SUPERCONDUCTING QUANTUM INFORMATION PROCESSORS: COHERENCE, CONTROL AND QUANTUM SPECTROSCOPY

Antonio D'Arrigo, Elisabetta Paladino, Marco Berritta, Elena De Leo, and Giuseppe Falci
Dipartimento di Metodologie Fisiche e Chimiche (DMFCI)
Università degli Studi di Catania, Viale A. Doria 6
95125 Catania, Italy
& MATIS CNR - INFM
Catania, Italy
adarrigo@dmfci.unict.it

Abstract
Solid-state implementations of quantum bits are very promising for quantum computation, because of their potential scalability and integrability. On the other side solid state noise represents a serious limitation towards the target of solid state quantum computation. We illustrate various possibilities to apply quantum control techniques to solid state qubits. We focus on open loop quantum control, and show that a simple *closed loop* protocol can greatly improve the coherence time of single qubit gates.

Key words
Decoherence; Quantum control; 1/f -noise.

1 Introduction

Solid state coherent system are at the forefront of present day research because of the perception that large scale integration may be combined with new physical properties to yield new paradigms for nanoelectronics. With this original motivation the possible implementation of quantum computers [Nielsen and Chuang, 2000; Ekert and Jozsa, 1996] with solid state nanodevices has been proposed in the last decade [Loss and Di Vincenzo,1998; Makhlin, Schön and Shnirman, 2001; Falci et al, 2000]. Besides possible applications in quantum information processing, operating advanced control of the dynamics in a nanodevice would open a wide scenario for both fundamental and applied physics. Therefore recently some effort has been spent to understand how to implement in the solid state, coherent effects typical of quantum optics and NMR. In this respect nanofabrication may give certain advantages. For instance coupling energies larger than in atomic physics are easily achieved, thus reducing typical time scales for operations. At the same time flexibility in the design offers several solutions for tuning couplings, allowing in principle to implement via advanced control the Hamiltonian driving any desired state transformation.

On the other side solid state noise represents a serious limitation towards the target of a solid state quantum processor. The variety of noise sources typical of the solid state may severely limit coherence times. So understanding how to limit or counteract the effect of the noise is a crucial issue.

Three classes of strategy have been proposed to defeat noise, namely: (a) Quantum Error Correction (QEC) [Preskill, 1998], (b) design of decoherence free [Lidar and Whaley,2003] Hilbert subspaces, (c) dynamical decoupling by open-loop quantum control [Viola and Lloyd, 1998; Viola, Knill and Lloyd, 1999); Facchi, Nakazato and Pascazio, 2001; Falci et al, 2004; D'Arrigo, 2005]. Quantum error correction in nanodevices requires hardware resources unavailable at present, and has not been yet demonstrated, as well as the existence of decoherence-free subspaces which rely on too strong idealization of the noisy environment. Open-loop control techniques instead appear more feasible. *Echo protocol* has been demonstrated, and *bang-bang protocol* might effectively limit the effects of low frequency noise. Indeed, recently, improved filtering of high-frequency noise has lead to a new generation of devices [Vion et al, 2002; Poletto et al.,] where most of the suppression of the signal is due to solid-state noise from low frequencies up to the MHz regime.

Optimizing the tradeoff between efficient control and noise by exploring the flexibility in the design of devices and gates is the main task of present day research for these devices. They allow to explore subspaces which are partially protected from low-frequency noise [Mastellone et al., 2008; D'Arrigo et al., 2008] as well as various dynamical strategies of protection [Falci et al, 2000; Siewert, Brandes and Falci, 2009; Siewert, Brandes and Falci, 2006]. Two promising aspect of quantum control are the possible design of closed loop protocols [Korotkov, 2003], which we argue should greatly improve the visibility of the output signal, and the fact that coherent nanodevices may be used as mesoscopic probes for quantum spectroscopy of the environment [Zazunov et al., 2007; Falci et al., 2006; Paladino et al., 2008; Mastellone et al., 2008]

The paper is organized as follows. We first present a model for the noisy dynamics of a qubit, then we illustrate various control techniques. We discuss echo and Bang-bang open loop control, and a closed loop protocol. We briefly illustrate how to implement the protocol *STimulated Raman Adiabatic Passage* [Bergmann,Theuer and Shore, 1998] in solid state. Finally we give a snapshot on Quantum Spectroscopy .

