Superconducting flux qubits

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theory
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Mike Tinkham
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mesoscopic Josephson junction circuits

Josephson coupling energy

$U_J = E_J\,(\,1 - \cos\phi\,)$

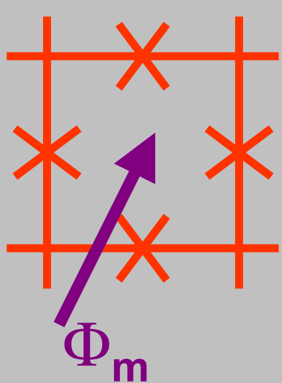
$E_J = 2\Delta\,(h/e^2)\,/\,(8R_n)$

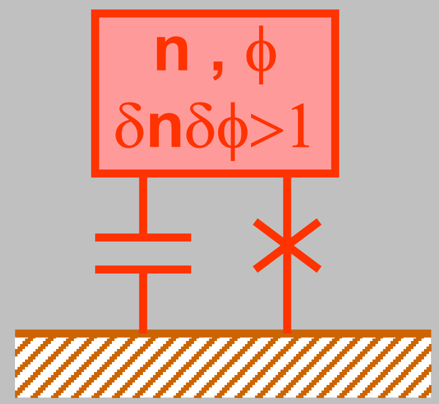
Coulomb charging energy

$U_C = E_C\,4n^2$

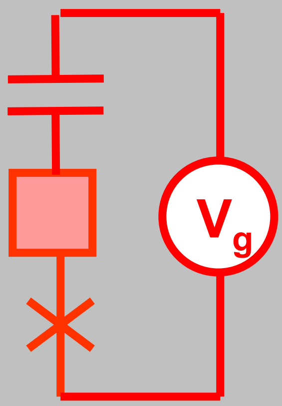
$E_C = e^2\,/\,2C$

$E_J/E_C >> 1$
phase excitations
fluxons





$E_C/E_J >> 1$
charge excitations



decoherence spin-oscillator bath Grifoni et al.

spin $H = \varepsilon\sigma_z + \Delta\sigma_x$ $\delta E = 2(\Delta^2+\varepsilon^2)^{1/2}$ (Δ tunnel, ε field energy)

oscillator spectral density

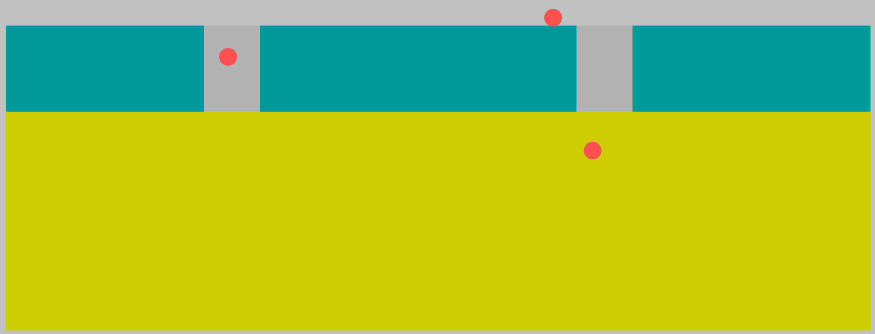
$$J(\omega) = \pi/2 \, \Sigma \, c_i^2/C_1\omega_i^2 \;\; \delta(\omega-\omega_i)$$

relaxation rate

$$\Gamma_r = ½ \, (\Delta/\delta E)^2 \, J(\delta E/\hbar) \, \coth(\delta E/2k_BT)$$

dephasing rate

$$\Gamma_\phi = \Gamma_r/2 + (\varepsilon/\delta E)^2 \, \alpha \, 2\pi k_B T/h$$

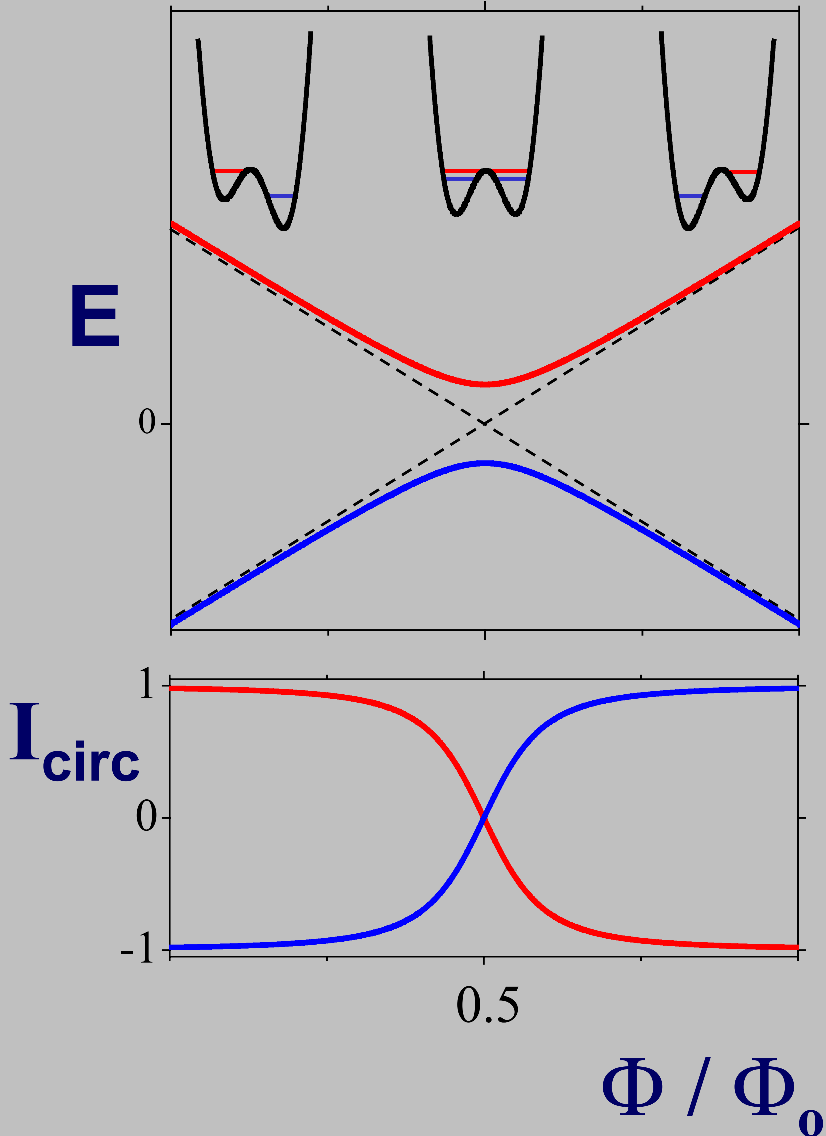


1/f noise

- charge noise: charged defects in barrier, substrate or surface lead to non-integer induced charge. Static offset, 1/f noise.

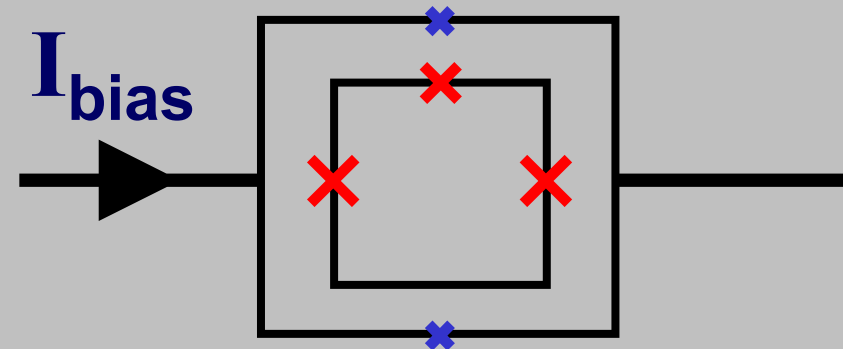
- flux noise: trapped vortices, magnetic domains, magnetic impurities.

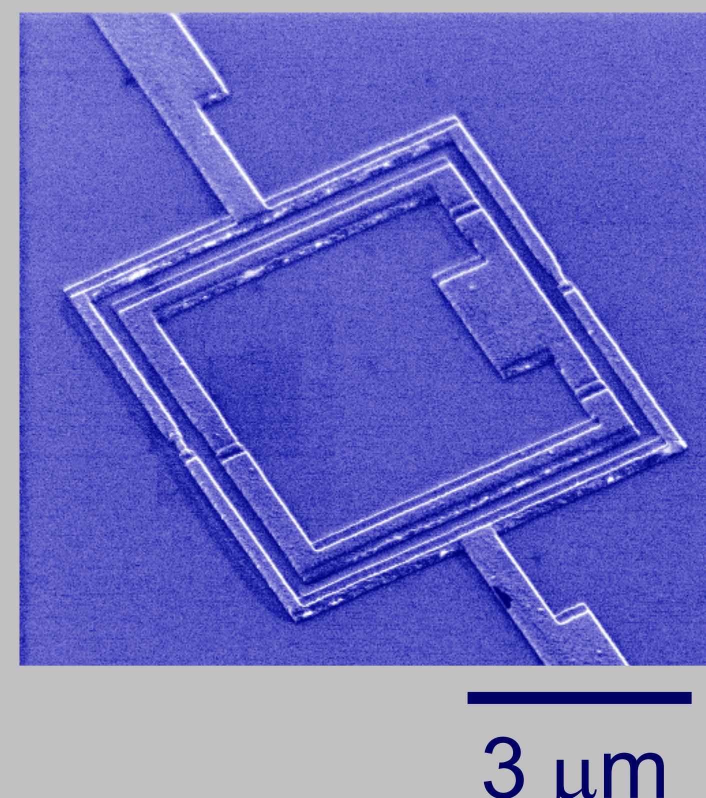
- critical current noise: neutral defects in barrier.

