QUANTUM COHERENCE OF
JOSEPHSON RADIO-FREQUENCY
CIRCUITS

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and Collège de France, Paris

OUTLINE

1. Motivation: Josephson circuits and quantum information
2. Quantum-mechanical superconducting LC oscillator
3. A non-dissipative, non-linear element: the Josephson junction
4. The Cooper pair box artificial atom circuit
5. Readout of the Cooper pair box qubit
6. Coherence of Josephson circuits
7. Quantum bus concept
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IMPLEMENTATIONS OF A SINGLE, MANIPULABLE, QUANTUM-MECHANICALLY COHERENT SYSTEM

Coupling with env't.

- PHOTON
- NUCLEAR SPIN
- ION
- ATOM
- MOLECULE
- ATOMIC-SIZE DEFECT IN CRYSTAL
- QUANTUM DOT
- JOSEPHSON RF CIRCUIT (Leggett, '80)
CLASSICAL RADIO-FREQUENCY CIRCUITS

Communications

1940’s: MHz

2000’s: GHz

Computation

US Army Photo

WHAT IS A RADIO-FREQUENCY CIRCUIT?

A RF CIRCUIT IS A NETWORK OF ELECTRICAL ELEMENTS

TWO COLLECTIVE DYNAMICAL VARIABLES CHARACTERIZE THE STATE OF EACH DIPOLE ELEMENT AT EVERY INSTANT:

Voltage across the element:

\[ V_{np}(t) = \int_{n}^{p} E \cdot \overrightarrow{d\ell} \]

Current through the element:

\[ I_{np}(t) = \iint_{np} j \cdot \overrightarrow{d\sigma} \]
CONSTITUTIVE RELATIONS

EACH ELEMENT IS TAKEN FROM A FINITE SET OF ELEMENT TYPES

EACH ELEMENT TYPE IS CHARACTERIZED BY A RELATION BETWEEN VOLTAGE AND CURRENT

<table>
<thead>
<tr>
<th>LINEAR</th>
<th>NON-LINEAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>inductance:</td>
<td>diode:</td>
</tr>
<tr>
<td>$V = L \frac{dI}{dt}$</td>
<td>$I = G(V)$</td>
</tr>
<tr>
<td>capacitance:</td>
<td>transistor:</td>
</tr>
<tr>
<td>$I = C \frac{dV}{dt}$</td>
<td>$I_{ds} = G(I_{gs}, V_{ds}) V_{ds}$</td>
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<tr>
<td>resistance:</td>
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<tr>
<td>$V = RI$</td>
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<td></td>
<td>$I_{gs} = 0$</td>
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QUANTUM INFORMATION ECONOMY

suppose a function $f$ $j \in \{0, 1023\} \rightarrow k = f(j) \in \{0, 1023\}$

Classically, need $1000 \times 10$-bit registers (10,000 bits) to store information about this function and to work on it.

Quantum-mechanically, a 20-qubit register can suffice!

$$|\Psi\rangle = \frac{1}{2^{N/2}} \sum_{j=0}^{2^N-1} |j\rangle |f(j)\rangle$$

Function encoded in a single quantum state of small register! (but a highly entangled one)
QUESTION:

CAN WE BUILD A COMPLETE SET OF QUANTUM INFORMATION PROCESSING PRIMITIVES OUT OF SIMPLE CIRCUITS THAT WE WOULD CONNECT TO PERFORM ANY DESIRED FUNCTION?

<table>
<thead>
<tr>
<th>QUANTUM OPTICS</th>
<th>QUANTUM RF CIRCUITS</th>
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<td>FIBERS, BEAMS</td>
<td>TRANSM. LINES, WIRES</td>
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<td>BEAM-SPLITTERS</td>
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<td>MIRRORS</td>
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<td>LASERS</td>
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<td>PHOTODETECTORS</td>
<td>AMPLIFIERS</td>
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<td>ATOMS</td>
<td>JOSEPHSON JUNCTIONS</td>
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</table>

DRAWBACKS OF CIRCUITS: ARTIFICIAL ATOMS PRONE TO VARIATIONS

ADVANTAGES OF CIRCUITS: • PARALLEL FABRICATION METHODS
• LEGO BLOCK CONSTRUCTION OF HAMILTONIAN
• ARBITRARILY LARGE ATOM-FIELD COUPLING
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A CIRCUIT BEHAVING QUANTUM-MECHANICALLY AT THE LEVEL OF CURRENTS AND VOLTAGES?

