Applications of Unique Superconductor Quantum Phenomena in Electronics

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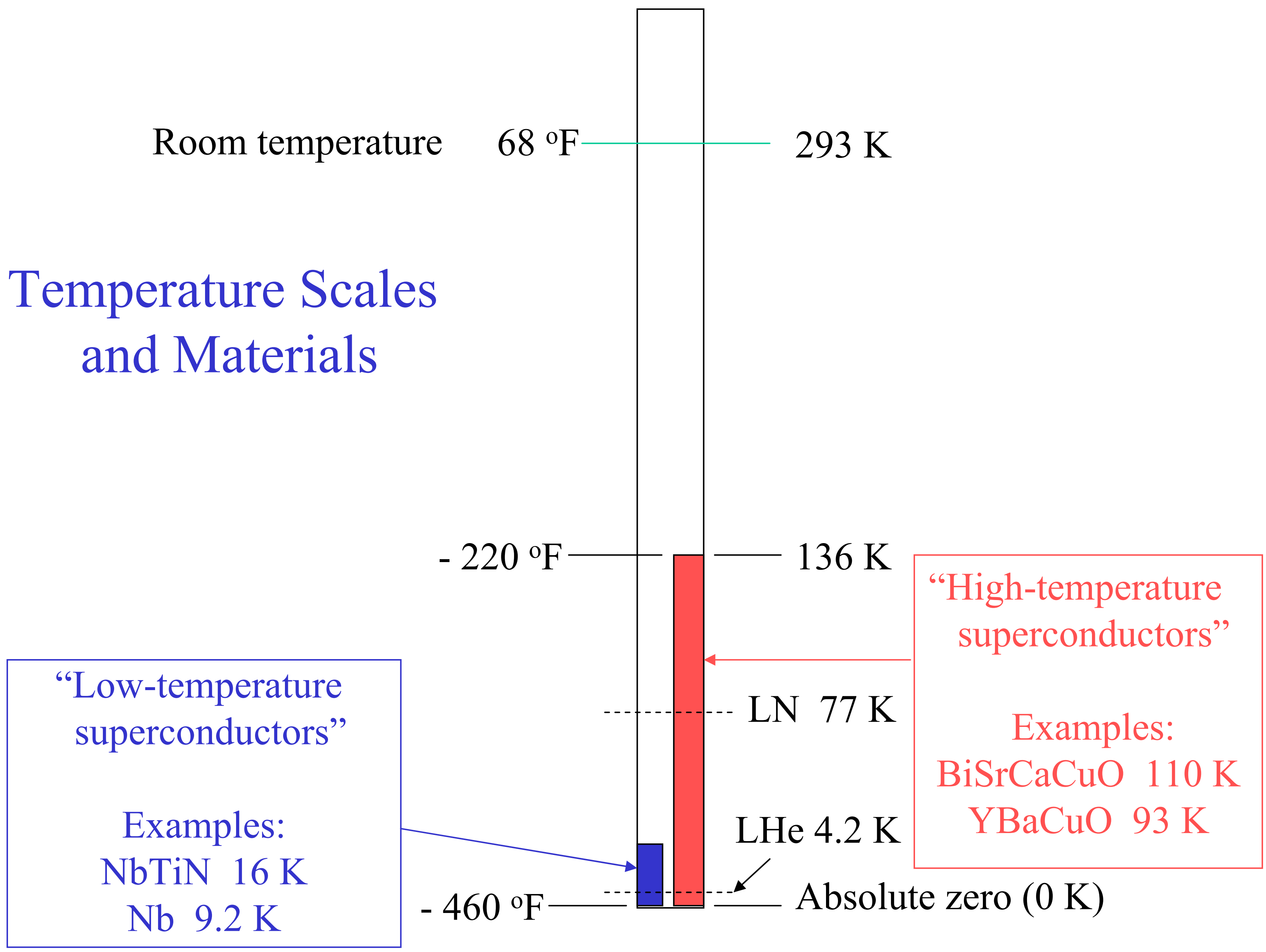
- Elements of superconductor phenomena
- Existing applications
- Emerging medical applications
- Digital and analog-to-digital circuits
- Forefront research directions

IEEE

IEEE Council on Superconductivity
http://www.ewh.ieee.org/tc/csc

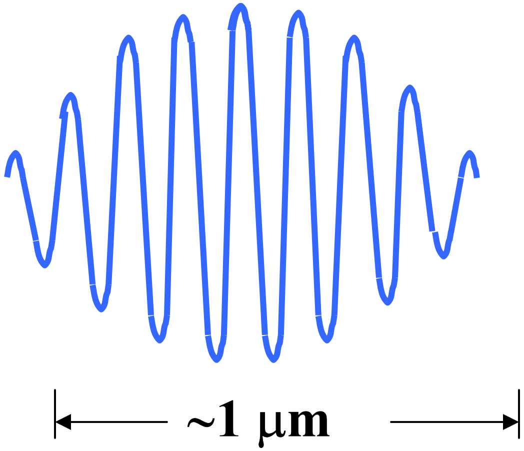
UC Berkeley
Cryoelectronics

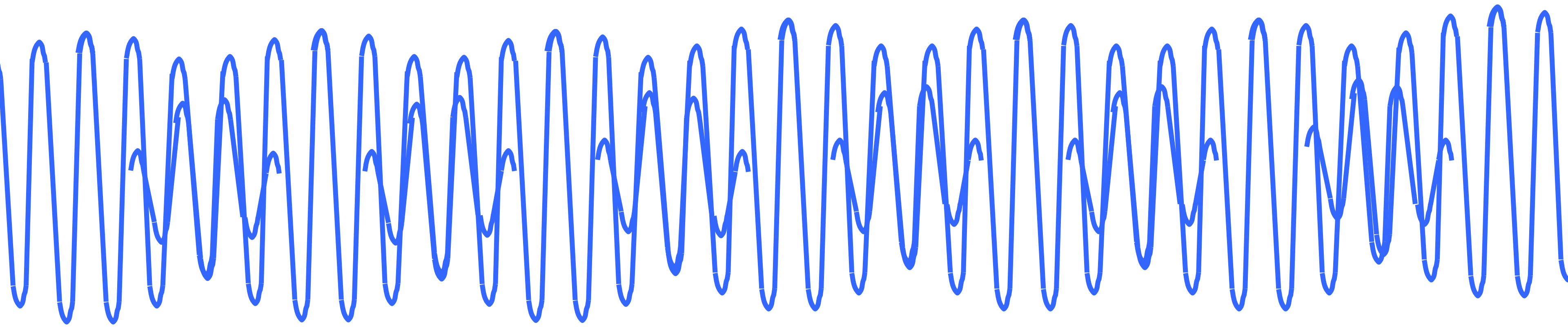
Superconductor Fundamentals


Room temperature
68 °F
293 K
Temperature Scales
and Materials
- 220 °F
136 K
"High-temperature superconductors"
Examples:
BiSrCaCuO 110 K
YBaCuO 93 K
LN 77 K
LHe 4.2 K
"Low-temperature superconductors"
Examples:
NbTiN 16 K
Nb 9.2 K
- 460 °F
Absolute zero (0 K)

BCS Pairing Concept

Cooper pair wave function

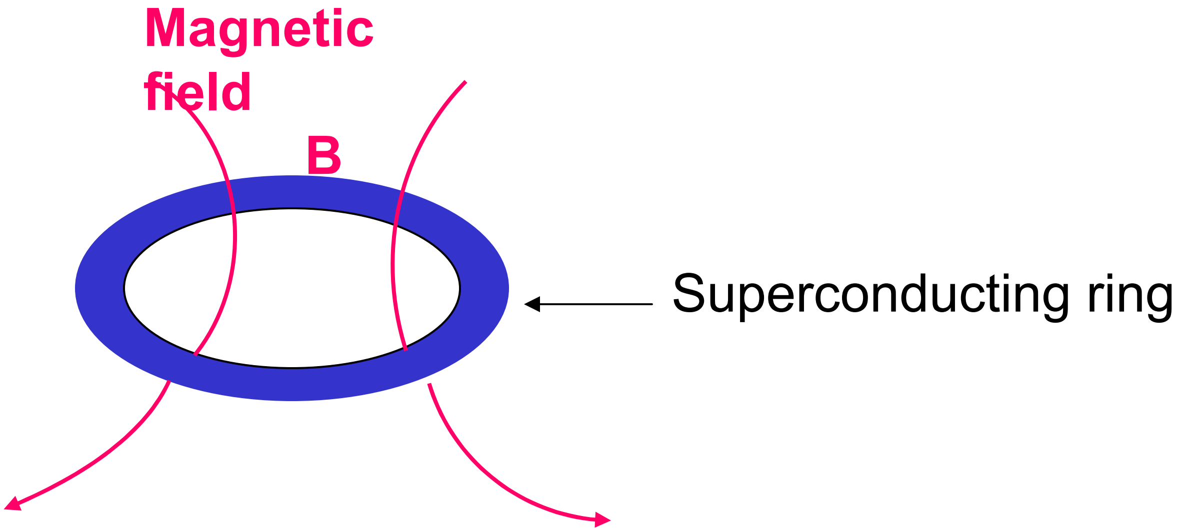




$\psi = |\psi| e^{i\theta(r)}$

At nonzero temperature, pairs are mixed with unpaired electrons.

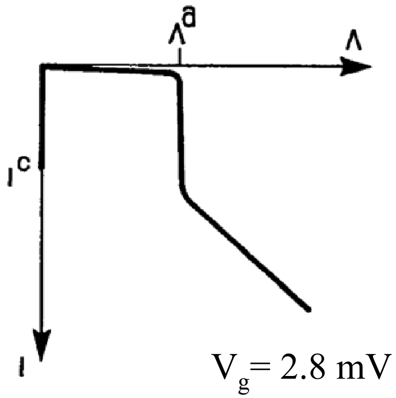
Magnetic Flux Quantization



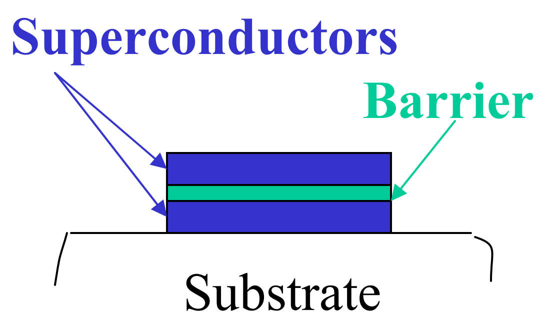
In superconductors, magnetic flux is quantized in units of

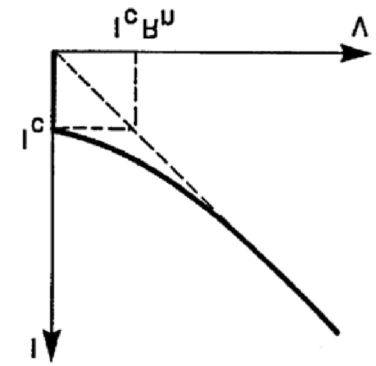
$$\Phi_0 = h/2e = 2.07 \times 10^{-15} \text{ weber}$$

TYPES OF JOSEPHSON JUNCTIONS

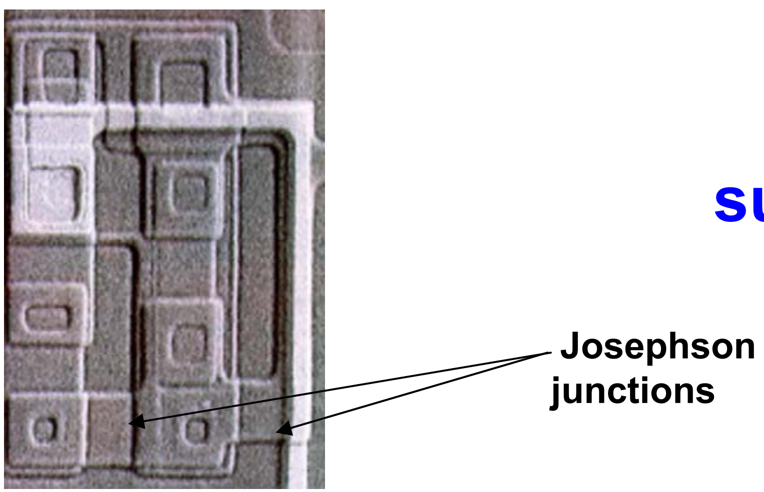


Tunnel junction





Conductive barrier junction



Thin-film superconductor integrated circuit

EXISTING APPLICATIONS

COMMERCIAL

- Cellular base stations
- Volt standard
- Ultra-sensitive magnetometers
- NMR detector coils