2 Single qubit and noise model

In the spirit of the present analysis, we can describe the effect of the unwanted interaction between a solid state qubit and its environment by a classical stochastic process $\xi(t)$. The Hamiltonian is:

$$\begin{aligned} \mathcal{H}_Q(t) = & -\frac{\Omega}{2}\cos\theta\,\sigma_z - \frac{\Omega}{2}\sin\theta\,\sigma_x \\ & -\frac{1}{2}\,\xi(t)\,\sigma_z - \frac{1}{2}\,A(t)\,\sigma_x \end{aligned} \tag{1}$$

where Ω is the qubit level splitting, the polar angle θ defines qubit working point, and $A(t)$ is a control field. We characterize $\xi(t)$ by its power spectrum $S_\xi(\omega) = \int d\tau e^{-i\omega\tau}\langle\xi(t)\xi(t+\tau)\rangle$, where where $\langle\cdot\rangle$ indicates the ensemble average. Typically solid state noise is broadband and structured, i. e. the noise spectrum extends to several decades, it is non-monotonic, sometimes a few resonances are present. We focus on slow noise frequency components. Indeed actual measurements protocols require numerous repetitions so that they are particularly sensitive to the unstable device calibration due to low-frequency fluctuations. The leading effect of such kind of noise is defocusing of the measured signal, analogous to inhomogeneous broadening in NMR [Slichter, 1996].

Peculiarly, at low frequencies $S_\xi(\omega)$ has a characteristic $1/\omega$ behavior. Its physical origin varies from device to device and depends on the specific material. A well-established theory explains 1/f noise by an ensemble of microscopic bistable fluctuators (BF) with switching rates γ distributed with $P(\gamma) \propto 1/\gamma$ [Weissman, 1988]. The BF-1/f spectrum is $S_\xi(\omega) = 1/2\sum_i v_i^2\gamma_i/(\gamma_i^2+\omega^2)$. If $\gamma \in [\gamma_m, \gamma_M]$, in the same interval of frequencies it is approximated by $S_\xi(\omega) = [(\pi/4)N_{BF}\overline{v}^2/\ln(\gamma_M/\gamma_m)]\omega^{-1}$, where N_{BF} is the total number of fluctuators, and $\overline{v}$ is the average coupling strength between the fluctuators and the qubit. While the low frequency cut-off (γ_m) depends also

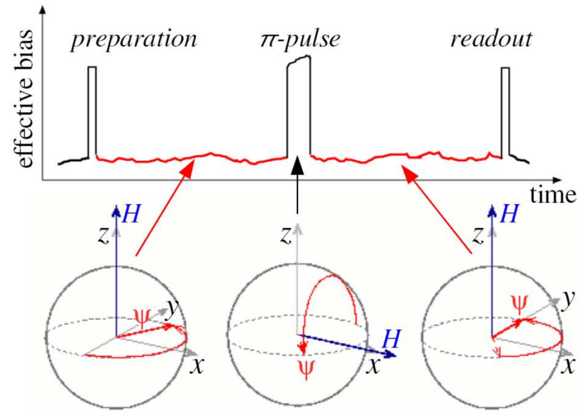

Figure 1. Top: pictorial representation of the pulse sequences for echo. Bottom: Bloch sphere representation of the protocol. The preparation pulse consists in a $\pi/2$ rotation setting the system in a superposition of computational states of $\mathcal{H} = \Omega\sigma_z/2$, then the system freely precesses for a time Δt around $\hat{z}$. A instantaneous π-pulse around $\hat{x}$ switches the qubit back, and the second $\pi/2$ measurement pulse after Δt projects back the state along the computational axis. The ideal echo protocol implements the identity operation, it singles out decay when an environment is present.

on the measurement time of the protocol, the intrinsic high-frequency cut-off (γ_M) is hardly detectable. Some experiments suggest a cut-off near 1 MHz [Vion et al, 2002].