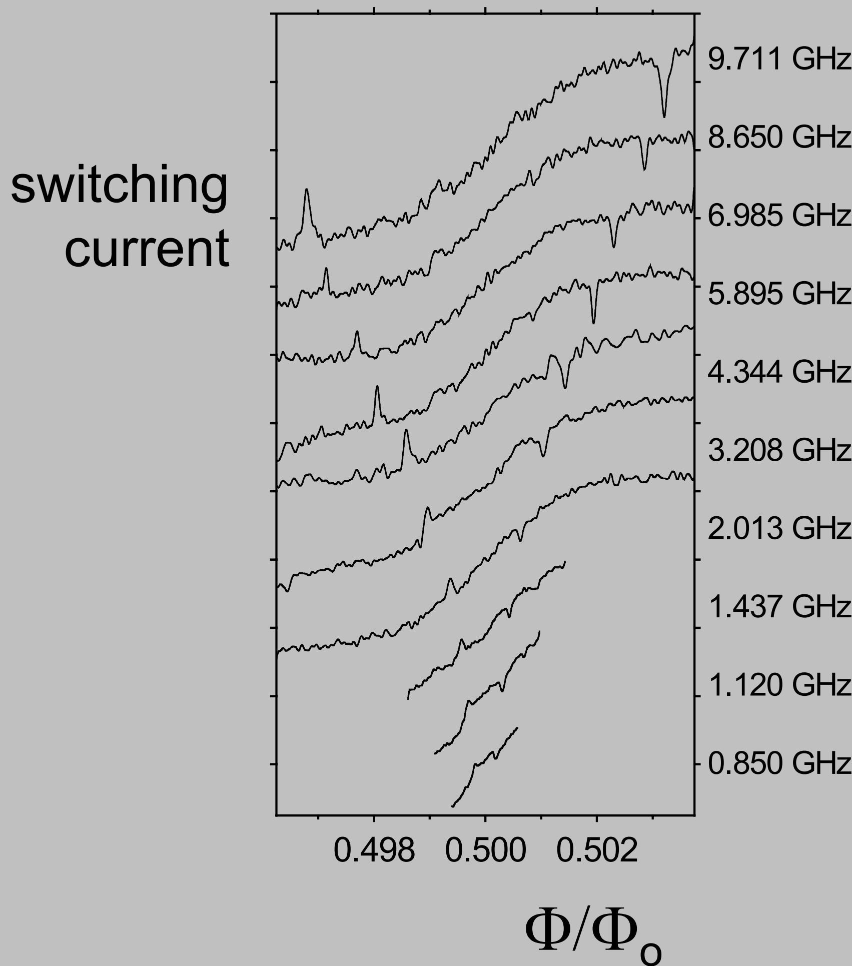


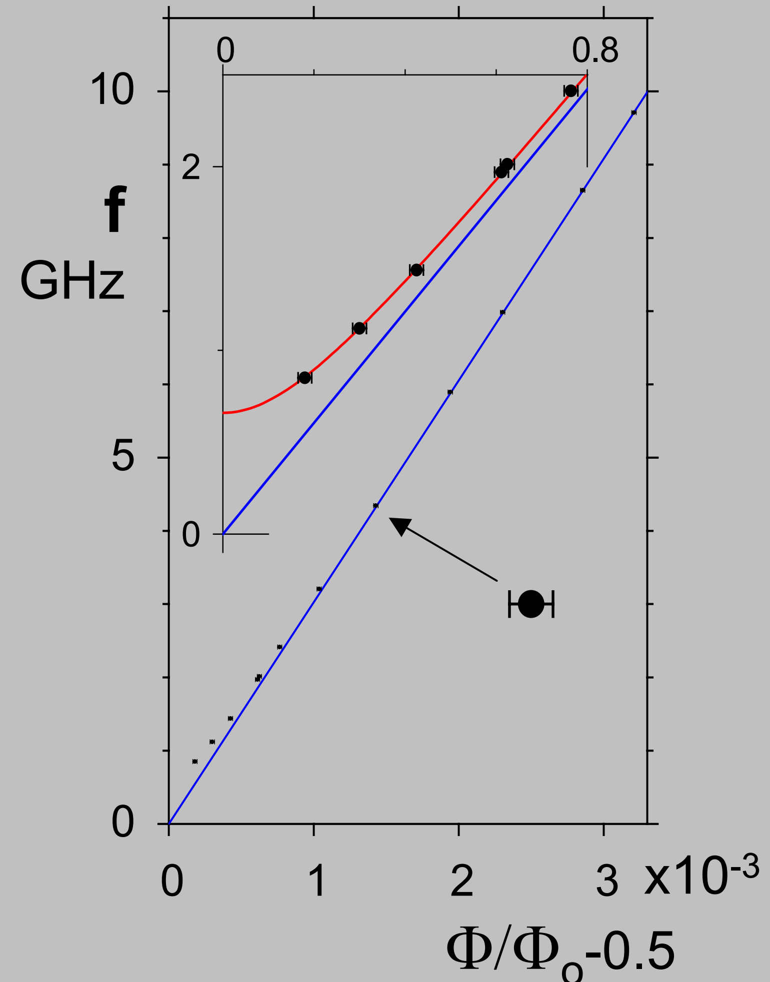
$I_{circ} = \partial E/\partial(\Phi/\Phi_o)$

$LI_{circ} = 10^{-3}\ \Phi_o$





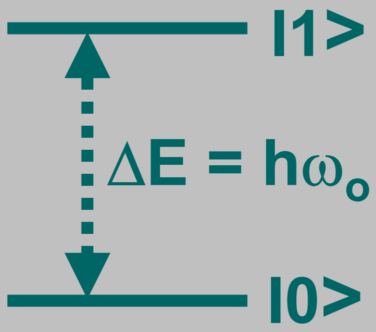




Caspar van der Wal

also SUNY

quantum bit: two level quantum system

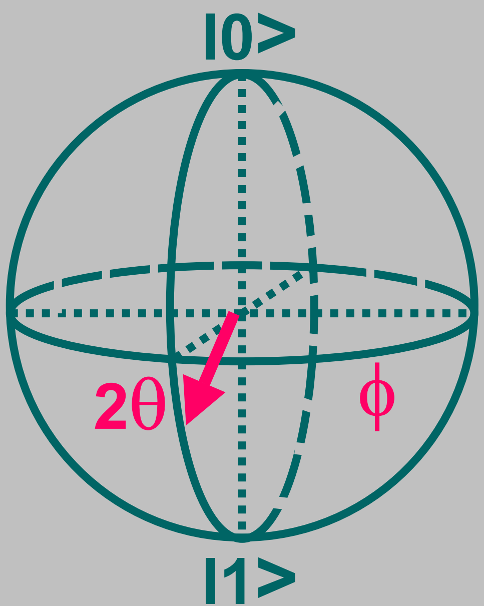


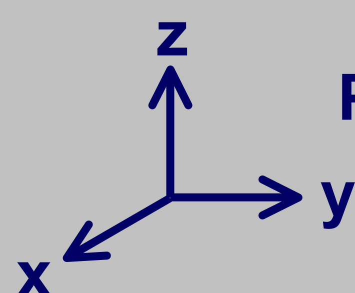
$$\Psi = \alpha\, |0\rangle + \beta\, |1\rangle$$