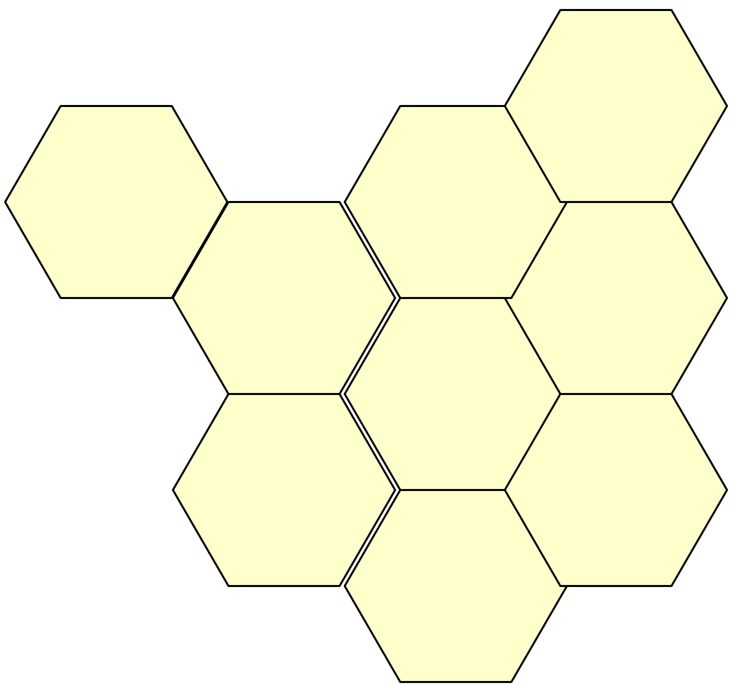
SCIENTIFIC

- Radio astronomy millimeter-wave receivers

Cellular-Base-Station Receivers

with high-T_c superconductor filters

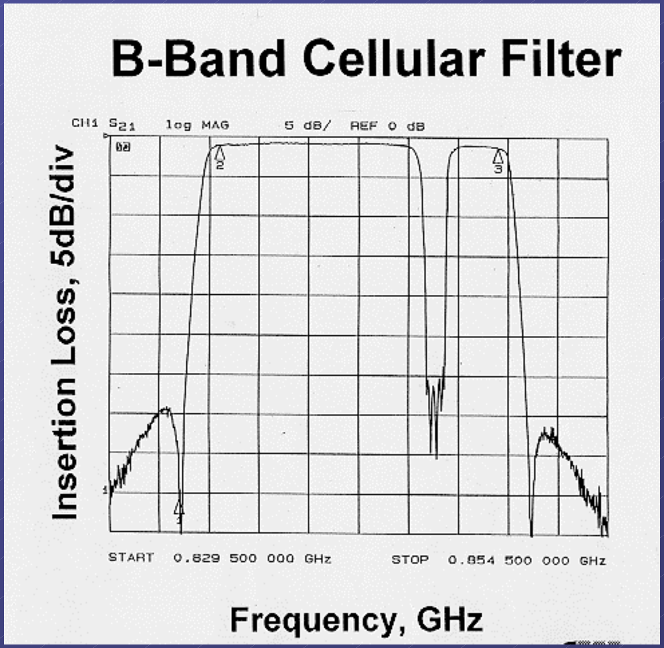
More than 3000 in service, or on order



STI SuperFilter® Systems

SuperFilter® System

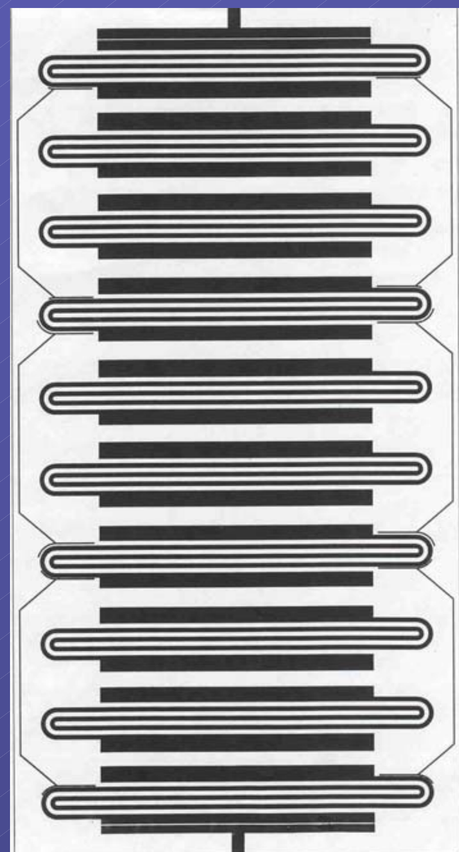
- 12 superconducting preselector filters
- 6 Low Noise Amplifiers
- Cryo-package & controls smaller than conventional

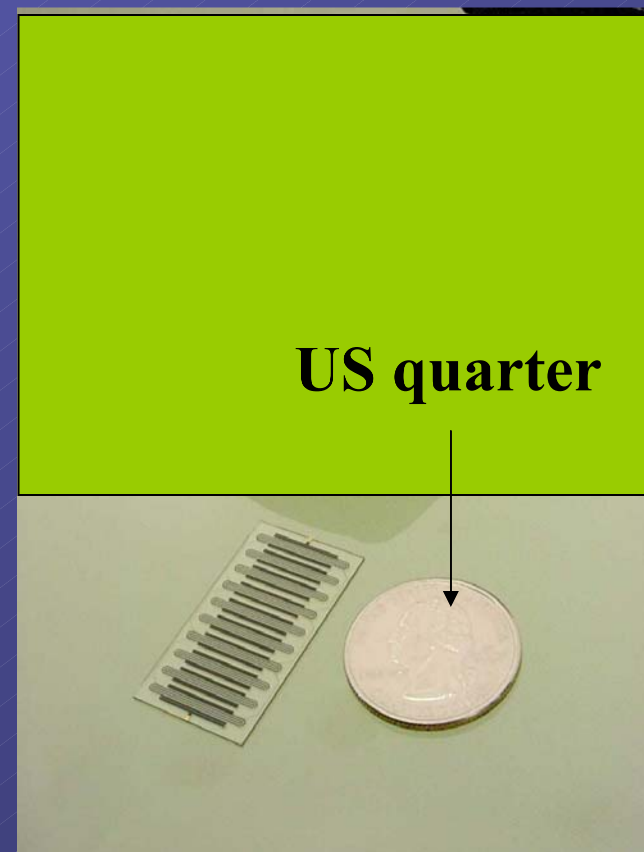


SUPERCONDUCTOR TECHNOLOGIES

High Performance HTS Bandpass Filter

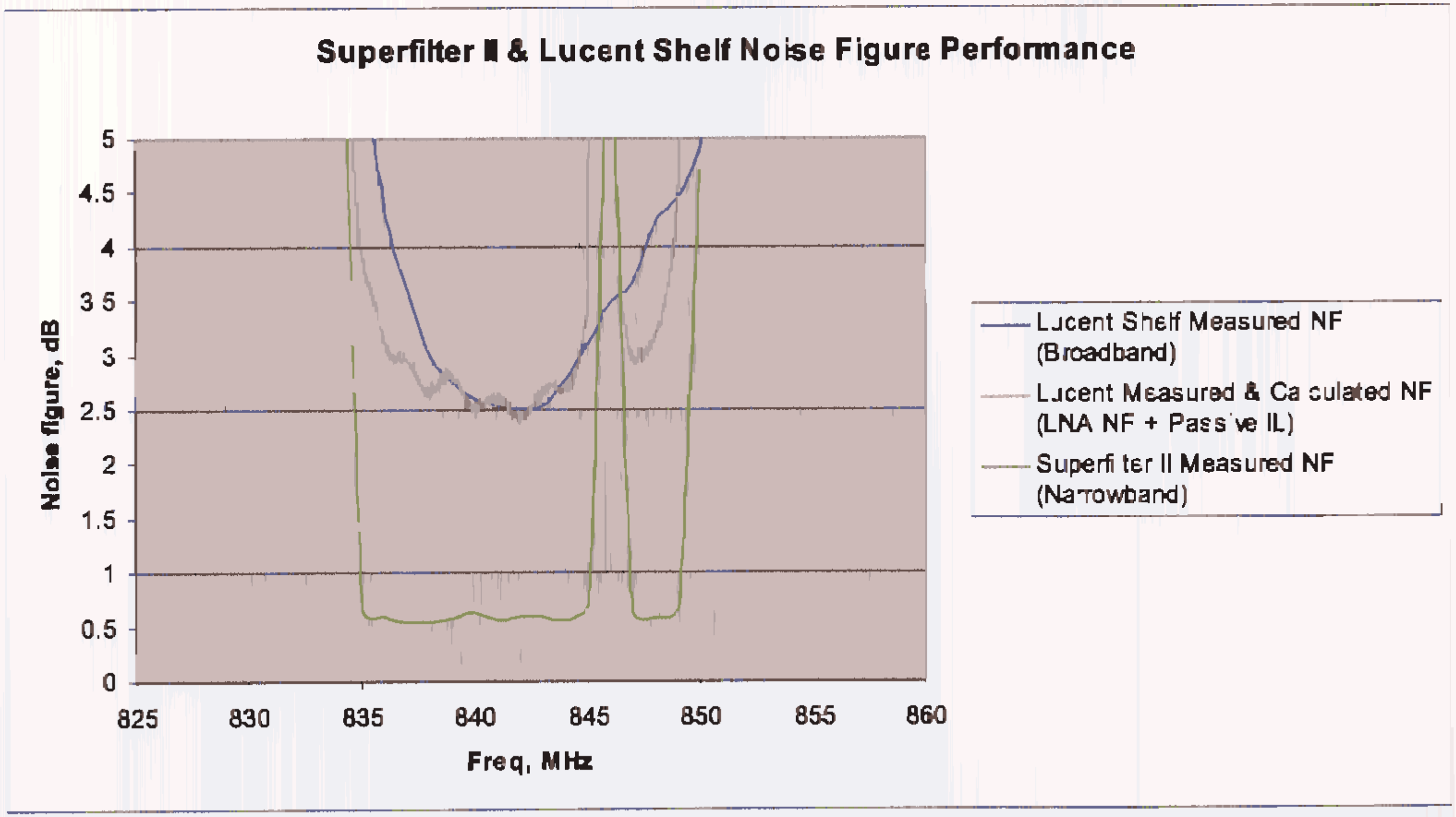
34mm X 18mm Die
10 HTS Resonators
Qu = 80,000
6 Cross Couplings
6 Tx Zeros
High Yield Production