SIMPLEST EXAMPLE: SUPERCONDUCTING LC OSCILLATOR CIRCUIT

d ~ 0.5 mm
A CIRCUIT BEHAVING QUANTUM-MECHANICALLY AT THE LEVEL OF CURRENTS AND VOLTAGES?

SIMPLEST EXAMPLE: SUPERCONDUCTING LC OSCILLATOR CIRCUIT

MICROFABRICATION \( L \sim 3\,\text{nH}, C \sim 1\,\text{pF}, \omega_r/2\pi \sim 5\,\text{GHz} \)

\[ d \ll \lambda: \text{LUMPED ELEMENT REGIME} \]

---

INCOMPRESSIBLE ELECTRONIC FLUID SLOSHES BETWEEN PLATES.
NO INTERNAL DEGREES OF FREEDOM.

SUPERCONDUCTIVITY \( \text{ONLY ONE COLLECTIVE VARIABLE} \)
DEGREE OF FREEDOM IN ATOM vs CIRCUIT: SEMI-CLASSICAL DESCRIPTION

Rydberg atom

Superconducting LC oscillator

velocity of electron $\rightarrow$ voltage across capacitor
force on electron $\rightarrow$ current through inductor

2 Possible correspondences:

charge dynamics
- velocity of electron $\rightarrow$ current through inductor
- force on electron $\rightarrow$ voltage across capacitor

field dynamics
- velocity of electron $\rightarrow$ voltage across capacitor
- force on electron $\rightarrow$ current through inductor
DEGREE OF FREEDOM IN ATOM vs CIRCUIT

semiclassical picture

Rydberg atom

Superconducting LC oscillator

\[ \phi \]

\[ L \]

\[ C \]

2 Possible correspondences:

charge dynamics

velocity of electron → current through inductor

force on electron → voltage across capacitor

field dynamics

velocity of electron → voltage across capacitor

force on electron → current through inductor

FLUX AND CHARGE IN LC OSCILLATOR

position variable: \( \phi \) ↔ \( X-X_{eq} \)

momentum variable: \( Q \) ↔ \( P \)

generalized force: \( I \) ↔ \( f \)

generalized velocity: \( V \) ↔ \( V \)

generalized mass: \( C \) ↔ \( M \)

generalized spring constant: \( \frac{I}{L} \) ↔ \( k \)
**HAMILTONIAN FORMALISM**

\[ H(\phi, Q) = \frac{Q^2}{2C} + \frac{(\phi - \phi_{eq})^2}{2L} \]

\[ H(X, P) = \frac{P^2}{2M} + \frac{k(X - X_{eq})^2}{2} \]

**HAMILTON'S EQUATION OF MOTION**

\[ \dot{\phi} = \frac{\partial H}{\partial Q} = \frac{Q}{C} \]

\[ \dot{Q} = -\frac{\partial H}{\partial \phi} = \frac{\delta \phi}{L} \]

\[ \omega_r = \sqrt{\frac{1}{LC}} \]

\[ \dot{X} = \frac{\partial H}{\partial P} = \frac{P}{M} \]

\[ \dot{P} = -\frac{\partial H}{\partial X} = k\delta X \]

\[ \omega_r = \sqrt{\frac{k}{M}} \]
FROM CLASSICAL TO QUANTUM PHYSICS:  
CORRESPONDENCE PRINCIPLE

\[ X \rightarrow \hat{X} \]  position operator

\[ P \rightarrow \hat{P} \]  momentum operator

\[ H(X, P) \rightarrow \hat{H}(\hat{X}, \hat{P}) \]  hamiltonian operator

\[ \frac{\partial A \partial B}{\partial X \partial P} - \frac{\partial A \partial B}{\partial P \partial X} = \{A, B\}_{PB} \rightarrow [\hat{A}, \hat{B}] / i\hbar \]  commutator

\[ \{X, P\}_{PB} = 1 \rightarrow [\hat{X}, \hat{P}] = i\hbar \]  position and momentum operators do not commute