3 Open loop dynamical decoupling

Ensuring a sufficient high degree of control over both environmental and operational errors is a chief requirement for physical realizations of quantum information, shared to a lesser or greater extent by the large variety of device technologies which are nowadays being considered. Dynamical decoupling methods [Viola and Lloyd, 1998; Viola, Knill and Lloyd, 1999)] for open quantum systems derive their basic physical intuition from coherent averaging techniques in high-resolution NMR spectroscopy [Slichter, 1996; Vandersypen and Chuang, 2004]. In the prototypical application of decoupling the objective is the *averaging* of the environmental couplings responsible for decoherence. The basic idea is to act *on the system* with a judiciously chosen time-dependent control in such a way that the resulting controlled dynamics depends only on the system variables.

The simplest example of these procedures consists in the spin-echo protocol a sequence of three pulses pictorially schematized in Fig.1, in which we consider the case $\theta = 0$. Anisotropic noise acting along $\hat{z}$ effectively induces a random fluctuating splitting $\Omega(t)$. If the characteristic correlation time of these fluctuations $\tau_c = \gamma_M^{-1}$, is much longer than Δt, the echo protocol is expected to remove the effect of noise.

Spin-echo protocols have been implemented with superconducting nanocircuits revealing an effective par-

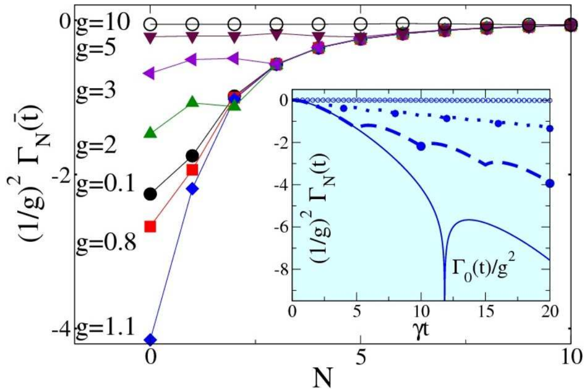

Figure 2. Decay of $\langle \sigma_y \rangle \propto \exp -\Gamma_N(t)$ at fixed $\bar{t} = 10/\gamma$ for increasing number of pulses N. The parameter is $g = v/\gamma$, the qubit Hamiltonian is along the noise axis. For $N > 5$ we have $2\Delta t < \gamma^{-1}$ where we expect efficient decoupling. Inset:$\Gamma_N(t)$ for $g = 1.1$ and different Δt are compared with the free noisy dynamics, $\Gamma_0(t)$.

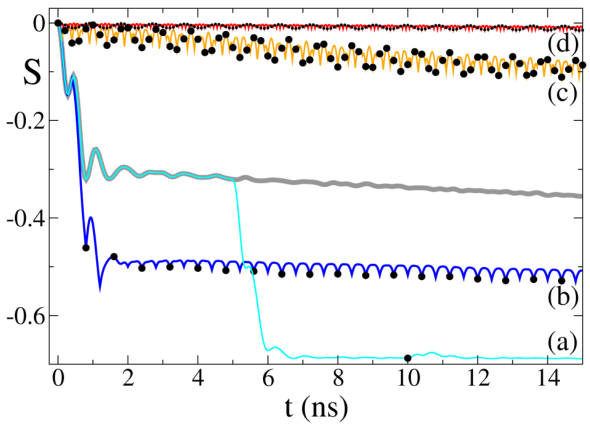

Figure 3. Purity $S(t)$ for $\mathcal{H}$ forming a $\pi/4$ angle with the noise axis $\hat{z}$ and in the presence of $1/f$ noise. The uncontrolled dynamics (gray) is compared with BB for different pulse lengths, (a) $\Delta t = 5ns$, (b) $\Delta t = 0.4ns$, (c) $\Delta t = 0.1ns$, (d) $\Delta t = 0.05ns$. Dots indicate the stroboscopic times $2N\Delta t$. Noise level is typical of experiments with charge qubits and extends in $[10^5, 10^9]$Hz, the qubit level splitting is 10^{10}rad/s.