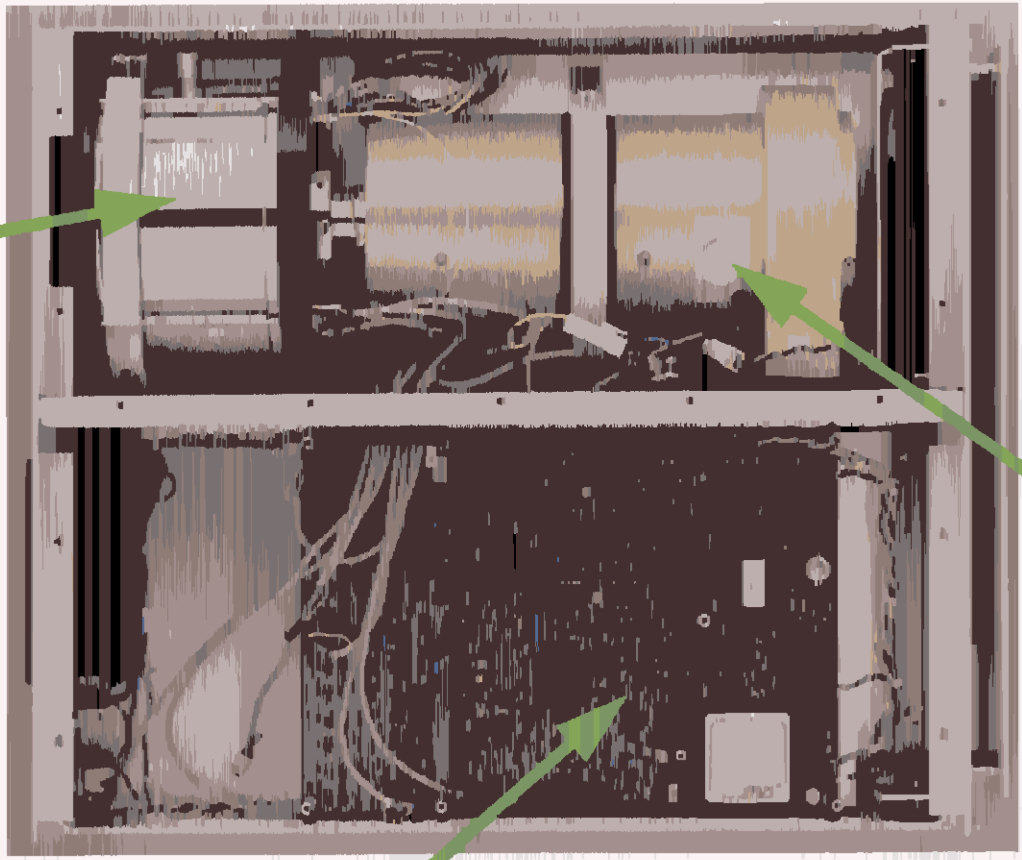


SUPERCONDUCTOR
TECHNOLOGIES

Extremely Low Noise, with High Selectivity



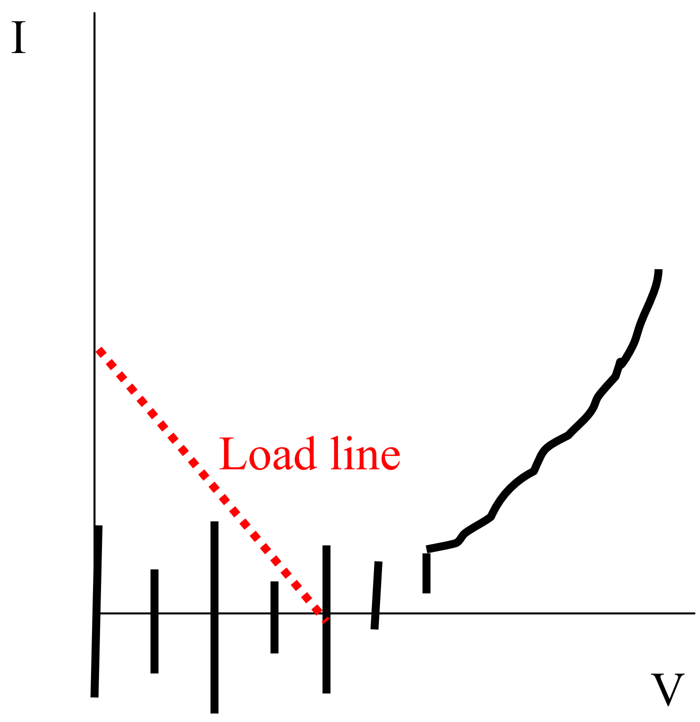
SuperFilter “under the hood”

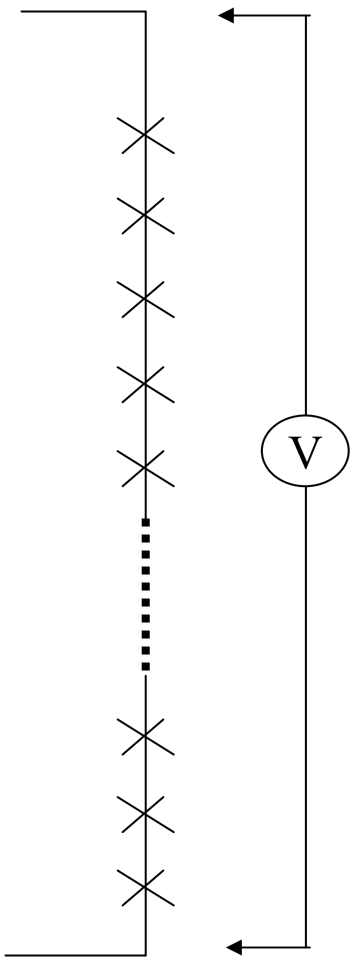


The Volt Standard
using Josephson junctions

About 70 systems in national, industrial, and military standards laboratories worldwide

VOLT STANDARD



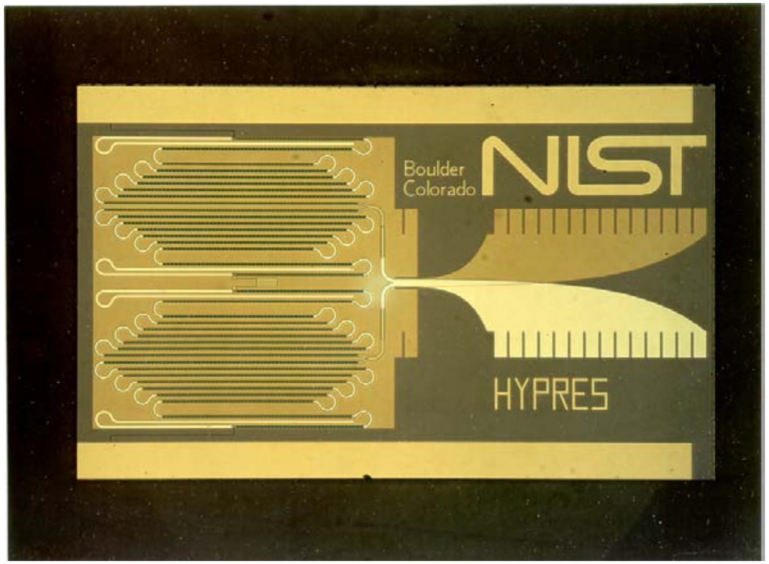


3600 junctions

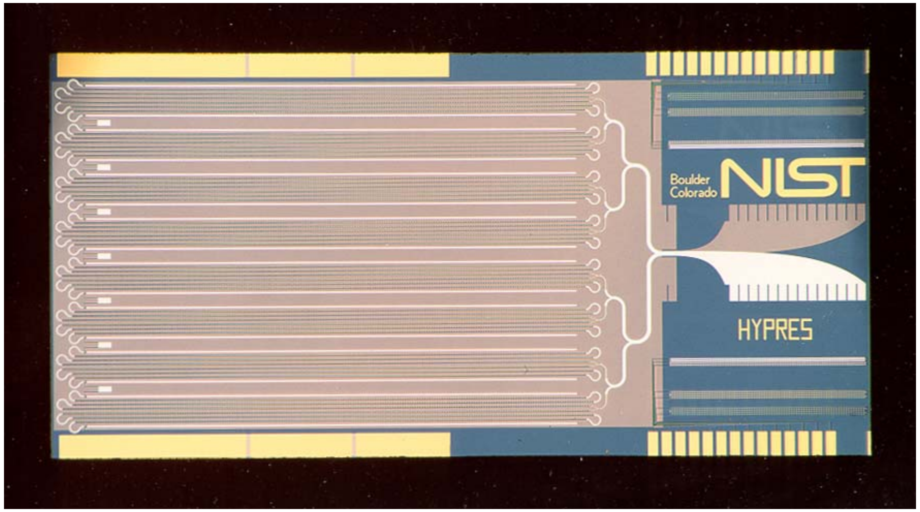
V = n(hf/2e)

-6000 < n < 6000

-1.2 < V < 1.2



1 volt (3660 JJs)



10 volts (20,208 JJs)

HYPRES Primary Volt-Standard System

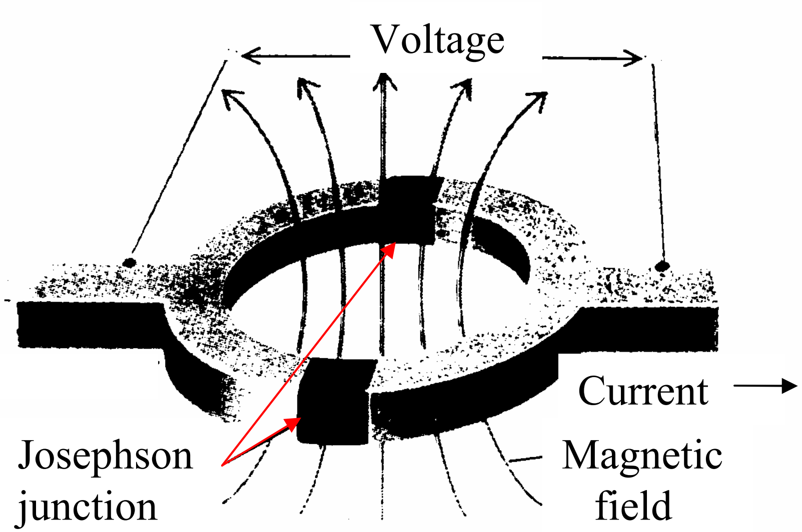
(0.05 ppm)

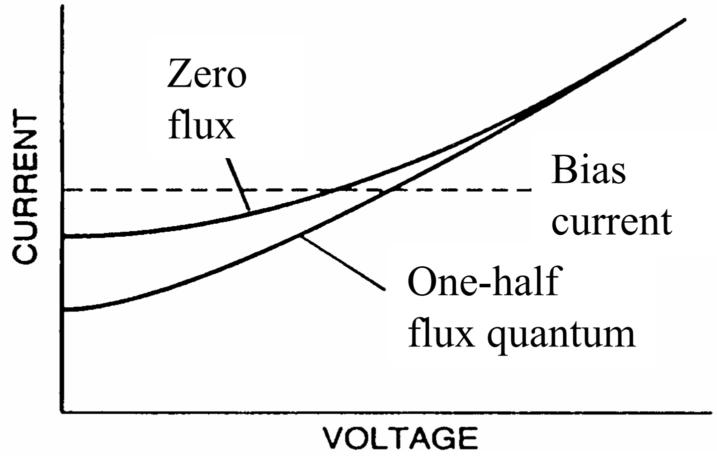
- Closed cycle refrigeration
- Microprocessor controlled

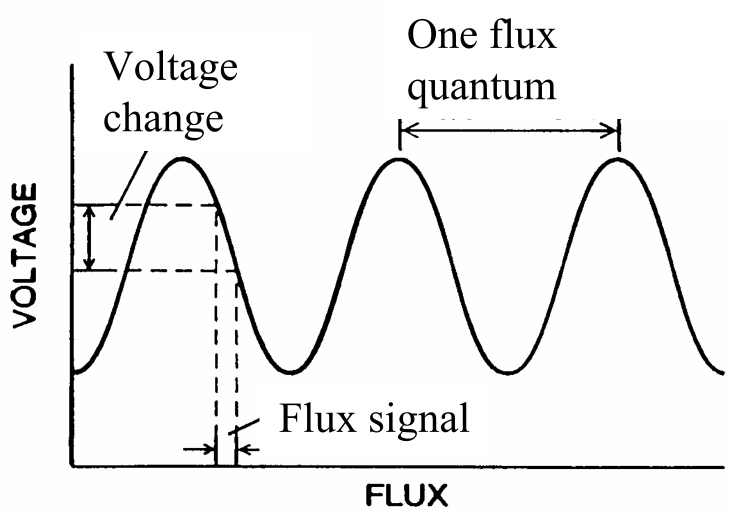
Ultra-Sensitive Magnetometers

(10^{-10} x Earth's magnetic field)