$$|\alpha|^2 + |\beta|^2 = 1$$

$$\alpha = \cos\theta \qquad \beta = e^{i\phi} \sin\theta$$

$$d\phi/dt = \omega_o$$





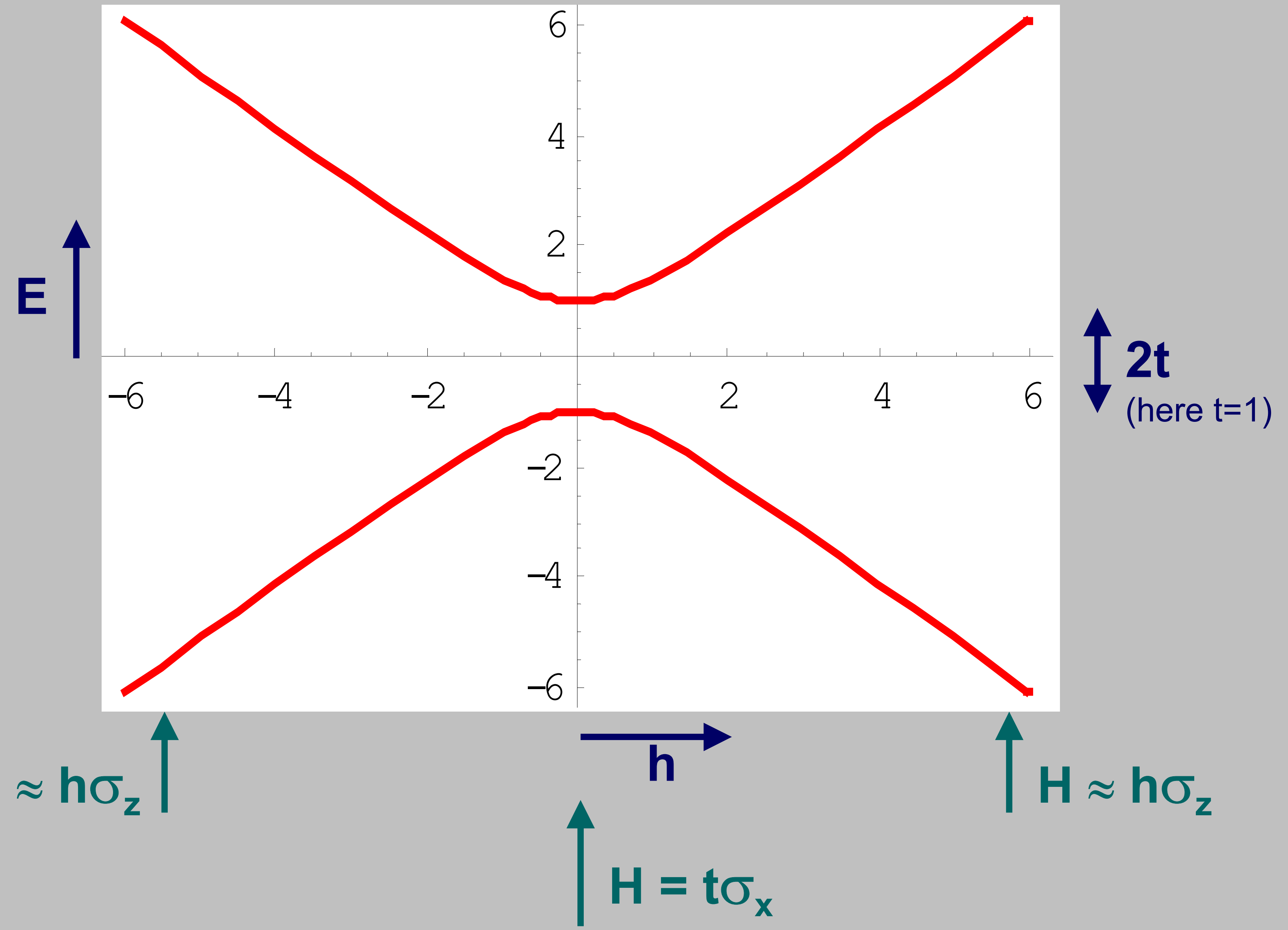
Pauli spin matrices

$$\sigma_x \quad \sigma_y \quad \sigma_z$$

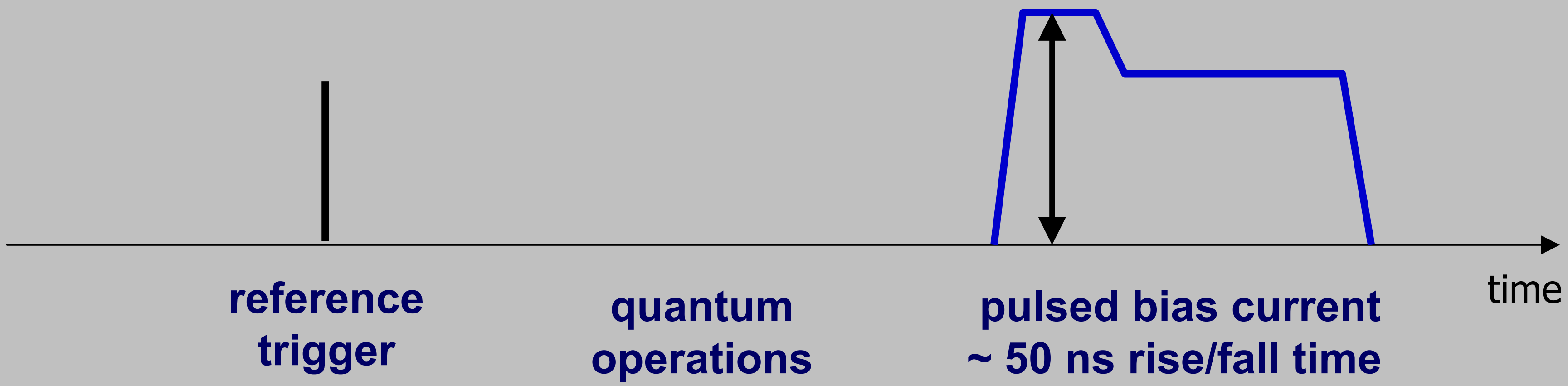
h set by external flux

t set by fabrication

$$H = h\sigma_z + t\sigma_x$$



SQUID readout:

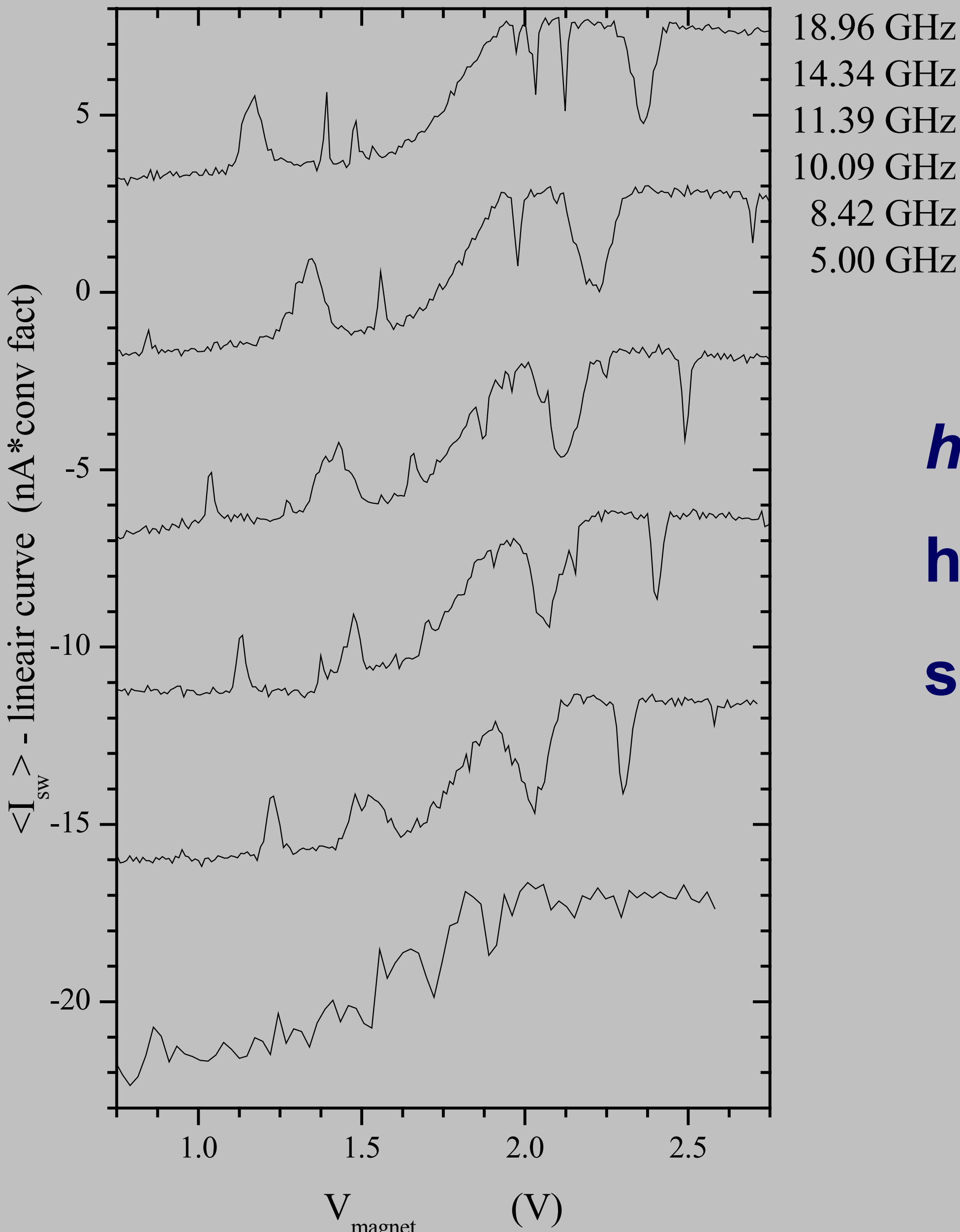


only two possible outputs:

SQUID switched to gap voltage

SQUID still at V=0

pulse height adjusted to give ~50% switching

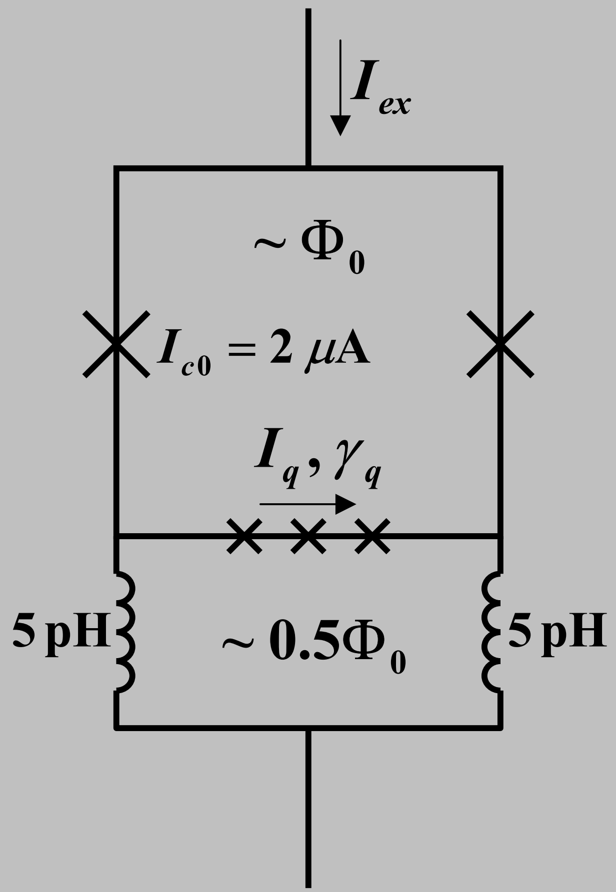


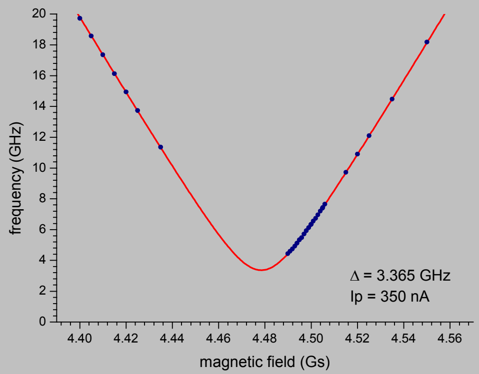
high power:

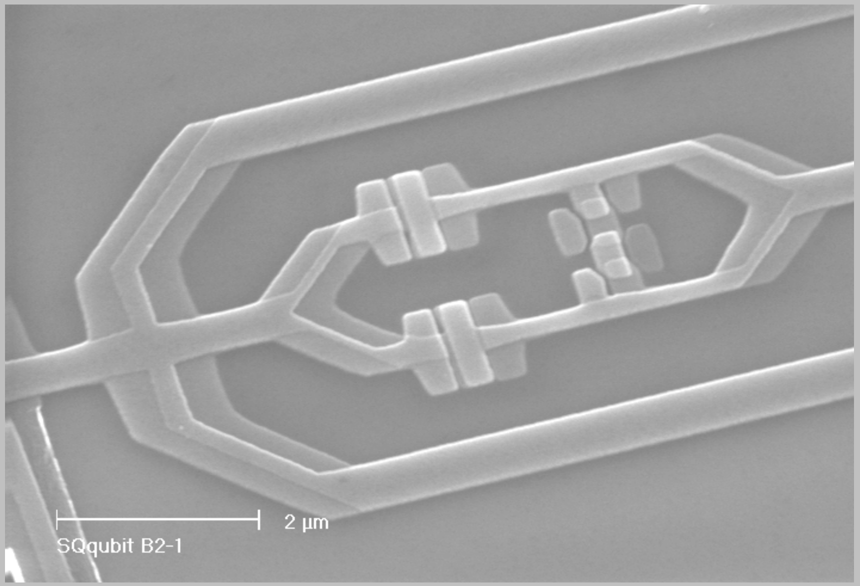
harmonics

subharmonics

Irinel Chiorescu and Yasu Nakamura

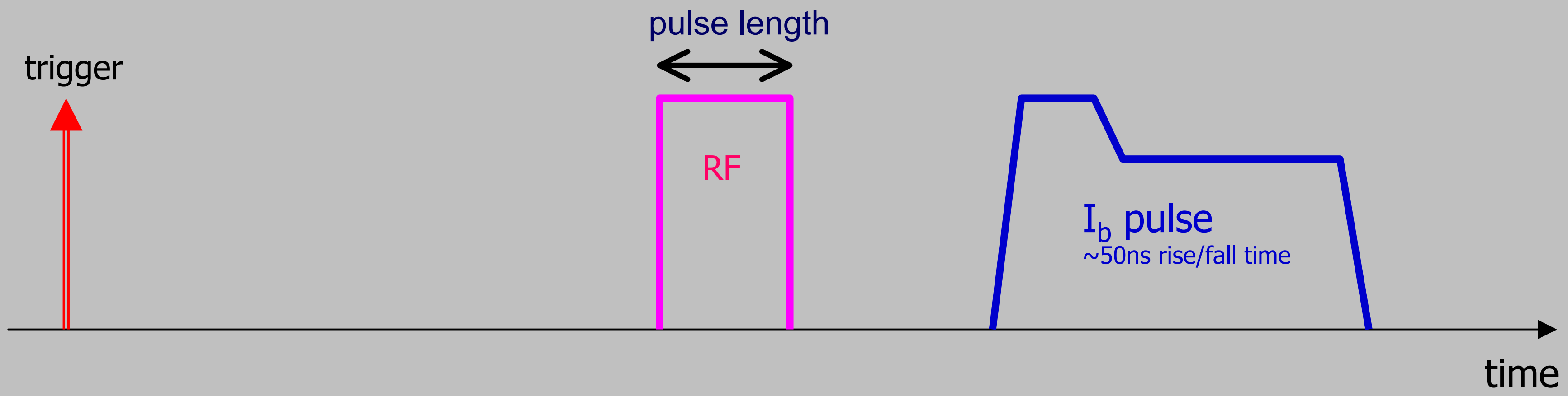


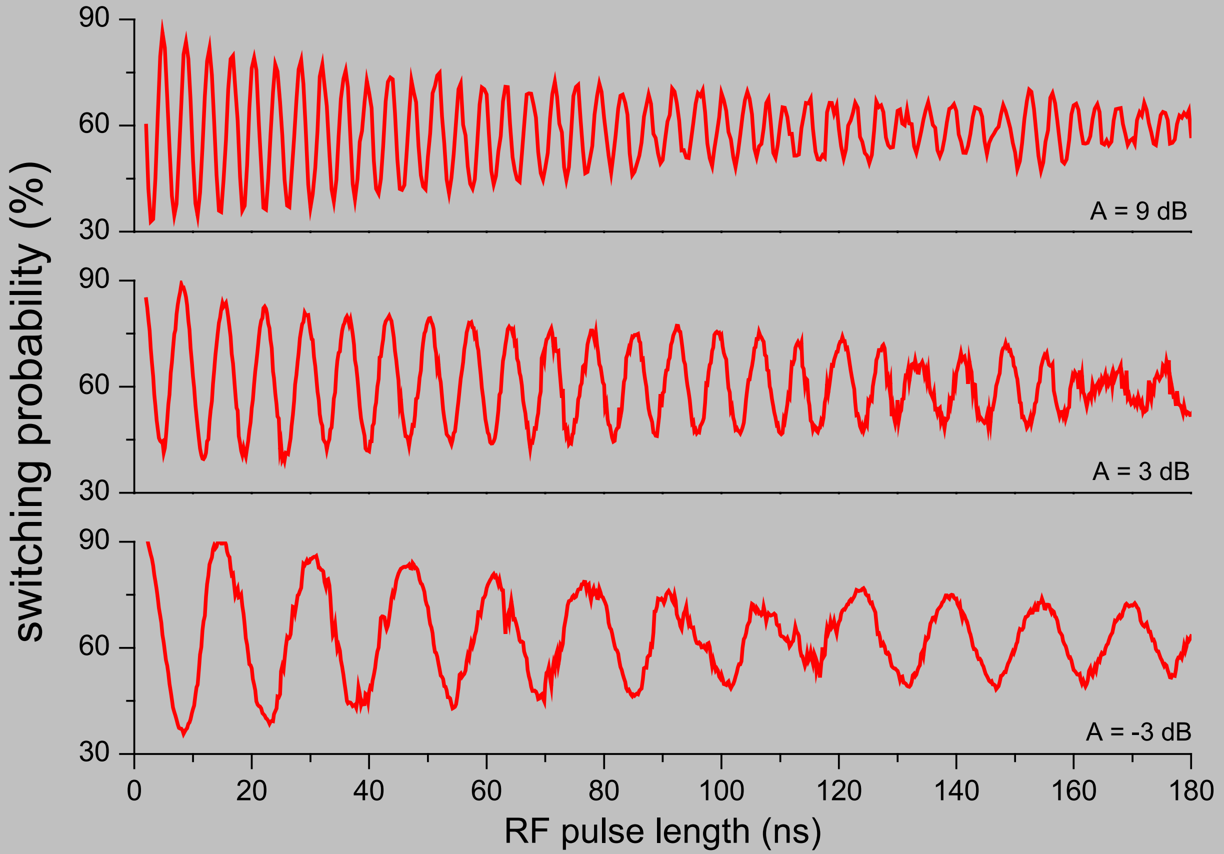




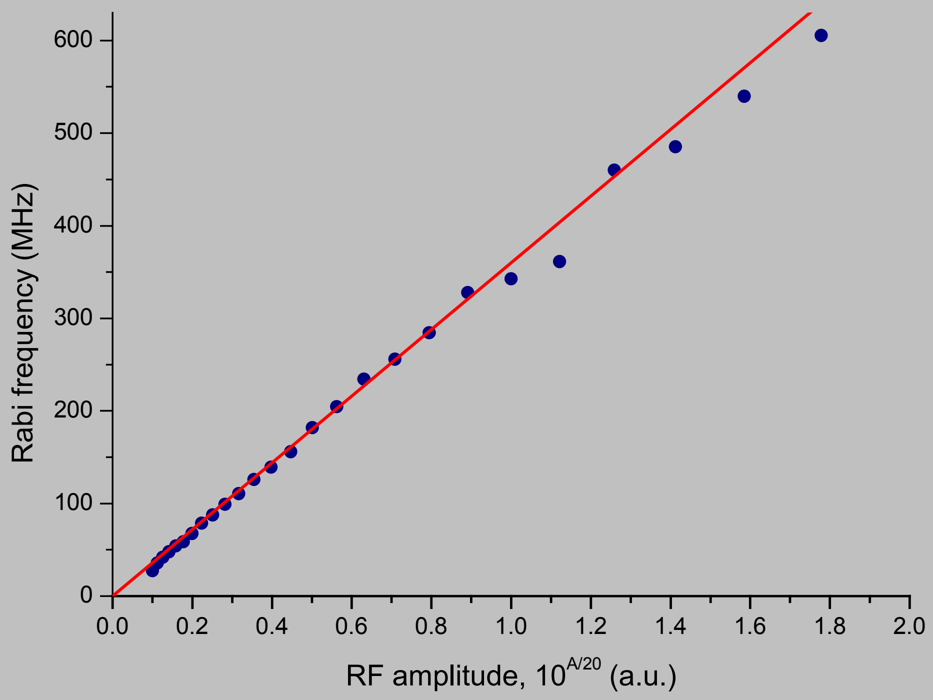
- qubit flux-biased in symmetry point
- ramp of SQUID bias current I_{ex} changes circulating current in SQUID
- SQUID-qubit coupling: qubit adiabatically driven from symmetry

Rabi: microwave pulse with varying length

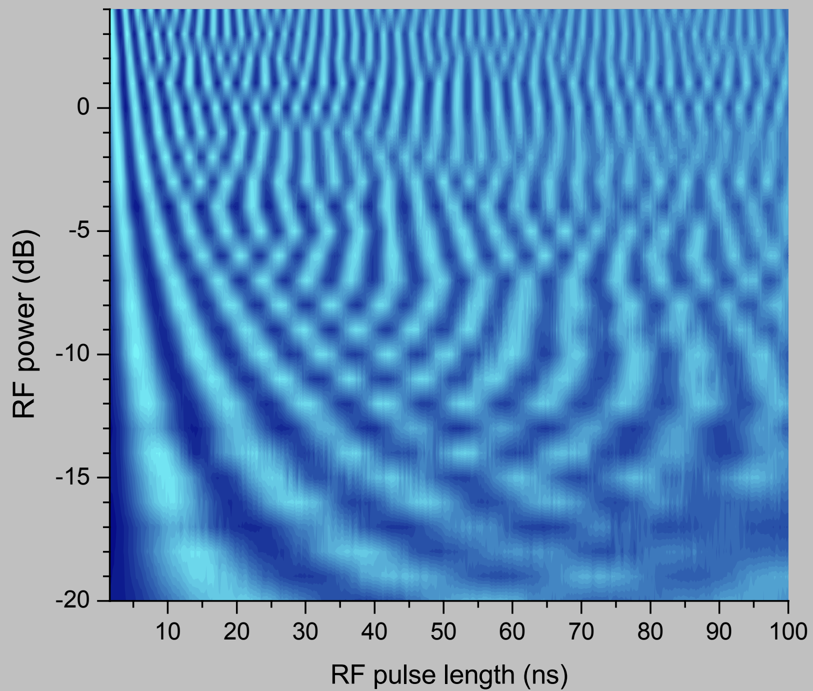




switching probability (%)
90
60
30
A = 9 dB
A = 3 dB
A = -3 dB
0
20
40
60
80
100
120
140
160
180
RF pulse length (ns)

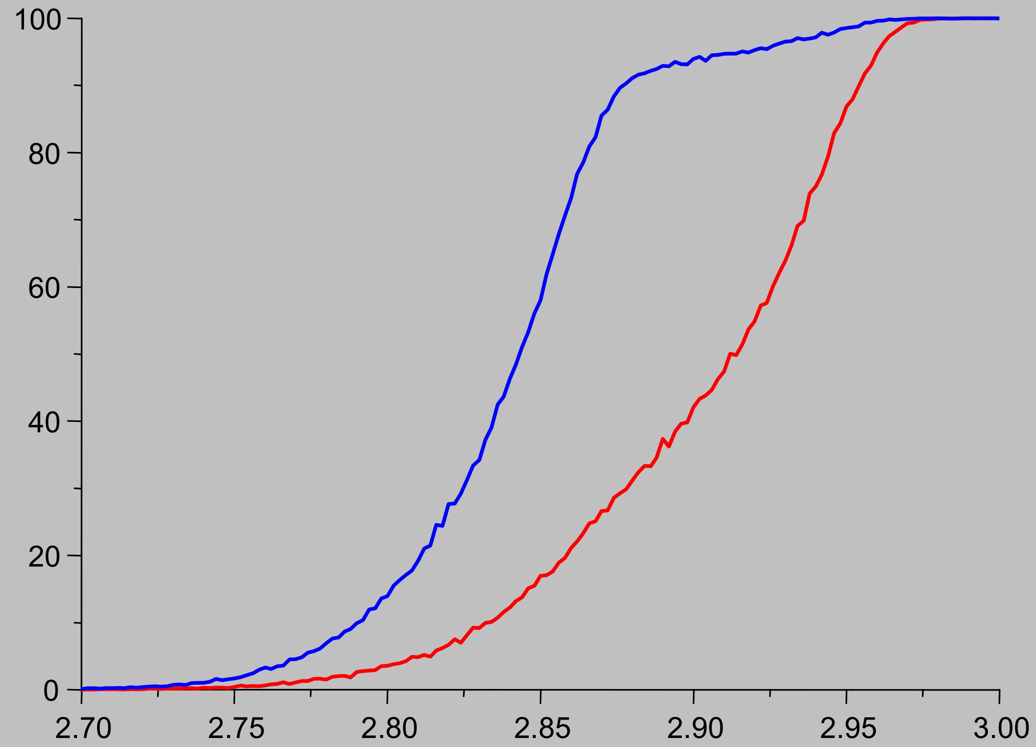


Rabi frequency (MHz)
RF amplitude, $10^{A/20}$ (a.u.)
0
100
200
300
400
500
600
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0



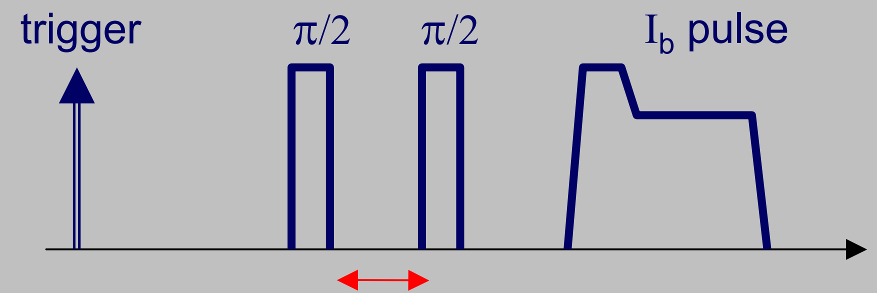
RF power (dB)
RF pulse length (ns)
0
-5
-10
-15
-20
10
20
30
40
50
60
70
80
90
100