tial removal of low-frequency noise [Nakamura et al., 2002; Vion et al, 2002], the major problem for quantum state processing [Paladino et al., 2002; Paladino et al.,2003; Falci et al. 2005]. A sequence of N echo pulses realizes the so-called bang-bang decoupling (BB) [Viola and Lloyd, 1998; Viola, Knill and Lloyd, 1999)], which is expected to decouple the qubit from the noise for times $t = 2N\Delta t$. In refs [Falci et al., 2004], [D'Arrigo, 2005] we have studied dynamical decoupling of superconducting qubits from random telegraph noise and $1/f$ noise. We found that very large pulse frequencies effectively compensate decoherence, leading to a universal behavior. This is illustrated in Fig.2, in which we consider the case of a qubit coupled to a single bistable impurity switching with rate γ. We plot the decay rate Γ_N of the expectation value of the observable σ_y, as a function of the number of the applied pair of echo pulses. The duration t of the entire protocol is fixed, so that increasing the number N of the pulses pair means reducing the interval Δt between two pulses.

Dynamical decoupling of $1/f$ noise is illustrated in Fig.3, in which we set the qubit working point at $\theta = \pi/4$. We plot the purity $S(t) = ln[Tr(\rho^2)]$, a convenient quantity measuring deviations from unitary dynamics (ρ is the qubit density matrix). A successful decoupling protocol yields a pure state with $S = 0$. In the absence of pulses noise induces a initial decay of the purity on a scale $T_2^* \approx 1ns$. In case (a) Δt is larger than the shortest times scales of the noise, $\Delta t > 1/(2\gamma_M), T_2^*$. The Bloch vector is almost aligned with the initial Hamiltonian when the first pulse is applied, then decoheres along the new Hamiltonian. This accelerates the decay to the equilibrium state. Curves (b)-(d) refer to higher pulse rates $\Delta t < 1/(2\gamma_{max})$ where one would expect decoupling. Instead in the experimental relevant case of intermediate pulse frequencies BB may also *enhance decoherence*. This effect, unexpected in the naive description of BB, is reminiscent of the inverse Zeno effect [Facchi, Nakazato and Pascazio, 2001]. Thus the qualitative effect of BB turns out to be very sensitive to short-time features of the system dynamics in the absence of pulses which strictly depends of the working point of the device.

4 Closed loop control

Various options to eliminate effects of low frequency noise up to the MHz regime, as protected subspaces [3] and open-loop control dynamical decoupling suppress as well interactions necessary to drive the system. An alternative approach is suggested by preliminary numerical results shown in Fig.4 where initial conditions of an environment of thousands bistable fluctuations with broadband spectrum was studied. It is shown that by suitable resetting of the environment a substantial increase of the signal amplitude is obtained. Indeed contrary to the usual scenario of quantum optics, dephasing due to broadband noise depends on the preparation. The simulation mimicks an ideal closed loop feedback procedure. The leading dephasing effect in this protocol is due to fluctuations during time evolution. Therefore, on a time scale of t^* (in Fig.4 we set $t^* = 1\mu$s, as in actual experiments), the resulting signal is only sensitive to the noise arising from fluctuators with $\gamma \gtrsim 1/t^*$, and the effect strongly depends on the high frequency cut-off γ_M. This protocol cancels the effect of inhomogeneous broadening, and it is expected to show different characteristic behavior in time (compare cyan and blue curves with the black one, Fig.4). We derived a analytic expressions for this regime with the perspective of designing a possible closed-loop procedure, along the ideas of Ref. [Korotkov, 2003].