SQUID FLUX-TO-VOLTAGE CONVERSION

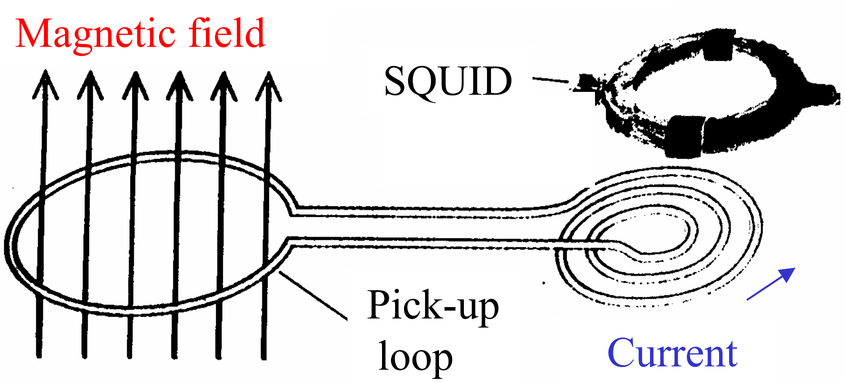




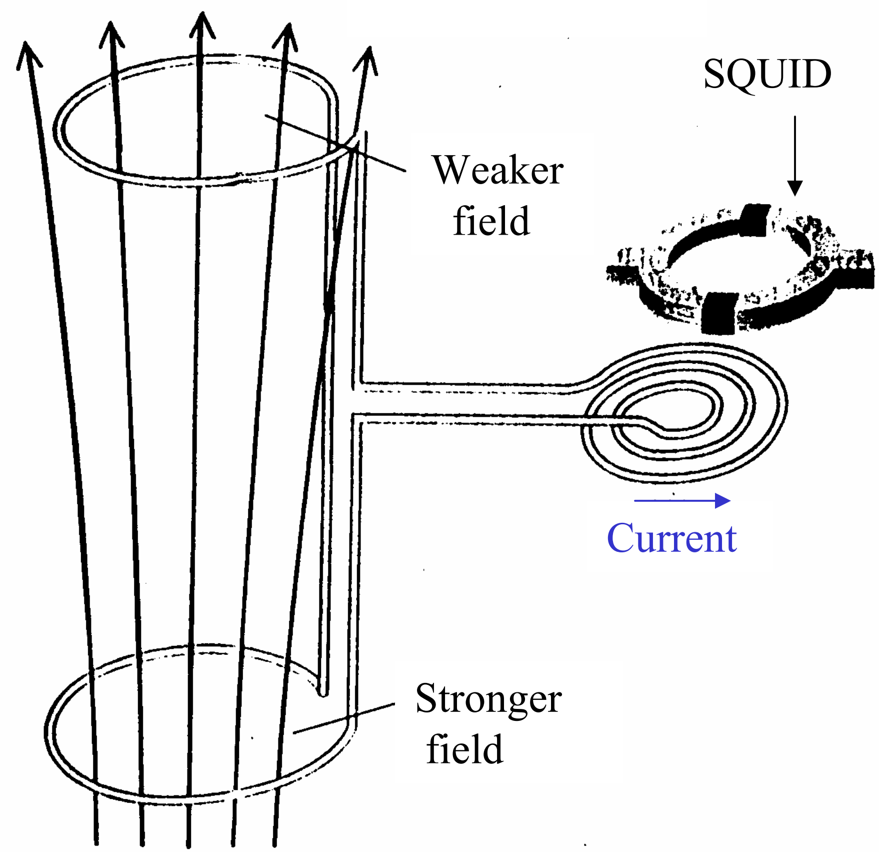


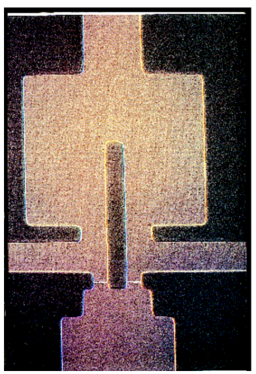
COUPLING FLUX TO A SQUID

Magnetometer

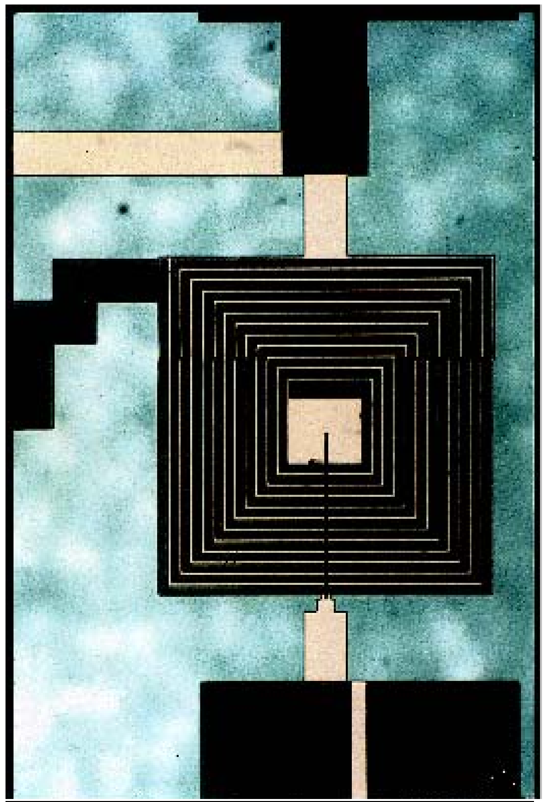


Gradiometer





SQUID



Input transformer

Gradiometer

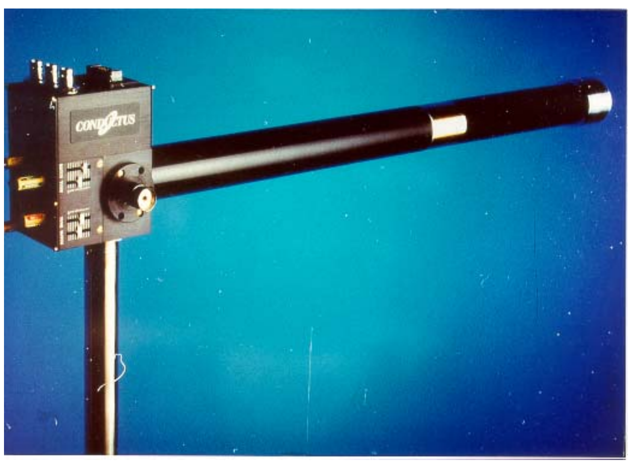
Laboratory SQUID Systems

iMAG® components

LTS Measurement System

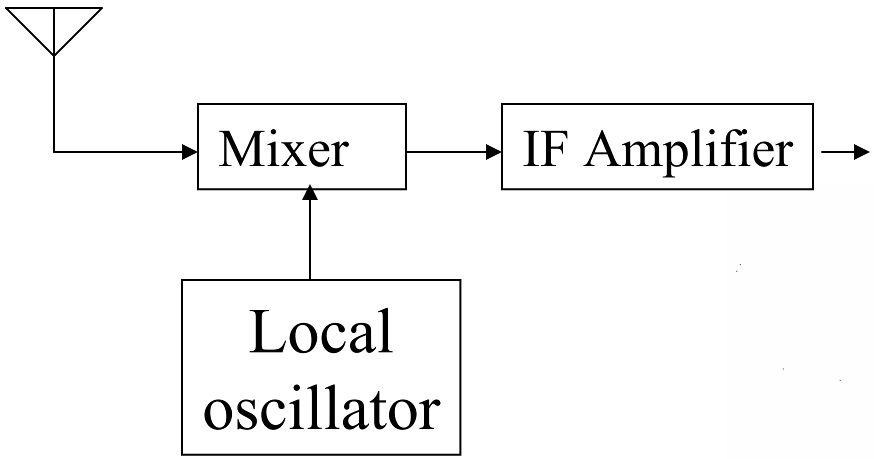
MPMS Susceptometer

NMR sensitivity enhancement with HTS probe coil



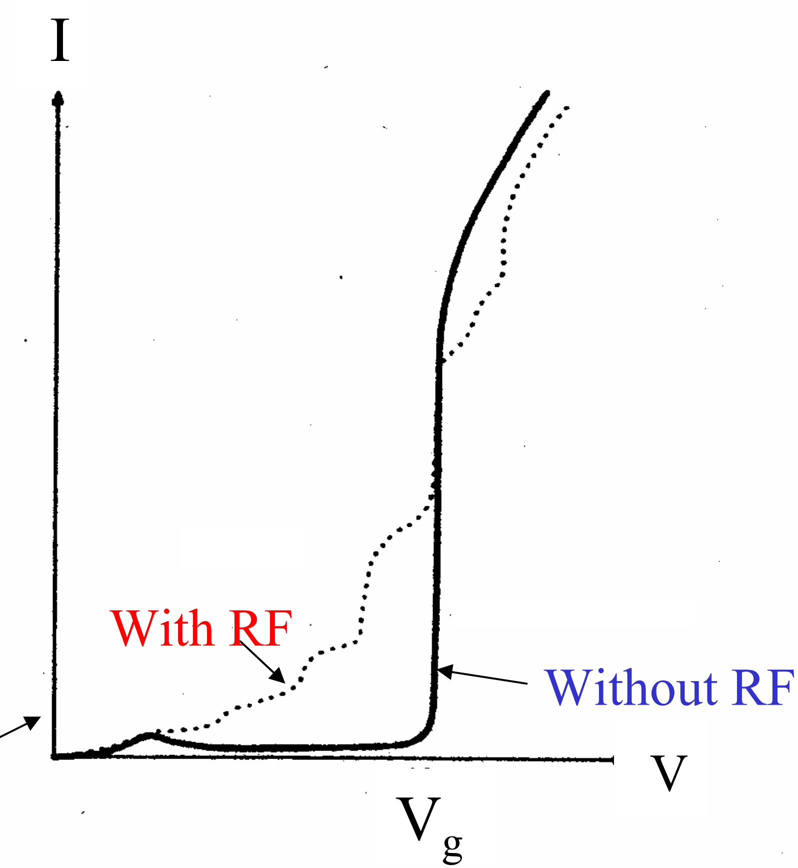
Radio Astronomy
Millimeter-Wave Receivers

SIS Tunnel Junction Mixing



Receiver noise temperature

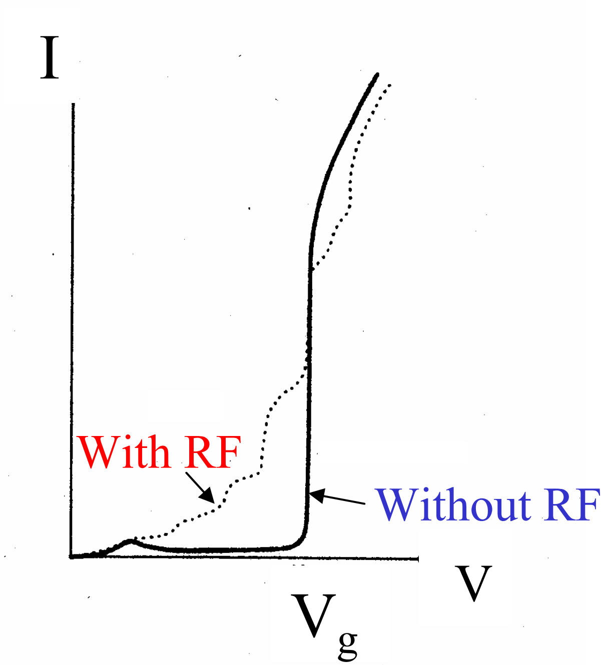
$$T_R = T_{mixer} + T_{IF}/G_{mixer}$$



- **Low mixer noise T_{mixer}**
- **Conversion gain G**

Josephson pair current
is suppressed by magnetic field

Millimeter Wavelength SIS Mixing



Currently 75 SIS mixers

Array under construction in Chile----900 SIS mixers

Radio Astronomy Array at Hat Creek, CA

Two receivers/antenna with SIS mixers 80-116 GHz and 220-270 GHz

Emerging Medical Applications of SQUID Systems

Heart, brain, lungs, liver, nerves,
skeletal muscle, stomach, intestines, eyes, etc.

Detection of fetal heart arrhythmia

Magnetocardiography (MCG)

(Mapping, imaging, and localizing heart magnetic activity)

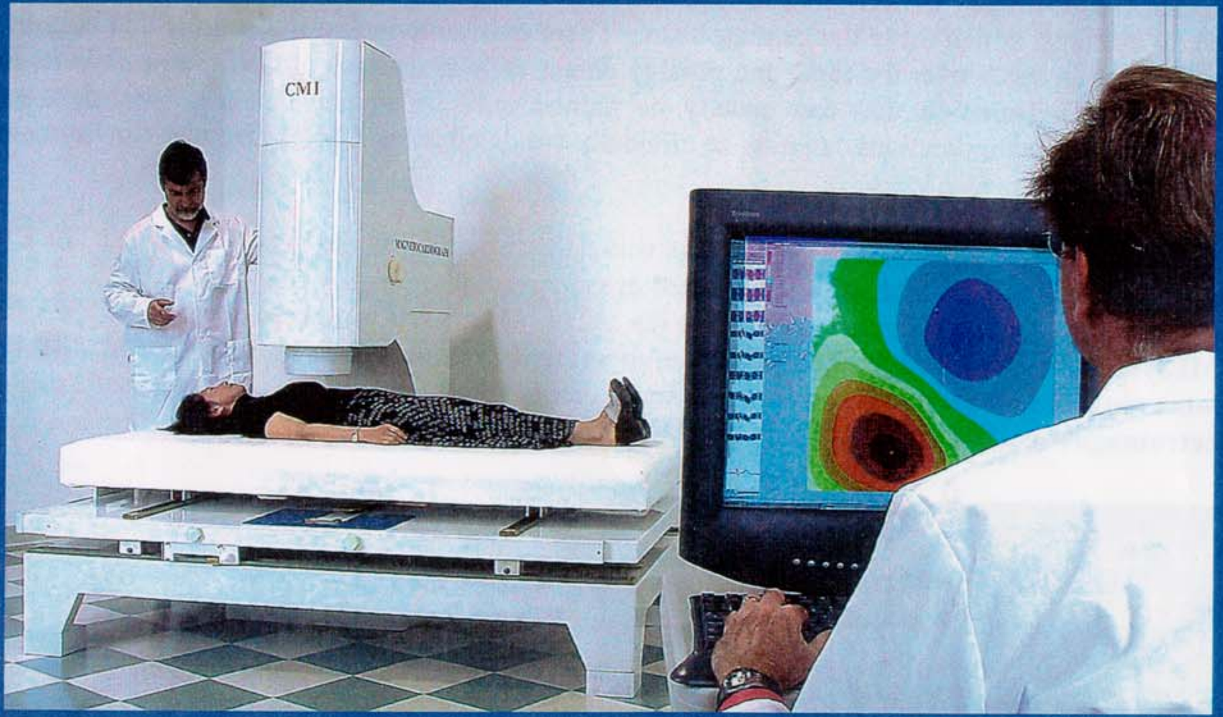
Ten-minute MCG Test

provides

Accurate Diagnosis

helping physicians

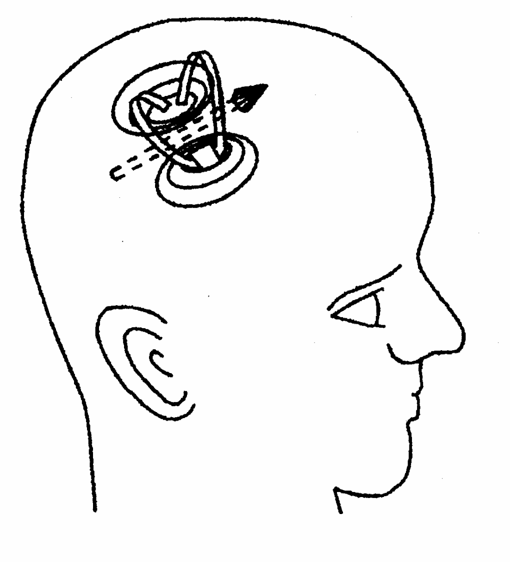
SAVE LIVES



CardioMag Imaging, Inc.

