 July 2005.
[71] Invited lectures B.Georgeot: *Quantum algorithms and quantum chaos*, at the "Enrico Fermi" School on *Quantum Computers, Algorithms and Chaos*, Varenna, Italy, 5-15 July, 2005.
[72] Invited talk B.Georgeot: *Quantum computing of Poincare recurrences and periodic orbits*, at the 9th International Conference on Squeezed States and Uncertainty Relations, Besancon, France, 3-7 May 2005.
[73] Invited talk B.Georgeot: *Quantum computing for physics research*, at X International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT 2005), Zeuthen, Germany, 22-27 May, 2005.

[74] Contributed talk B.Georgeot: *Quantum maps for quantum computation*, at ERATO conference on quantum information science (EQIS 2005), Tokyo, Japan, 26-31 August, 2005.
[75] Contributed talk B.Georgeot: *Realistic quantum computation*, at SQUBIT-2 - RS-FQubit - EuroSQIP Workshop, Karlsruhe, Germany, 12-14 October, 2005.
[76] Invited talk B.Georgeot: *Quantum chaos and quantum computation*, at workshop *Energy relaxation versus phase relaxation in many-body systems*, Centro Internacional de Ciencias, Cuernavaca, Mexique, 30 October - 5 November, 2005.

Appendix C2 - List of Events organized by EDIQIP partners

[1] Organizers: D.Shepelyansky, *Quantware workshop*,
Workshop at Univ. Paul Sabatier, Toulouse, France, 1 - 14 July 2002 (web page: http://www.quantware.ups-tlse.fr/ws2002/index.html ; about 30 participants)
[2] Directors: G.Casati, D.Shepelyansky, P.Zoller; Scientific secretary: G.Benenti,
International School of Physics Enrico Fermi *Quantum Computers, Algorithms and Chaos*, Varenna, Italy, 5-15 July 2005
(webpage: http://scienze-como.uninsubria.it/benenti/varenna2005.html ; about 90 participants)

[3] Directors: G. Casati (Como), S. Lloyd (MIT), G.J. Milburn (Qeensland), Local Organizers: G. Benenti and G. Carlo (Como),
Workshop on *Noise and Instabilities in Quantum Mechanics* Trieste, Italy, 3-7 October 2005 (webpage: http://www.ictp.it/ ; about 70 participants)

[4] Organizers: G. Casati (Como) and S. Pascazio (Bari).
Conference on *Quantum Mechanics and Quantum Computation*, Vietri sul Mare, Italy, 18-20 March, 2005 (webpage: http://www.ba.infn.it/~pascazio/vietri_programma.html; about 70 participants)

[5] Organizers: Ph.Grangier, M.Santha and D.Shepelyansky
The Programme on *Quantum information, computation and complexity* at the Institut Henri Poincaré, Paris, 4 Jan - 7 April, 2006 is now in the final preparation stage. Webpage: http://www.quantware.ups-tlse.fr/IHP2006/ ; about 120 participants.

Appendix D - List of PhD theses

[1] Andrei Pomeransky, Thesis of Universite Paul Sabatier (supported by ARO/NSA/ARDA): *Entanglement and imperfections in quantum computation.*
Jury:
V.Akulin (examinator, LAC, Orsay),
B.Georgeot (co-director, LPT, Toulouse),
K.Frahm (president, LPT, Toulouse),
J.-L.Pichard (referee, CEA, Saclay),
R.Schack (EDIQIP referee, RHUL, London),

D.Shepelyansky (director, LPT, Toulouse).
Defended at LPT, IRSAMC, Univ. P.Sabatier, Toulouse, October 22, 2004.
[2] Benjamin Lévi, Thesis of Universite Paris VII: *Computation of quantum systems by realistic quantum computers.*
Jury:
G.Alber (EDIQIP examinator, TUD, Darmstadt),
D.Feinberg (referee, CNRS Grenoble),
B.Georgeot (director, LPT, Tlse),
Ph.Lafarge (president, Paris VII),
D.Shepelyansky (examinator, LPT, Tlse),
D.Weinmann (referee, CNRS Strasbourg).
Defended at LPT, IRSAMC, Univ. P.Sabatier, Toulouse, November 9, 2004.