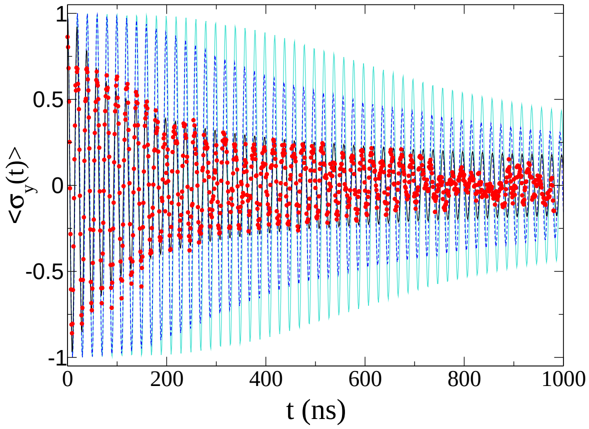

Figure 4. Effect of simulating a closed loop protocol by resetting environment initial conditions, for $\Omega = 10^{11}$ rad/s, and a $1/f$ noise with $\gamma \in [1, 10^6]$ Hz, $\overline{v} = 9.5 \cdot 10^7$ rad/s and $N_{BF} = 1500$. Without resetting, the signal amplitude has a strong initial decay, as seen in experiments (red dots) and simulations (black curve). Resetting enhances the amplitude: cyan and blue curves refer to a high-energy environment cutoff γ_M respectively at 1 MHz and 10 MHz; notice in this case the crossover to an initial slow power-law decay, triggered by the high-frequency cutoff.

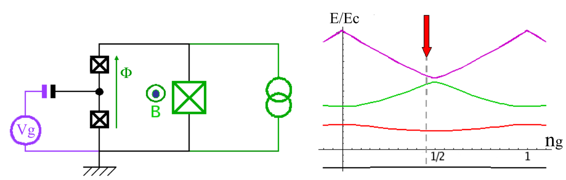

Figure 5. Left: electrical drawing of the Quantronium [Vion et al, 2002]. A split Cooper pair box formed by a superconducting island (dot) of total capacitance C connected to the circuit via two small Josephson junctions (boxes with cross). The charging energy $E_C = 4e^2/(2C)$ sets the scale of the electrostatic energy which is controlled by the gate-charge $n_g = C_g V_g/(2e)$, where $C_g << C$ is the gate capacitance. The phase Φ across the series of two junctions is a second knob for the device. This phase is controlled by the flux imposed through the loop by an external coil, and by a bias current. Right: The four lowest energy levels of the quantronium as a function of the gate-charge for Josephson energy $E_J = E_C$. STIRAP can be performed between the two lowest levels E_g (black), E_u (red) and the first excited level E_e (green).

5 Advanced control

Well known techniques from quantum optics such as Rabi oscillations, spin-echo experiments, observation of Ramsey fringes, have been successfully implemented with superconducting nanocircuits in the past years [Nakamura et al., 2002; Nakamura, Pashkin and Tsai, 1999; Vion et al, 2002].

Naturally one may expect that also more complex methods and topics from quantum optics find their "analogue" superconducting nanocircuits. Because of the stronger couplings involved and noise sources, this project requires more than a mere translation of the pro-