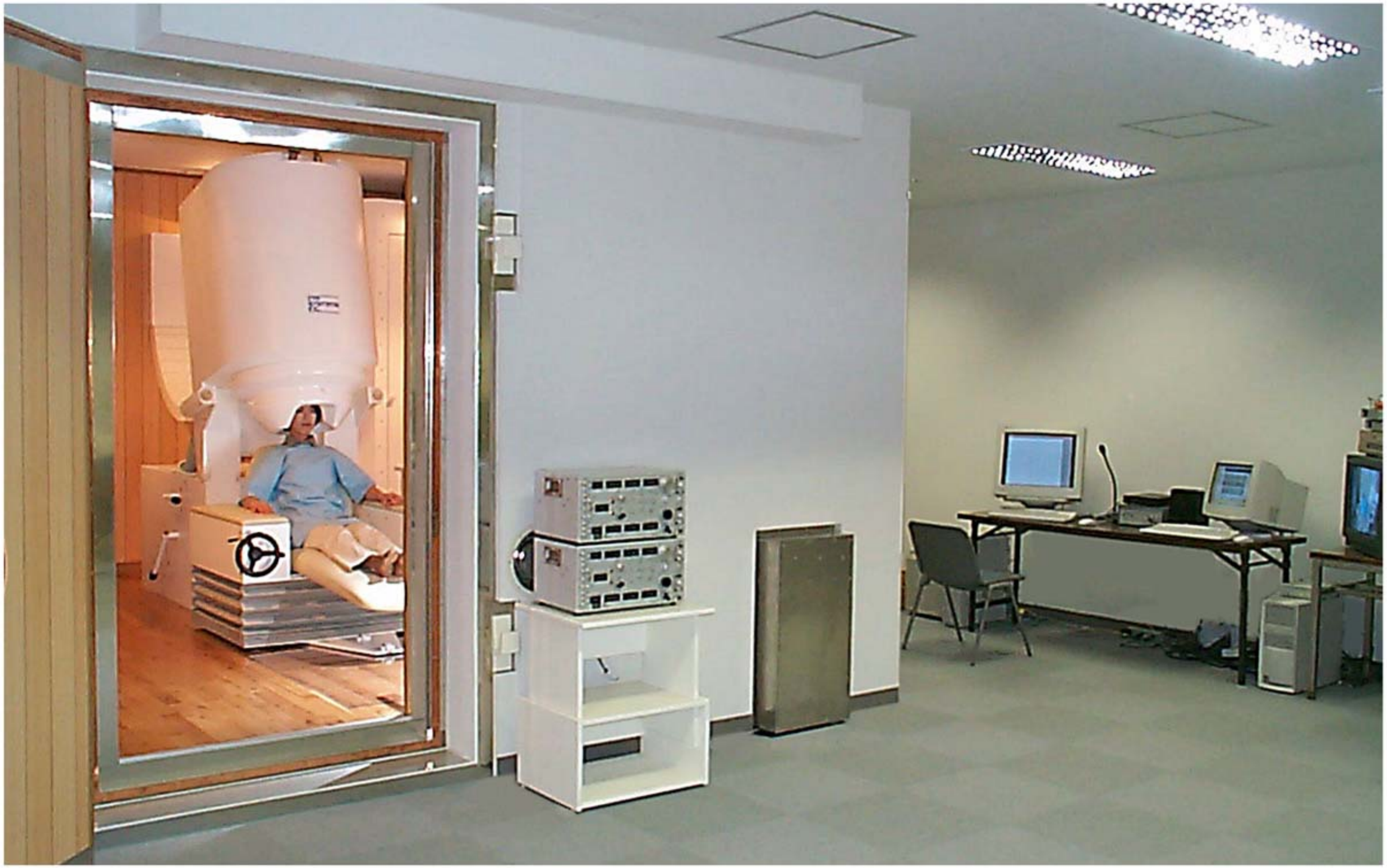
Magnetoencephlography (MEG)

Measurement of magnetic fields produced by currents in the brain



151 Channels

CTF Systems, Inc.



2618-J.V. Oct 01

CTF Systems Inc.
A Subsidiary of VSM MedTech Ltd.

Applications of MEG

- Pre-surgical mapping
- Localization of epileptic seizure foci
- Detection of slow waves associated with stroke, head trauma, and transient brain ischemia

Digital and analog-to-digital circuits

Superconducting single-flux-quantum circuits
for speeds beyond semiconductors

Toward Higher Speed Digital Electronics

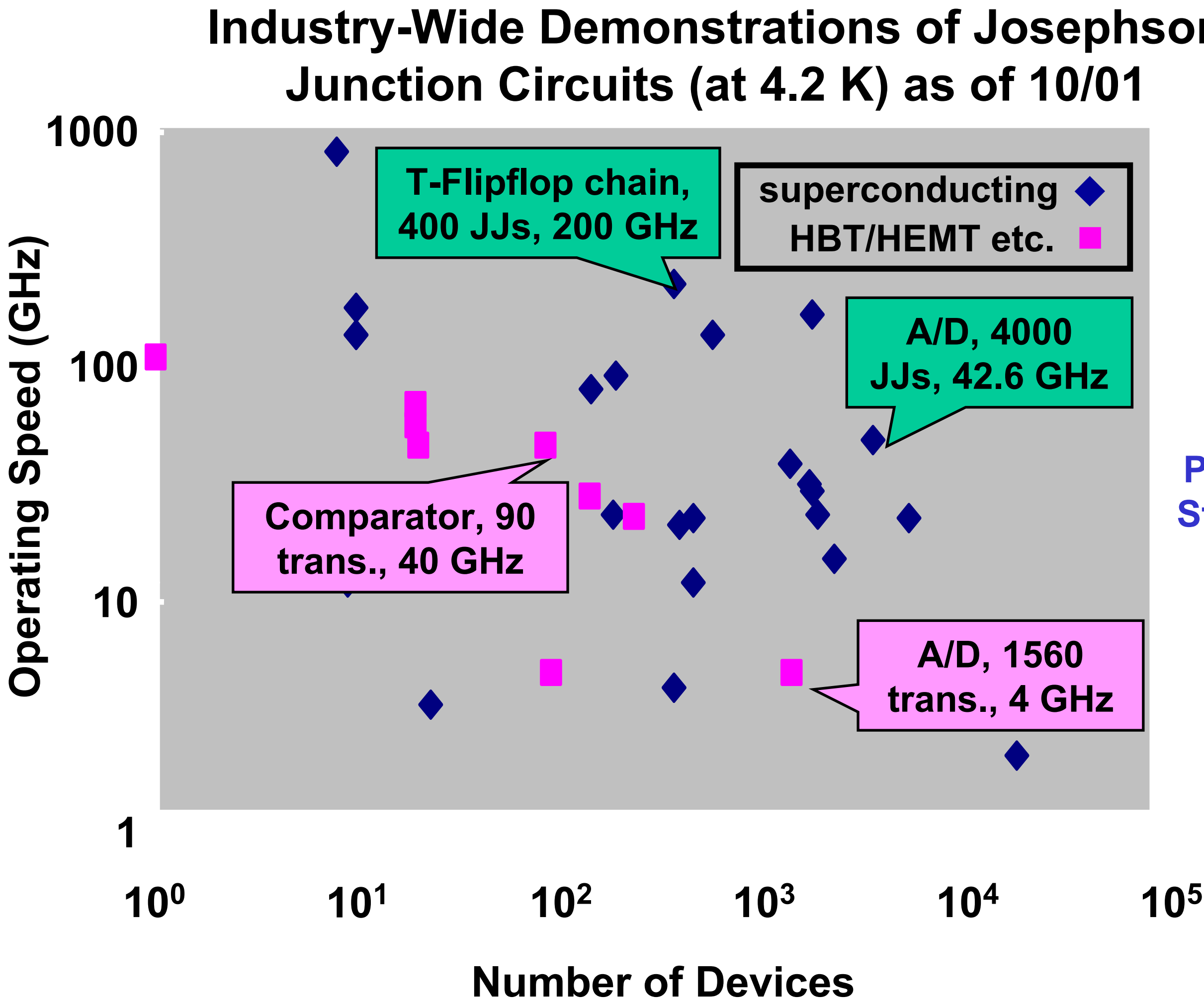
CMOS processor speed increase limited by:

- Shrinking gate oxide thickness
- Interconnect RC increase in scaled circuits
- Chip power dissipation
- Expense of fabricating smaller features

On the horizon for higher speed:

- Still some speed improvement for CMOS
- Compound semiconductor can give higher speed
  but gate count limited by power dissipation
- Nano-devices (incl. SET) will be slow
- Superconductor electronics

Overview of Superconductive Electronics



SOURCES

Superconducting

Hypres
TRW
Berkeley
Hitachi
IBM
Lincoln Laboratory
NEC
Northrop-Grumman
Phys.-Tech.-Bundesanstalt
State University of Moscow
U. of Stonybrook
U. of Rochester

HBTs/HEMTs

UCSB
Hughes
Lucent
CalTech
Conexant
JPL
GTRAN
IQE
NTT

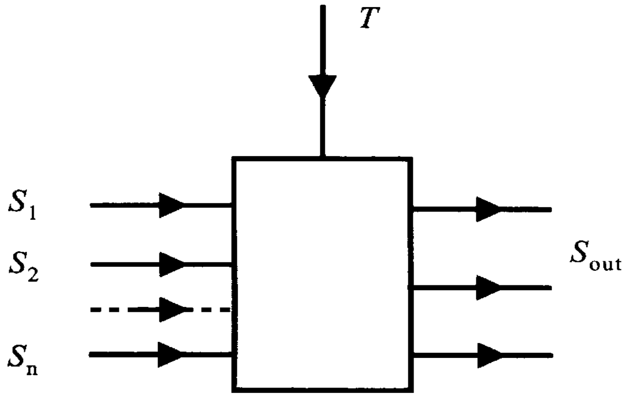
See comments on next slide

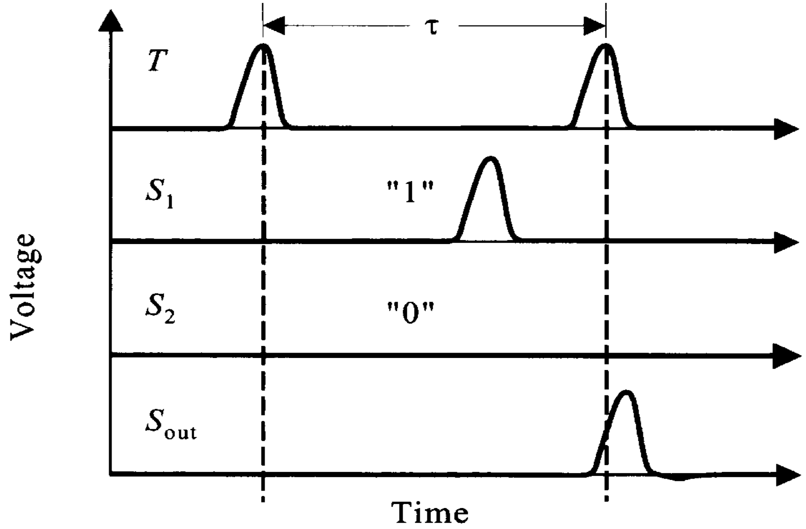
Demonstrations of High-Speed Circuits

(RE: Previous slide)

- Determined speed using only fastest elements
- Junction counts compared to transistor counts directly
- Some integration-scale numbers were estimated
- Includes digital and mixed-signal circuits
- List may still be incomplete

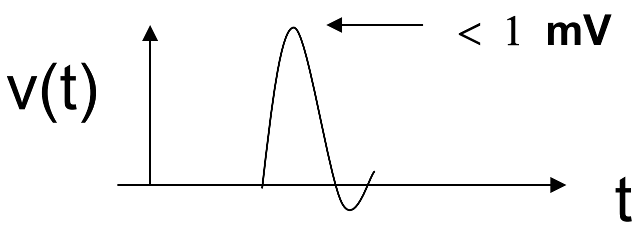
Rapid-Single-Flux-Quantum (RSFQ) Logic





Picosecond-scale pulses with amplitude less than 1 mV carry data between gates. Clock and data pulses are same.