switching ↑
probability



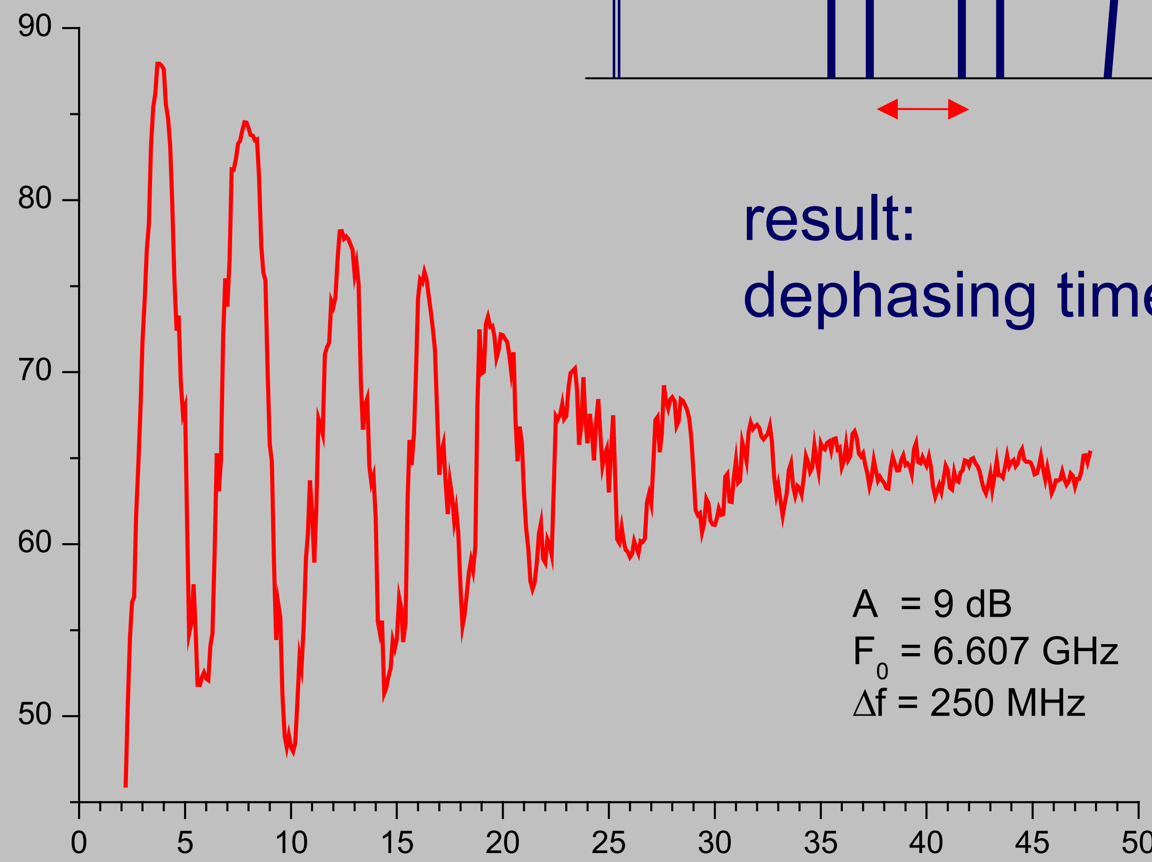
bias pulse height →

Ramsey
free induction decay

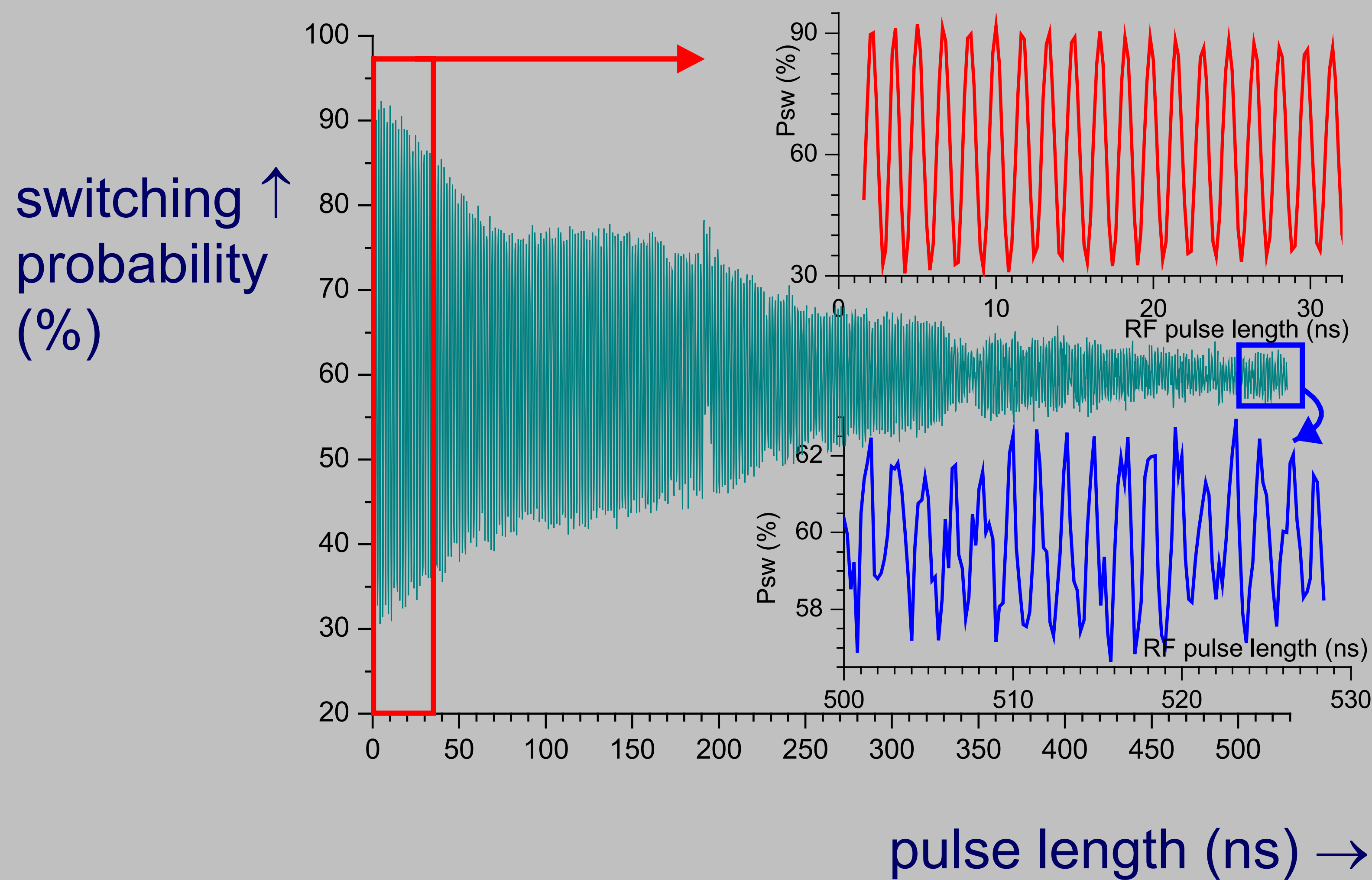


result:
dephasing time T_2= 20 ns

switching ↑
probability



time between π/2 pulses →



switching ↑
probability
(%)
Psw (%)
RF pulse length (ns)
Psw (%)
RF pulse length (ns)
pulse length (ns) →

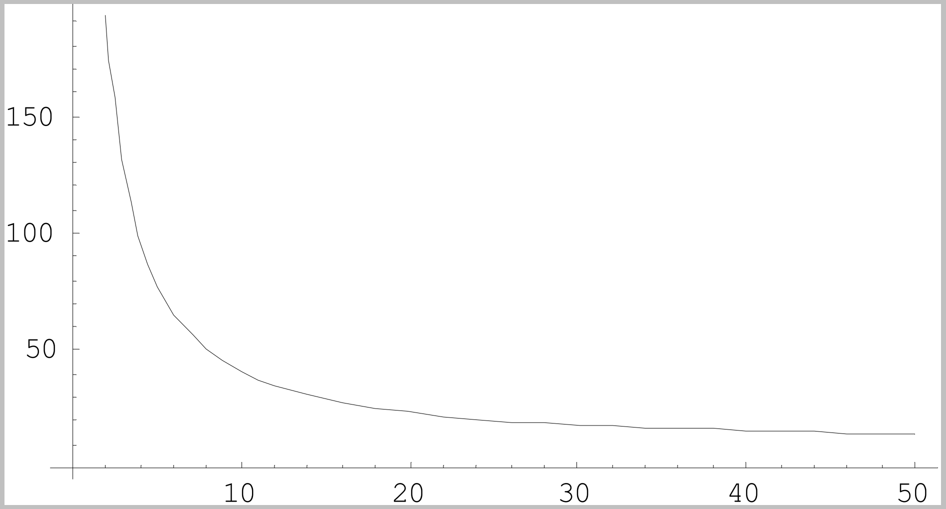
dephasing: flux noise leads to $\delta E=\hbar\delta\omega=\pi/\tau_\phi$