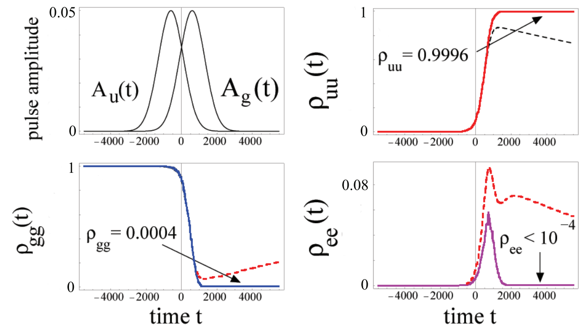

Figure 6. Population transfer by STIRAP in the Quantronium. Top: (left) Two Gaussian gate-voltage pulses $n_g(t) = n_g + A_g(t)\cos(\omega_g t) + A_u(t)\cos(\omega_u t)$ resonant with $\omega_g = E_e - E_g$ and $\omega_u = E_e - E_u$ are applied. For a charging energy $E_C = 50\mu eV$ the time unit corresponds to about 1.3×10^{-11}s. Remaining panels: time evolution of the populations of the ground states ρ_{gg}, ρ_{uu}, and of the excited state ρ_{uu} for the isolated system (solid lines) for initial state $|g\rangle$. The effect of quantum noise corresponding to a dephasing time of about 50ns is included (dashed lines). The only remarkable effect is extra decay $|u\rangle \longrightarrow |g\rangle$ at the end of the protocol.

tocol from quantum optics to the solid state. A particularly interesting issue is to obtain population transfer between different states of a many-body quantum systems exploiting the "stimulated Raman adiabatic passage" (STIRAP) [Bergmann,Theuer and Shore, 1998]. The STIRAP technique is based on a Λ configuration of two hyperfine ground states coupled to the same excited state by classical laser fields. By slowly varying the fields amplitudes it is possible to transfer the population from one ground state to the other, with no direct transition processes between them. We have shown that this protocol can be realized as well in a single charge-phase Cooper-pair box operated as a three level atom [Siewert, Brandes and Falci, 2009; Siewert, Brandes and Falci, 2006]. This circuit, nicknamed Quantronium [Vion et al, 2002] and shown in Fig.5, is a convenient device since its tunability may be easily exploited to obtain selective and relatively strong coupling to the fields allowing to perform STIRAP before decoherence takes place. The three lowest eigenstates are conveniently identified by a fixed gate voltage corresponding to $n_g = 0.45$ (red arrow in Fig.5). The AC part of the gate voltage provides the required drives, allowing almost complete population transfer even in the presence of considerable decoherence sources, Fig.6. Low-frequency noise due to impurities which can be considered static during each run of the protocol but switch on a longer time scale leading to statistically distributed level separations, may in principle spoil the transfer process. We found that STIRAP is robust also against low frequency noise. Despite the induced crossings of the instantaneous levels, Zener tunneling still allows almost complete population transfer. By exploiting the flexibility of the Quantronium it is also possible to generate Fock states in a resonating nanocirtuit [Siewert, Brandes and Falci, 2009; Siewert, Brandes and Falci, 2006].

6 Quantum Spectroscopy

A proper characterization of broadband solid-state noise is still lacking, except some general features at very low frequencies ($<<$ 1 KHz) [Zorin et al., 1996], and some figures at GHz frequencies [Astafiev et al.,2004]. Additional information would be valuable both from the point of view of material science and for the design of more complex architectures. We have shown that the response of driven system may be a probe for the KHz to GHz intermediate range. This is already the case of Rabi oscillations, whose pure dephasing is due to a substantial extent to sideband frequencies intercepting the $1/f$ noise spectrum in the 10-50 MHz range [Falci et al., 2009].

It is interesting to notice that also standard open-loop control procedures could be used for quantum spectroscopy since in the ideal case of absence of transitions regular train of pulses sample a series of frequencies depending on the pulse rate. The actual physics emerging (see Fig.2 and Fig.3) with a wide variety of Zeno and anti-Zeno behaviors is much more complicated, suggesting the possibility that BB techniques display much more spectroscopic information on the solid-state environment.

7 Conclusion

In conclusion, in this article we have illustrated the main effects of broadband noise affecting solid state qubits. Indeed, solid state noise is too strong to been corrected by means of Quantum Error Correction alone. In addition QEC requires hardware resources unavailable at present. So understanding how to operate at a physical level, in order to counteract noise, is an important ingredient. In this perspective, we discussed various control techniques on solid state devices. We have shown that some closed loop techniques could be particularly effective against low frequency noise, the main limitation to coherence times in solid state quantum hardware.

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