SFQ Logic Bit Energy



$\int v(t)dt = \Phi_0$

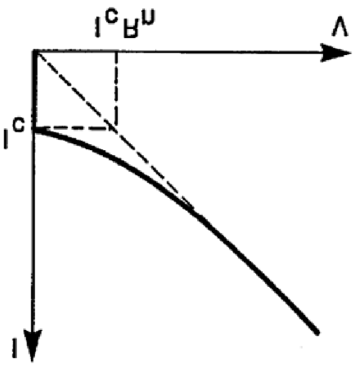
Energy $\cong \int I_c v(t)dt \cong I_c \Phi_0$

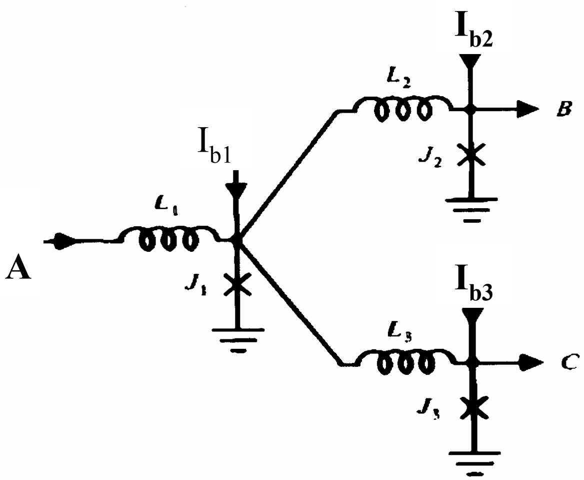
Typical $I_c \cong 0.1$ mA

Energy/bit $\cong 10^{-19}$ joules

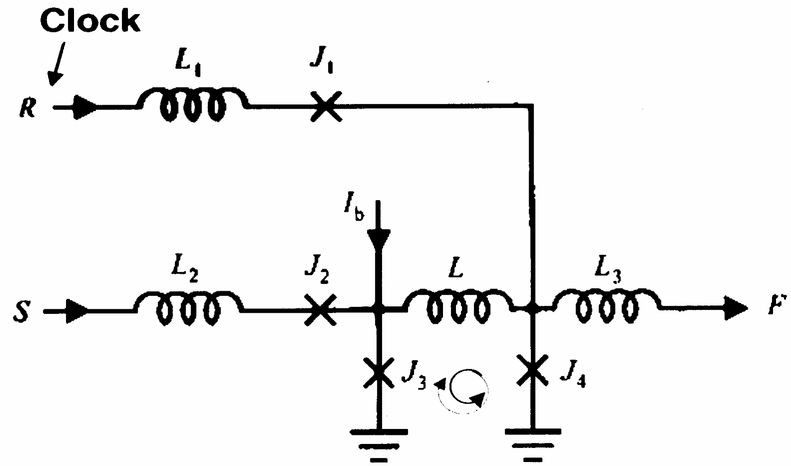
[Advanced CMOS switching energy
$\cong (1/2)CV_{dd}^2 \cong (1/2) \times 10^{-14}$ joules]

Rapid Single Flux Quantum (RSFQ) Circuits (Examples)



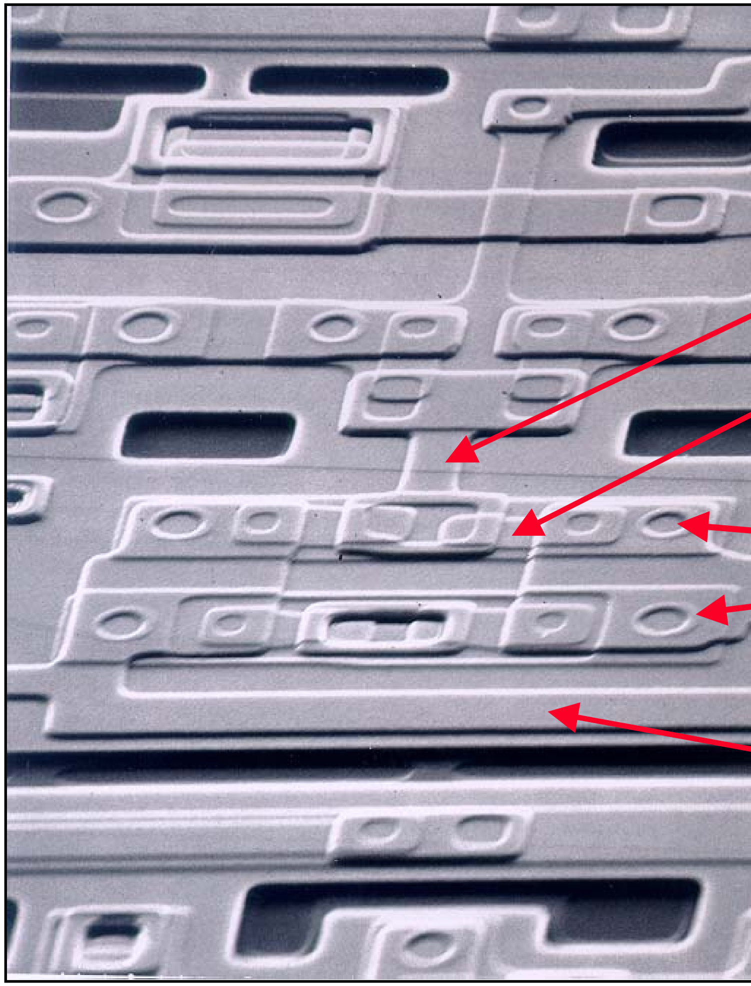


Pulse splitter



Set-Reset flip-flop

RSFQ Gate Physical Layout on IC



Toggle Flip-Flop Layout

Non-storage Inductance (~6 pH)

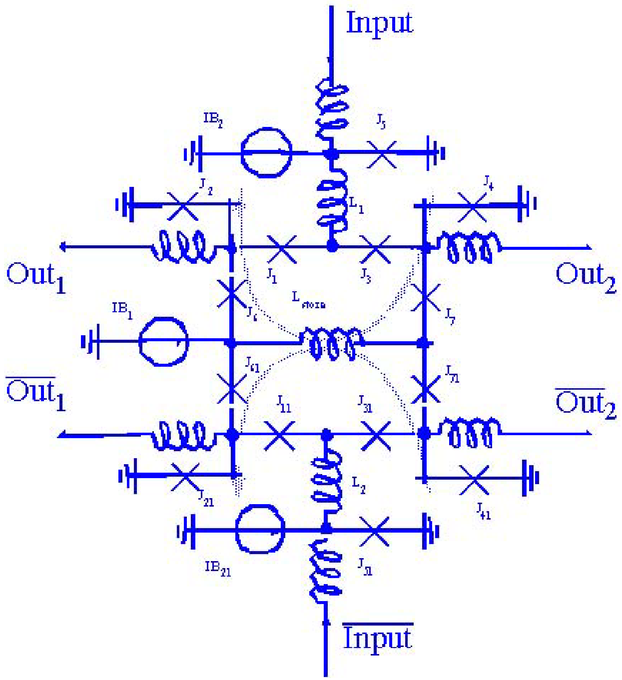
Junction Shunt (~1 Ω)

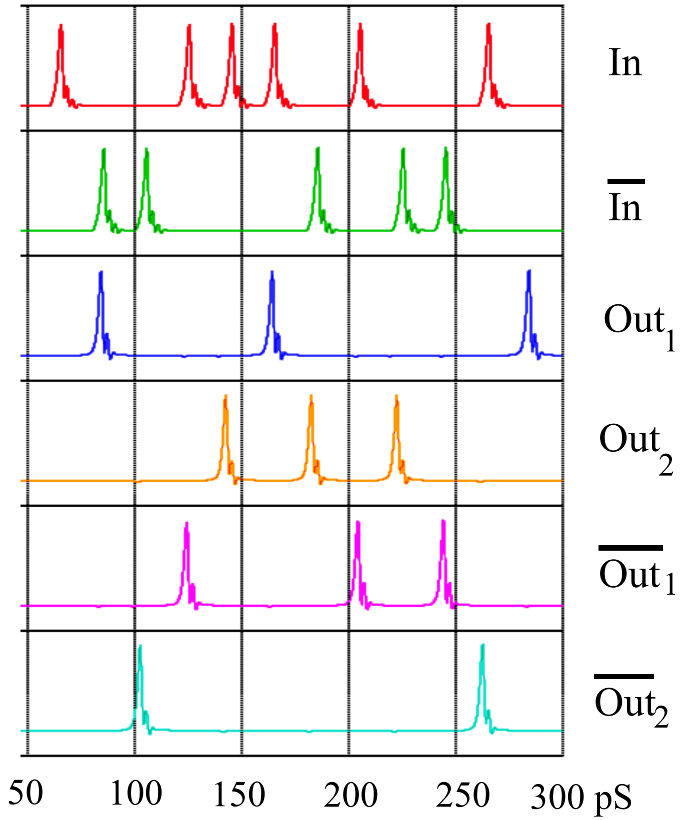
Junctions of different area
(min. area = 3 μm x 3 μm)

Storage Inductance (~12 pH)