FLUX AND CHARGE DO NOT COMMUTE

For every branch in the circuit:

\[ [\hat{\phi}, \hat{Q}] = i\hbar \]

We have obtained this result thru correspondance principle after having recognized flux and charge as canonical conjugate coordinates.

"Cannot quantize the equations of the stock market!"

A.J. Leggett

We can also obtain this result from quantum field theory thru the commutation relations of the electric and magnetic field. Tedium.
**LC CIRCUIT AS QUANTUM HARMONIC OSCILLATOR**

\[ \hat{H} = \hbar \omega_r \left( \hat{a}^\dagger \hat{a} + \frac{1}{2} \right) \]

\[ \hat{a} = \frac{\hat{\phi}}{\sqrt{Q_r}} ; \quad \hat{a}^\dagger = \frac{\hat{\phi}}{\sqrt{Q_r}} - \frac{i}{\hbar}\hat{Q}_r \]

\[ \phi_r = \sqrt{2\hbar \omega_r L} \]

\[ Q_r = \sqrt{2\hbar \omega_r C} \]

**SUPPRESSION OF THERMAL EXCITATION OF LC CIRCUIT**

Can place the circuit in its ground state

\[ \hbar \omega_r \gg k_B T \]

5 GHz \( \gg \) 10mK
In every energy eigenstate, (photon state) current flows in opposite directions simultaneously!

EFFECT OF DAMPING

important: as little dissipation as possible

dissipation broadens energy levels

\[ E_n = \hbar \omega_n \left[ n + i \left( \frac{1}{2} Q + \frac{1}{2} \right) \right] \]

\[ Q = RC\omega \]

see more later
ALL TRANSITIONS ARE DEGENERATE

CANNOT STEER THE SYSTEM TO AN ARBITRARY STATE IF PERFECTLY LINEAR

NEED NON-LINEARITY TO FULLY REVEAL QUANTUM MECHANICS
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JOSEPHSON JUNCTION PROVIDES A NON-LINEAR INDUCTOR
JOSEPHSON JUNCTION PROVIDES A NON-LINEAR INDUCTOR

\[ I = \frac{\phi}{L_J} \]

\[ L_J = \frac{\phi_0^2}{E_J} = \frac{\phi_0}{I_0} \]

\[ I = I_0 \sin \left( \frac{\phi}{\phi_0} \right) \]

\[ \phi_0 = \frac{\hbar}{2e} \]
COUPLING PARAMETERS OF THE JOSEPHSON JUNCTION "ATOM"

THE hamiltonian: (we mean it!)

$$\hat{H}_j = \frac{1}{2C_j} \left( \hat{Q} - q_{ext} \right)^2 - E_j \cos \frac{2e\phi}{\hbar}$$
TWO ENERGY SCALES

Two dimensionless variables:
\[ \tilde{\phi} = \frac{2e\hat{\phi}}{\hbar} \]
\[ \hat{\mathcal{N}} = \frac{\hat{Q}}{2e} \]

Hamiltonian becomes:
\[ \hat{H}_j = 8E_C \left( \frac{\hat{\mathcal{N}} - N_{\text{ext}}}{2} \right)^2 - E_J \cos \tilde{\phi} \]

Coulomb charging energy for 1e
\[ E_C = \frac{e^2}{2C_j} \]

Josephson energy
\[ E_J = \frac{1}{8} \frac{1}{N\mathcal{N}_T} \Delta \]

LOW-LYING EXCITATIONS OF ISOLATED JUNCTION: CHARGE STATES

\( n = N/2 = \)