τ_ϕ=20 ns corresponds to δf=25 MHz

Rabi frequency off-resonance

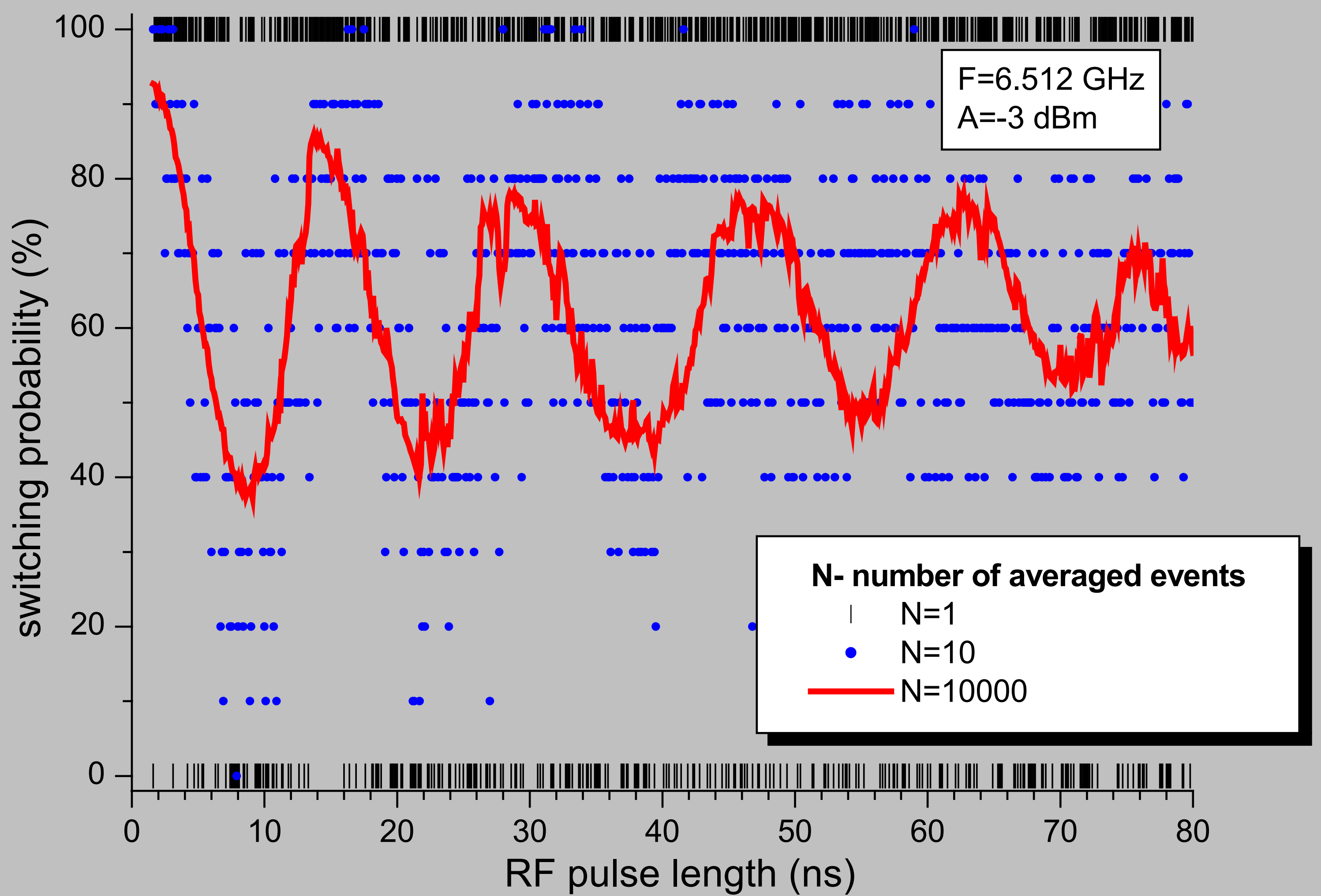
$$\omega_R' = \omega_R\,(1 + \delta\omega^2/\omega_R^2)^{1/2} = \omega_R\,(1+\pi^2/\omega_R^2\tau_\phi^2)^{1/2}$$

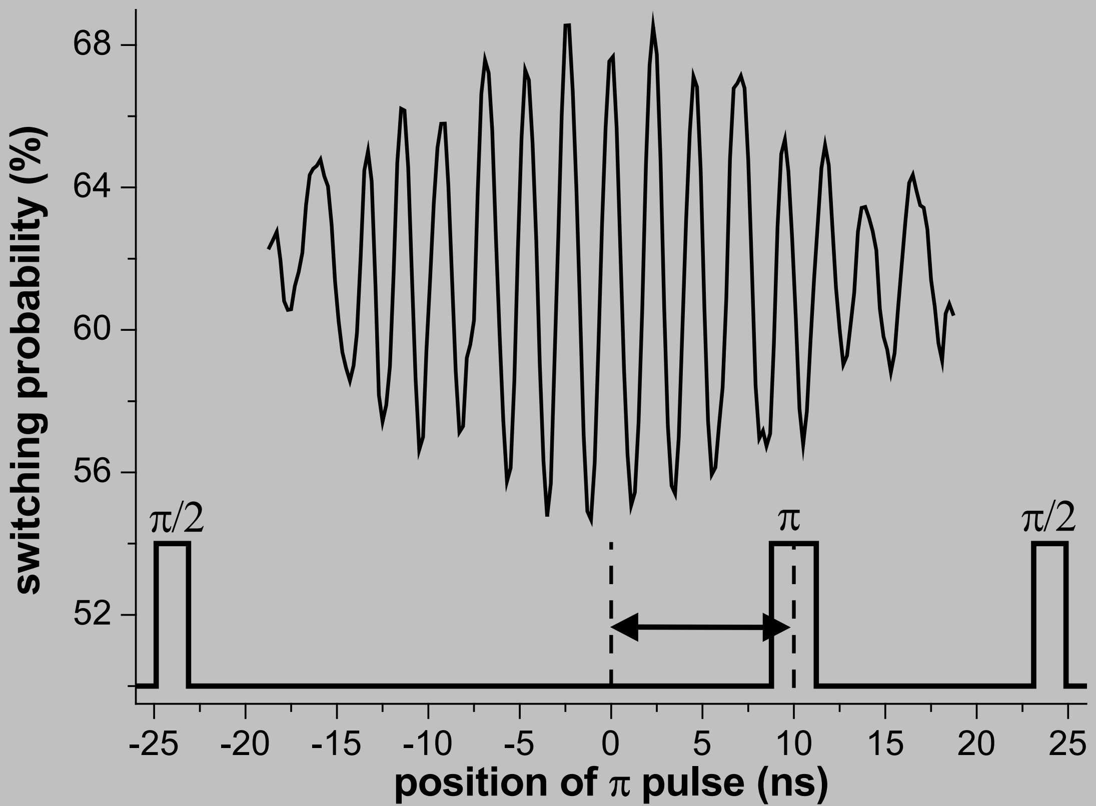
↑
Rabi dephasing time (ns) for $\delta\omega\leftrightarrow$25 MHz



Rabi period (ns) →

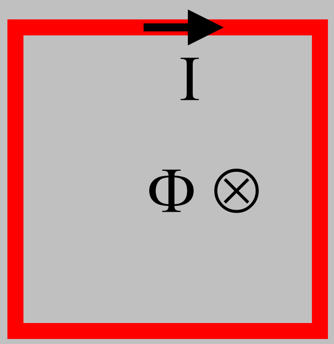
Rabi with low number of measurements, single shot contains some information

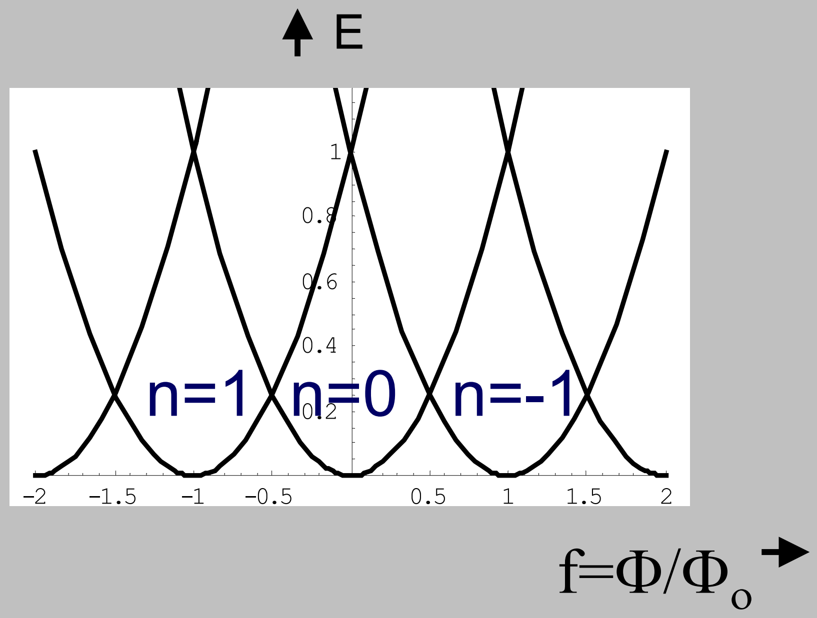


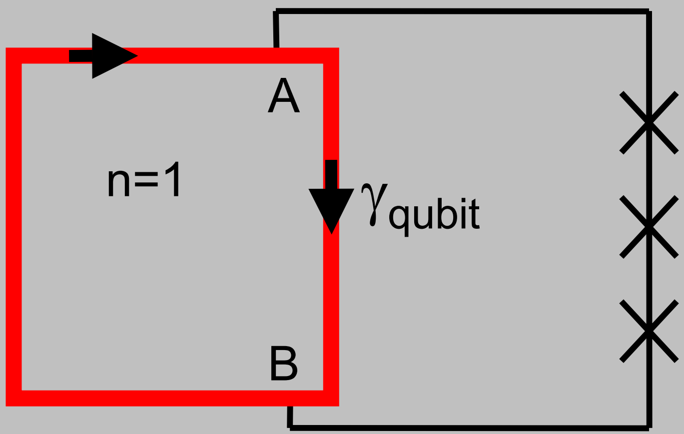


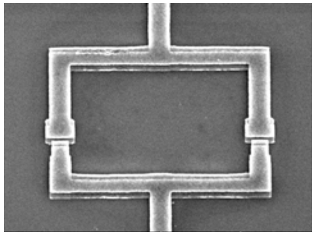
switching probability (%)
68
64
60
56
52
π/2
π
π/2
-25
-20
-15
-10
-5
0
5
10
15
20
25
position of π pulse (ns)