HYPRES

2-bit Dual –Rail DEMUX at 50 GHz

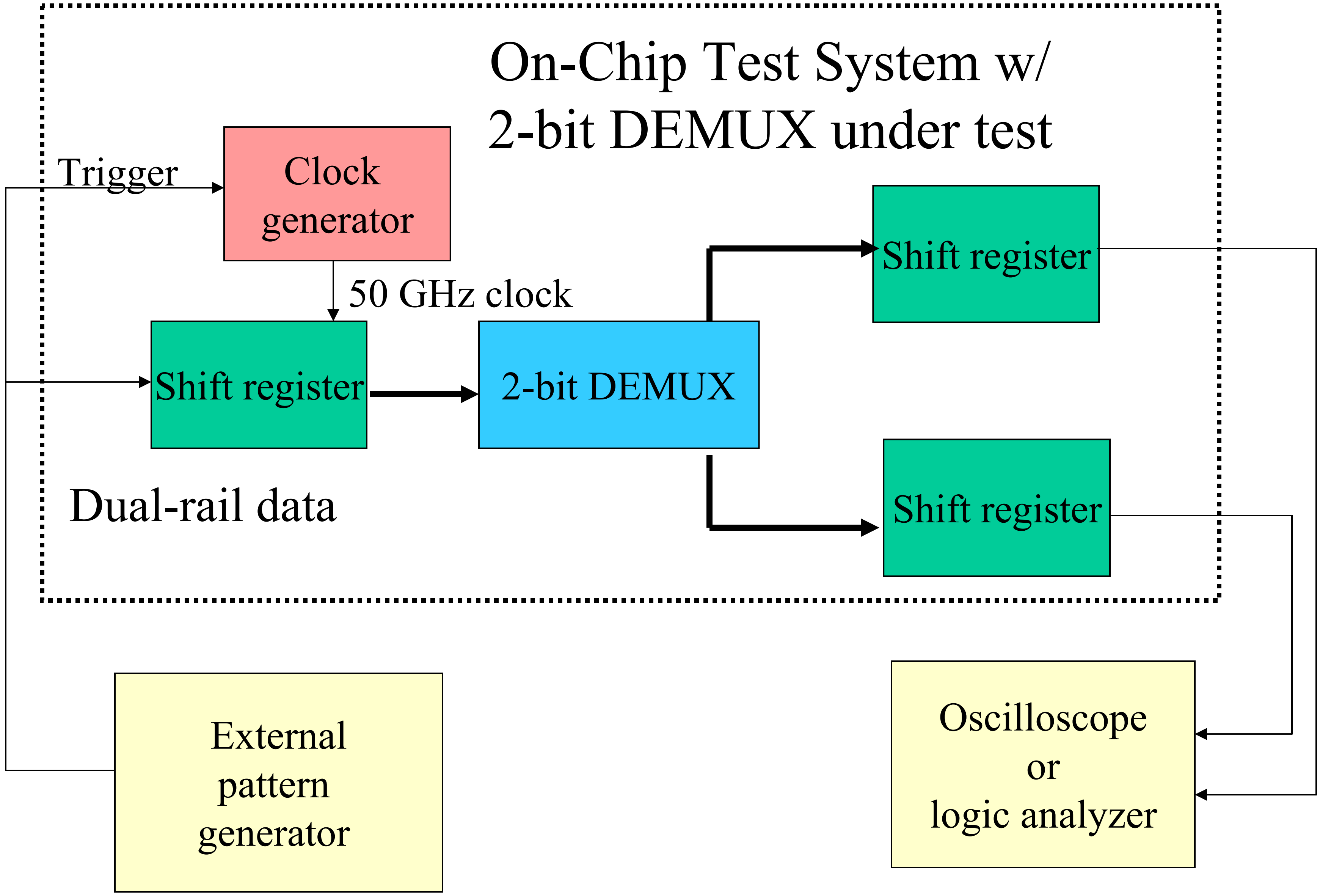




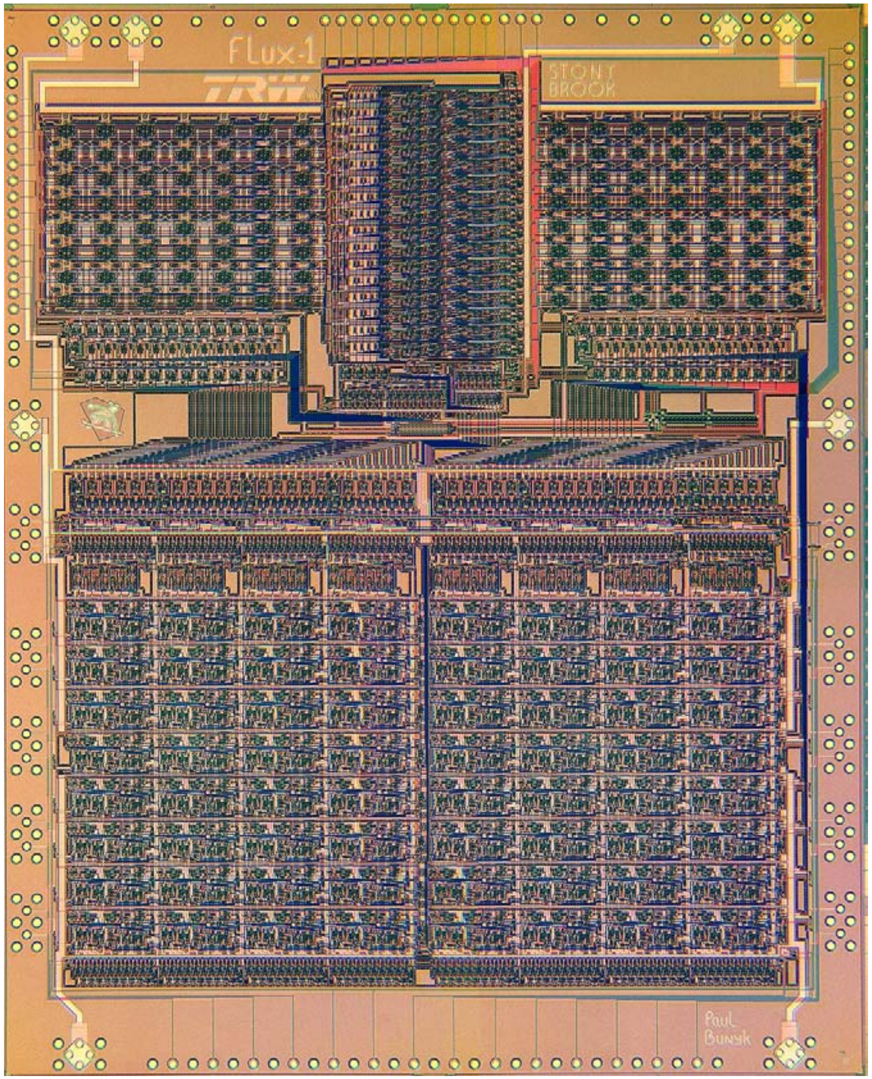
Demonstrated High-Speed RSFQ Circuits

- Record T flip-flop (770 GHz) SUNY, Stony Brook
- Demultiplexer and On-chip Test System (18 GHz)
  UC Berkeley/Yokohama National Univversity
- 4-bit decimation filter (11 GHz) Rochester University
- Clock Recovery Circuit (20 GHz) Conductus
- Shift registers (4-bit @ 60 GHz, 1024-bit @20 GHz) HYPRES
- Decimation Digital Filter (14-bit @ 20 GHz) HYPRES
- Pseudo-Random Bit Sequence Generator (40 GHz), TRW
- 6-bit Spread-Spectrum Modulator (5.4 GHz), Northrop Grumman

50 GHz Digital Test of DEMUX



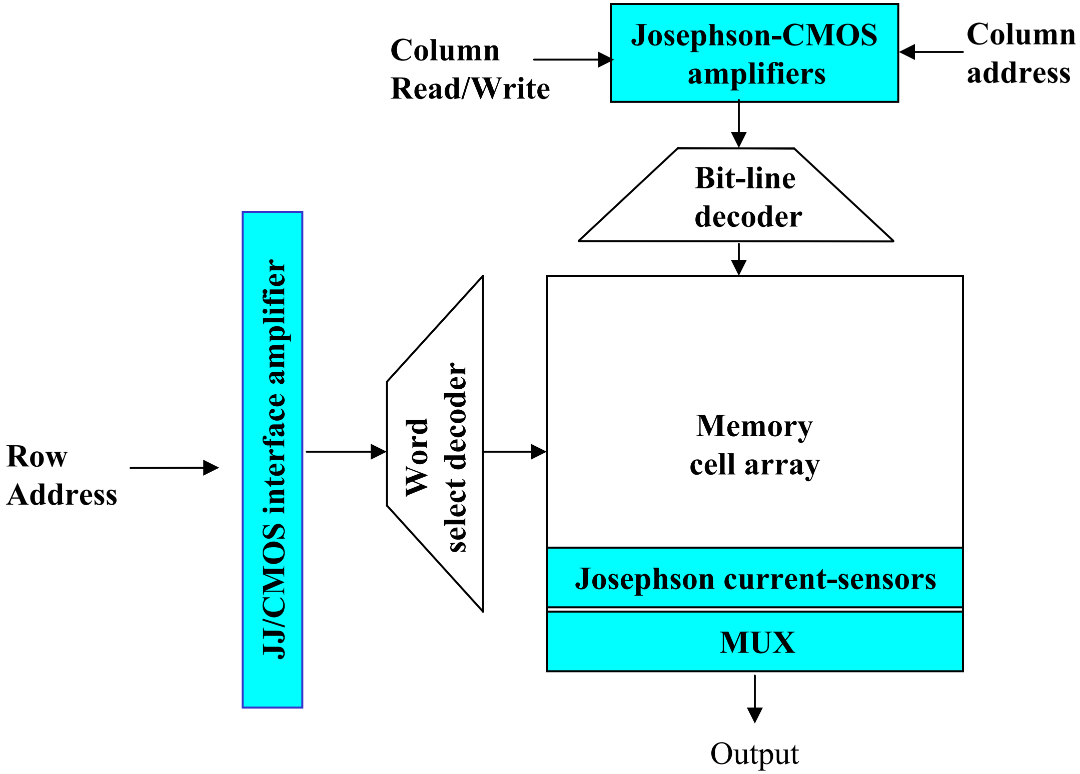
FLUX-1 Demonstration Status



- FLUX-1 chip designed and fabricated (photo at left)
- 10.65 mm x 13.2 mm chip
- FLUX-1 in test
- 1.75 μm, 4 kA/cm^2 Nb technology
- 20 GHz internal clock
- 5 GByte/sec inter-chip data transfer
- Scan path diagnostics included
- 70 K junctions, 5 K gate equivalent
- Power dissipation ~ 5 mW @ 4.5K

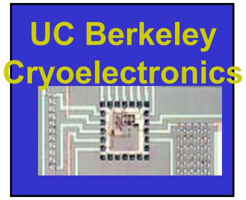
Josephson-CMOS Hybrid Memory

(A potential solution for the memory for Josephson logic)



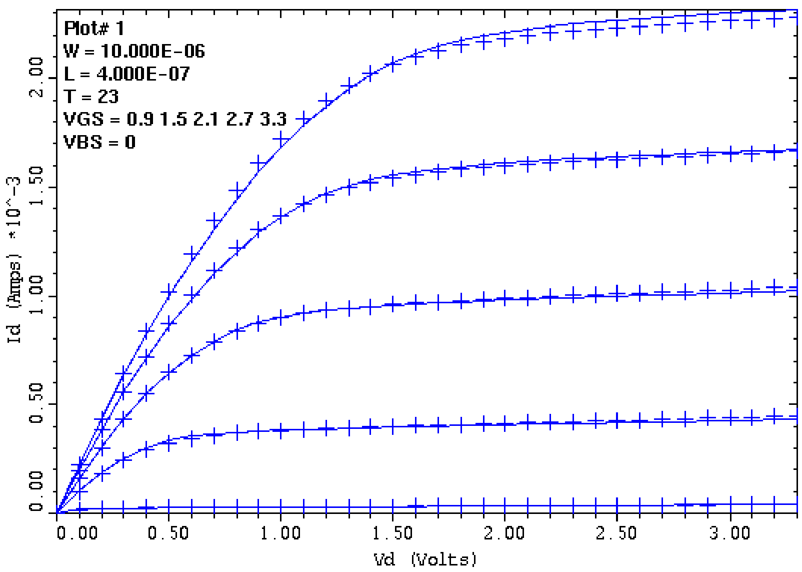
CMOS -- Uncolored

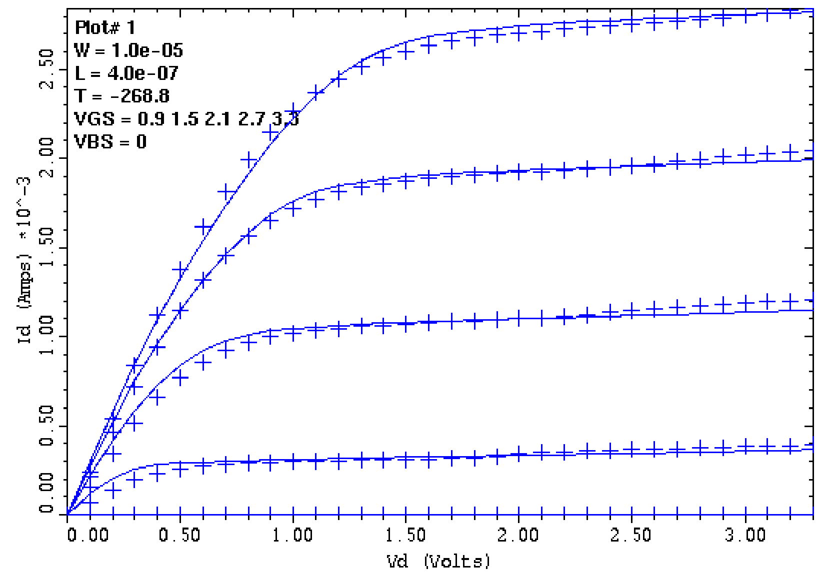
Josephson -- Blue



Project goal: 64-kbit subnanosecond random access memory
(Equivalent Josephson memory requires about 600,000 JJs.)