-4  -2  0  2  4  6  4E_C
MECHANICAL ANALOG OF JOSEPHSON COUPLING ENERGY

Rotating magnet

Angular velocity:
\[ \Omega = \frac{4E_C}{\hbar} N_{ext} \]

Compass needle

Angular momentum:
\[ N\hbar \]

Torque on needle due to magnet
Current through junction
Velocity of needle in magnet frame
Voltage across junction

CHARGE STATES vs PHOTON STATES

Hilbert spaces have different topologies
HARMONIC APPROXIMATION

\[ \hat{H}_j = 8E_C \left( \frac{\hat{N} - \hat{N}_{ext}}{2} \right)^2 - E_j \cos \hat{\phi} \]

\[ \hat{H}_{j,h} = 8E_C \left( \frac{\hat{N} - \hat{N}_{ext}}{2} \right)^2 + E_j \hat{\phi}^2 \]

Josephson plasma frequency \( \omega_p = \frac{\sqrt{8E_CE_J}}{h} \)

Spectrum independent of DC value of \( \hat{N}_{ext} \)

TUNNEL JUNCTIONS
IN REAL LIFE

\[ E_J \sim 50K \]
\[ \omega_p \sim 30-40GHz \]
\[ E_J \sim 0.5K \]
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3 TYPES OF BIASES

charge

\[ \begin{array}{c}
\text{2C}_g \\
\text{C} \\
\text{2C}_g \\
\hline
\end{array} \]

flux

\[ \begin{array}{c}
\Phi_b \\
\text{C} \\
\hline
\end{array} \]

current

\[ \begin{array}{c}
\text{I}_b \\
\text{C} \\
\hline
\end{array} \]
EFFECTIVE POTENTIAL OF 3 BIAS SCHEMES

\[ \frac{\varphi}{2\pi} = \frac{2e\phi}{h} \]

charge bias

\[ -1 \quad \frac{2e\phi}{h} \quad +1 \]

flux bias

phase bias

CEA Saclay, Yale
NEC, Chalmers, JPL, ...

TU Delft, NEC, NTT, MIT
UC Berkeley, IBM, SUNY
IPHT Jena, ...

UC Berkeley, NIST, UCSB,
U. Maryland, CRTBT Grenoble...
Cooper pair box soluble in terms of Mathieu functions (A. Cottet, PhD thesis, Orsay, 2002)

ANHARMONICITY vs CHARGE SENSITIVITY

Eastern University
ANHARMONICITY vs CHARGE SENSITIVITY IN THE LIMIT $E_C/E_J << 1$ ("TRANSMON")

Anharmonicity:

$$\frac{\omega_{12} - \omega_{01}}{(\omega_{12} + \omega_{01})/2} \rightarrow \sqrt{\frac{E_C}{8E_J}}$$

Peak-to-peak charge modulation amplitude of level $m$:

$$\epsilon_m \rightarrow (-1)^m E_C^2 \frac{2^{4m+5}}{m!} \sqrt{\frac{2}{\pi}} \left( \frac{E_J}{2E_C} \right)^{\frac{3}{2} + \frac{3}{4}} e^{-\sqrt{8E_J/E_C}}$$

J. Koch et al. 07

TRANSMON: SHUNT JUNCTION WITH CAPACITANCE

SPECTROSCOPY OF A COOPER PAIR BOX IN TRANSMON REGIME

Anharmonicity:

$$\omega_{01} - \omega_{12} = 455\text{MHz} \approx E_C$$

Sufficient to control the junction as a two level system

$T_1 > 2\mu$s
ATOM IN SEMI-CLASSICAL REGIME:
CIRCULAR RYDBERG ATOM

old Bohr theory essentially "exact"!

\[ m \omega r^2 = n \hbar \]

constraint

valid when:

\[ \left| \frac{\partial \omega(E)}{\partial E} \right| \ll \frac{1}{\hbar} \]