closed superconducting wire loop, w<λ

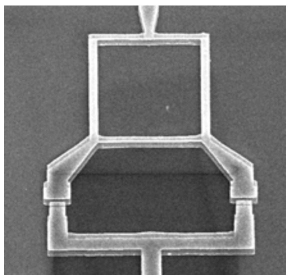




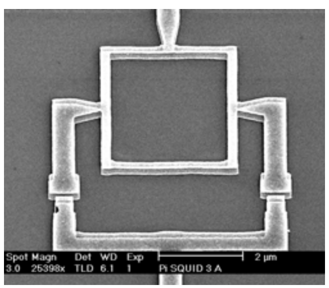




standard SQUID

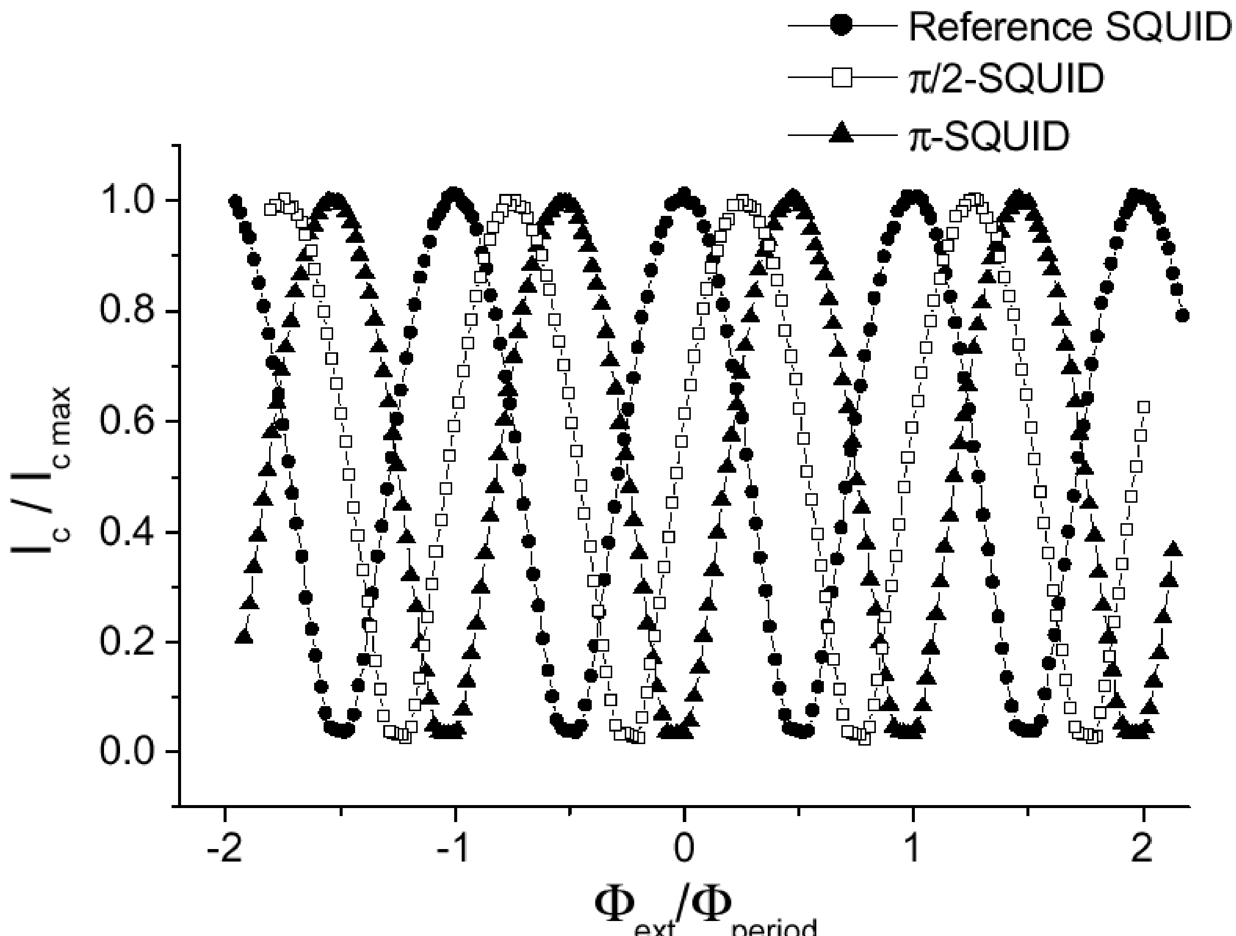


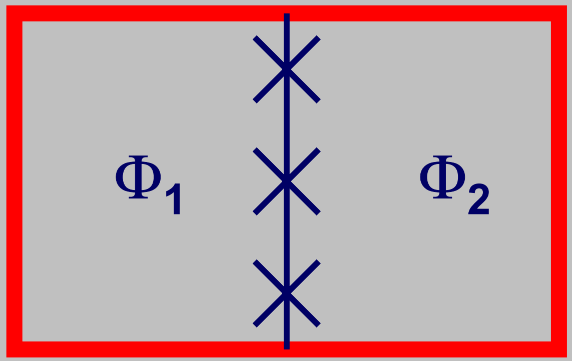
Π/2-SQUID



Π-SQUID

Hannes Majer, Jeremy Butcher





trapped fluxoid gradiometer qubit

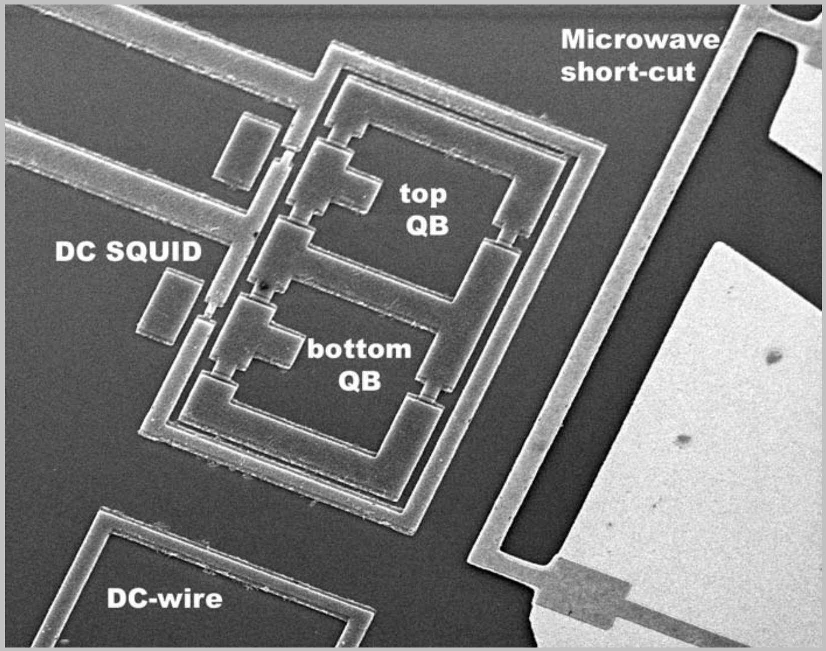
response only to Φ_1-Φ_2

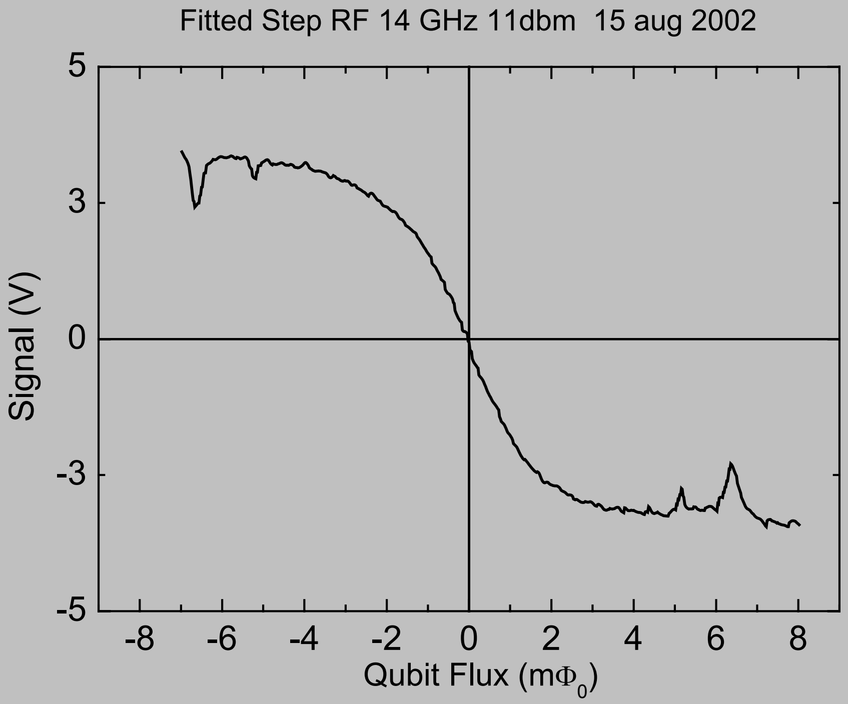
$$\Delta E = I_p(\Phi_1 - \Phi_2) - \zeta I_p(\Phi_o + \Phi_1 + \Phi_2)$$

asymmetry parameter $\zeta \approx 0.01$ (fabrication)

reduction flux noise by this factor

two coupled qubits
Hannes Majer, Floor Pauw





conclusions:

single qubits at present:
- decoherence time / operation time 20-50
- modulation range maximum 60%

gradiometer qubit, soon:
- determine origin flux noise
- improve coherence
- improve modulation range

two-qubit systems starting