TRANSMON AS ANALOG OF CIRCULAR
RYDBERG ATOMS

Josephson potential energy

Spectroscopic lines (high T):

\[ \omega_{n+1} - \omega_{n+1, n+2} \ll \omega_{n+1} \]
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THE READOUT PROBLEM

\[ |0\rangle \text{ or } |1\rangle \]

WANT:
1) SWITCH WITH LARGE ON-OFF RATIO
2) FAITHFUL READOUT CIRCUIT
DIVERSITY OF CIRCUIT STRATEGIES

- SACLUAY -- YALE (Quantronium)
- TU DELFT -- NEC -- NTT
- NIST -- UCSB

YALE (circuit-QED)

analogous to cavity QED expts by Haroche, Raimond, Brune et al.

DISPERNSIVE READOUT STRATEGY

rf signal in \( \omega \neq \omega_{01} \)

QUBIT CHIP

|0\rangle or |1\rangle
QUBIT CHIP

\[ |0\rangle \text{ or } |1\rangle \]

QUBIT STATE ENCODED IN PHASE OF OUTGOING SIGNAL, NO ENERGY DISSIPATED ON-CHIP

Requirements:
1) low noise in detection
2) enough phase shift

DO WITH ENOUGH PHOTONS TO GET 1 CLASSICAL BIT OF INFORMATION
DISPERESIVE READOUT STRATEGY

rf signal in

QUBIT CHIP

|0\rangle or |1\rangle

Requirements:
1) low noise in detection
2) enough phase shift

rf signal out

DO WITH ENOUGH PHOTONS TO GET
1 CLASSICAL BIT OF INFORMATION

PLACE QUBIT IN MICROWAVE CAVITY
TO FILTER OUT IRRELEVANT PART OF SPECTRUM

SUPERCONDUCTING MICROWAVE RESONATOR:
ANALOG OF FABRY-PEROT CAVITY

Si or Al2O3

Al or Nb

mirror = capacitors

can get Q up to 10^6
(in bulk: Q \sim 10^{10})

length \sim 1\text{cm}, but photon propagation length \sim 10\text{km}!

COPLANAR WAVEGUIDE: 2D VERSION OF COAXIAL CABLE
SUPERCONDUCTING MICROWAVE RESONATOR: ANALOG OF FABRY-PEROT CAVITY

Si or Al2O3

Al or Nb

length ~1cm, but photon propagation length ~ 10km!

RF GEN.

IN OUT

CHIP

ADC

1/2 photon: ~1nA
~100nV

very small mode volume

ν ~ 10GHz

w~20μm

can get Q
up to 10^6
(in bulk:
Q ~ 10^{10})
SUPERCONDUCTING CAVITY = FABRY-PEROT

"QUANTRONIUM" IN MICROWAVE CAVITY
HIGH FREQUENCIES, LOW TEMPERATURES

2-20 GHz

10-20 mK

QUANTRONIUM IN MICROWAVE CAVITY

OFF-RESONANT NMR-TYPE PULSE SEQUENCE FOR QUBIT MANIPULATION
QUANTRONIUM IN MICROWAVE CAVITY

READOUT PROBING PULSE

QUBIT STATE ENCODED IN PHASE OF TRANSMITTED PULSE

Metcalfe et al.
Phys. Rev. B6
174516 (2007)
QUANTRONIUM IN MICROWAVE CAVITY

Metcalfe et al.
Phys. Rev. B6
174516 (2007)

CAVITY BIFURCATION: ANALOG OF OPTICAL BISTABILITY

Latching effect due to bifurcation of cavity mode
HYSTERESIS

\[ \Omega/2\pi = 4.2 \text{GHz} \]

\[ T = 15 \text{mK} \]

1 ms sweep

MEASUREMENT OF READOUT FIDELITY

Relaxation induced by readout

Slope 3 times too small compared with thy

TOO MANY READOUT PHOTONS?
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CAVITY QUANTRONIUM RABI OSCILLATIONS

\[ \nu_{\text{Larmor}} = 14.5 \text{GHz} \]

Switching probability vs. time (\(\mu s\))

RAMSEY FRINGES

\[ T_2 = 500 \text{ns} \pm 200 \text{ns} \]
DISTRIBUTION OF RAMSEY DATA

method A of van Harlingen et al. 2004

\[ S_{N_e} (\omega) = \frac{e^2}{\omega} \alpha^2, \alpha \sim 1.9 \times 10^{-3} e \]

value OK

DISTRIBUTION OF RAMSEY DATA

van Harlingen et al. 2004

\[ S_{N_e} (\omega) = \frac{e^2}{\omega} \alpha^2, \alpha \sim 1.9 \times 10^{-3} e \]

value OK

E J/EC = 3.6

Need larger E J/EC
DECOHERENCE TIME ($T_2$)

\[ \Delta t (\text{ns}) \]

\[ Q_\phi = \omega_{\text{Larmor}} T_2 \]

"02 Vion et al. 50,000
"05 Siddiqi et al. 30,000
"05 Wallraff et al. 19,000
"06 Metcalfe et al. 70,000
"08 Houck et al. 100,000

$\nu_{\text{Larmor}} = 18.984\,\text{GHz}$
\[ \Delta \nu = 20\,\text{MHz} \]

1 param. fit $\rightarrow T_2 = 300\,\text{ns}$

SENSITIVITY OF BIAS SCHEMES TO NOISE (EXP$^D$)

<table>
<thead>
<tr>
<th>bias</th>
<th>$\Delta Q_{\text{off}}$</th>
<th>$\Delta E_J$</th>
<th>$\Delta E_C$</th>
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<tbody>
<tr>
<td>charge</td>
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<td>phase</td>
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CHARGED IMPURITY

TUNNEL CHANNEL

ELECTRIC DIPOLES

charge qubit

flux qubit

phase qubit
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QUANTUM BUS CONCEPT FOR SOLID STATE QUBITS

microwave transmission line resonator

artificial atom

coupling element

STRONG QUBIT-CAVITY COUPLING

Msmt. of qubit-cavity avoided crossing

vacuum Rabi splitting

\[ 2g = 250 \text{ MHz!} \]

STRONG QUBIT-CAVITY COUPLING

RESOLVING PHOTON NUMBER IN CAVITY

\[ P(n) = \frac{(\bar{n})^n}{n!} e^{-\bar{n}} \]

- Mean shifts
- Peaks are Poisson distributed
- Peaks get broader \( \propto n \)

Houck et al., Nature 07
RESOLVING PHOTON NUMBER IN CAVITY

CONDITIONAL QUBIT ROTATION POSSIBLE!

SCHEMATIC OF 2 COOPER PAIR BOXES IN A MICROWAVE CAVITY

SWAPPING INFORMATION BETWEEN QUBITS

Nota Bene:
(Using first generation transmon with 'short' T2=100 ns.)


PERSPECTIVES

QUANTUM COMPUTATION
violation of Bell’s inequalities
teleportation
error correction
algorithms

MEASUREMENTS AND CONTROL OF QUANTUM ENGINEERED SYSTEMS
amplification at the quantum limit
quantum noise squeezing (1-mode and 2-mode)
quantum feedback
single photon detection for radioastronomy
charge counting for metrology

Q_\phi \sim 10^7
NEW MATERIALS?
Q_\phi \sim 10^4
OK
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<tr>
<td>Post-Docs</td>
<td>I. SIDDIQI (UCB)</td>
<td>A. WALRAFF (ETH)</td>
<td>E. BOAKNIN (Mtrl)</td>
<td>A. MAHER (Vienna)</td>
<td>N. BERGEAL</td>
<td>A. HOUCK</td>
<td>D. SCHUSTER</td>
<td>L. FRUNZIO</td>
<td>F. MARQUARDT (Munich)</td>
<td>J. KOCH</td>
<td>J. GAMBETTA</td>
<td>A. BLAIS</td>
<td>A. CLERK (McGill)</td>
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<td>Undergrds</td>
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<td>J. SCHWEDE</td>
<td>D. ESTEVE</td>
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