Parameter Fitting using BSIM3 Device Model





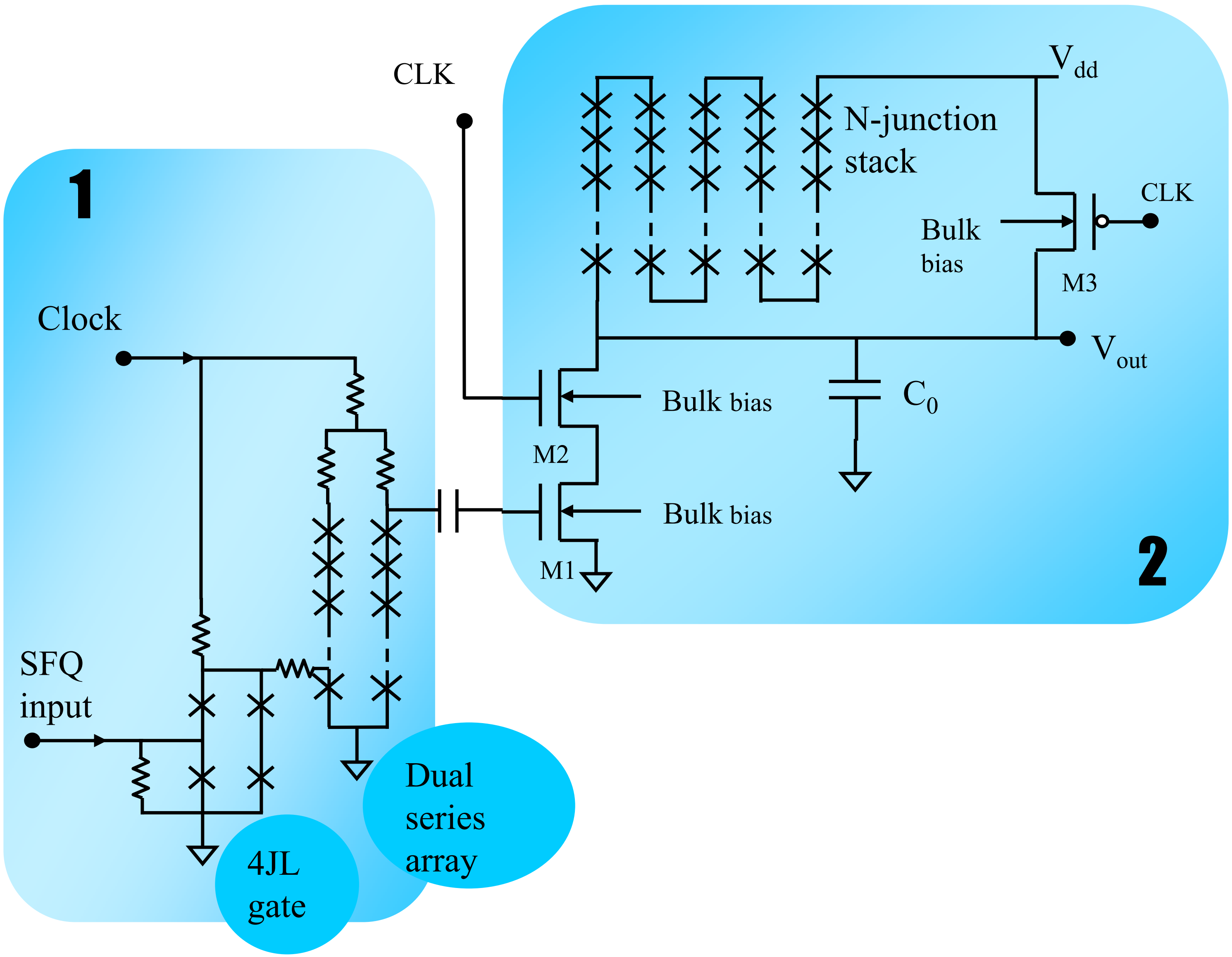
T = 300 K

T = 4.2 K

Rohm 0.35 um process
0.35 um x 10 um

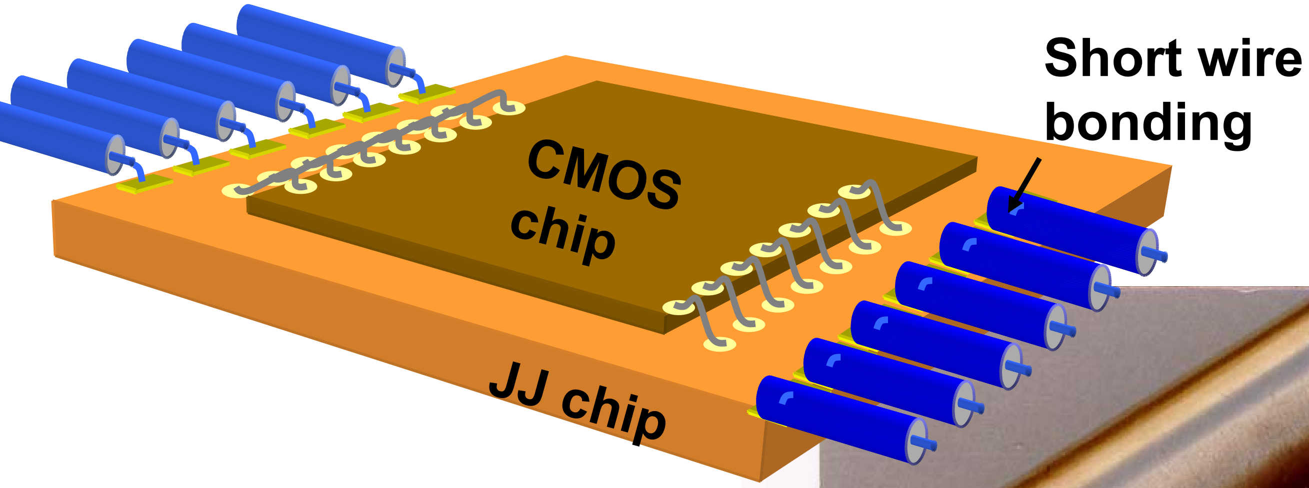
Optimizer: Aurora (Synopsis)

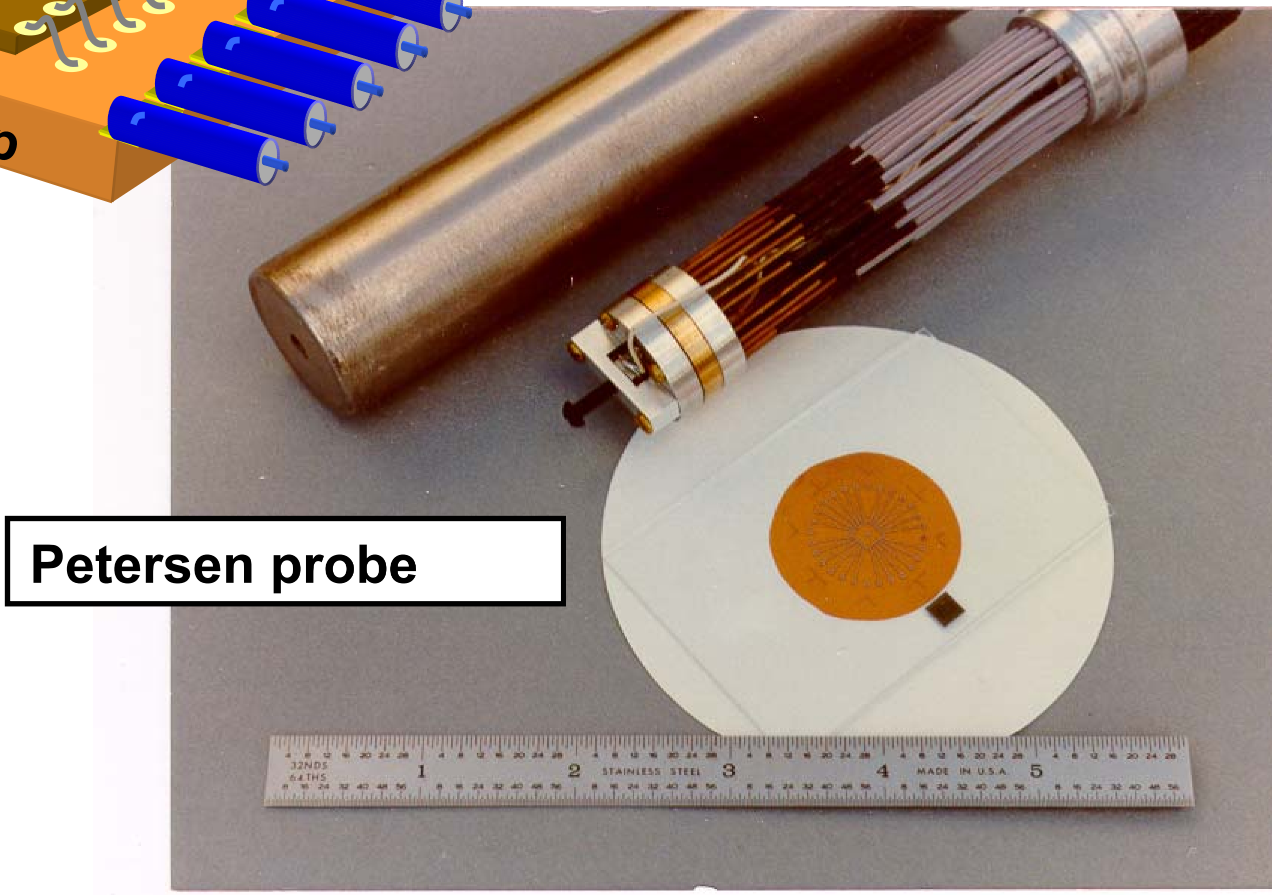
Complete Input Interface Amplifier



High-Speed Test Configuration

Stacked-chip structure

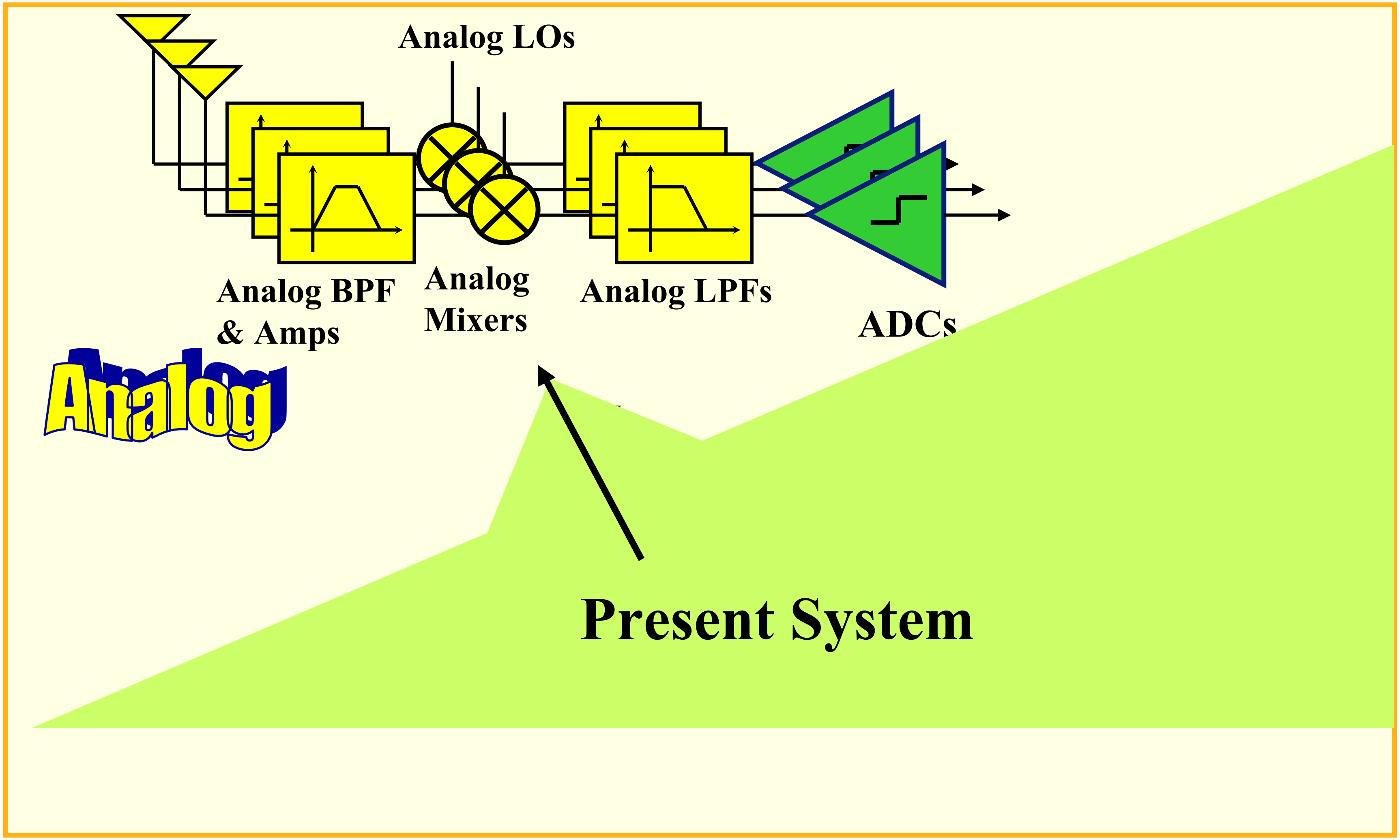




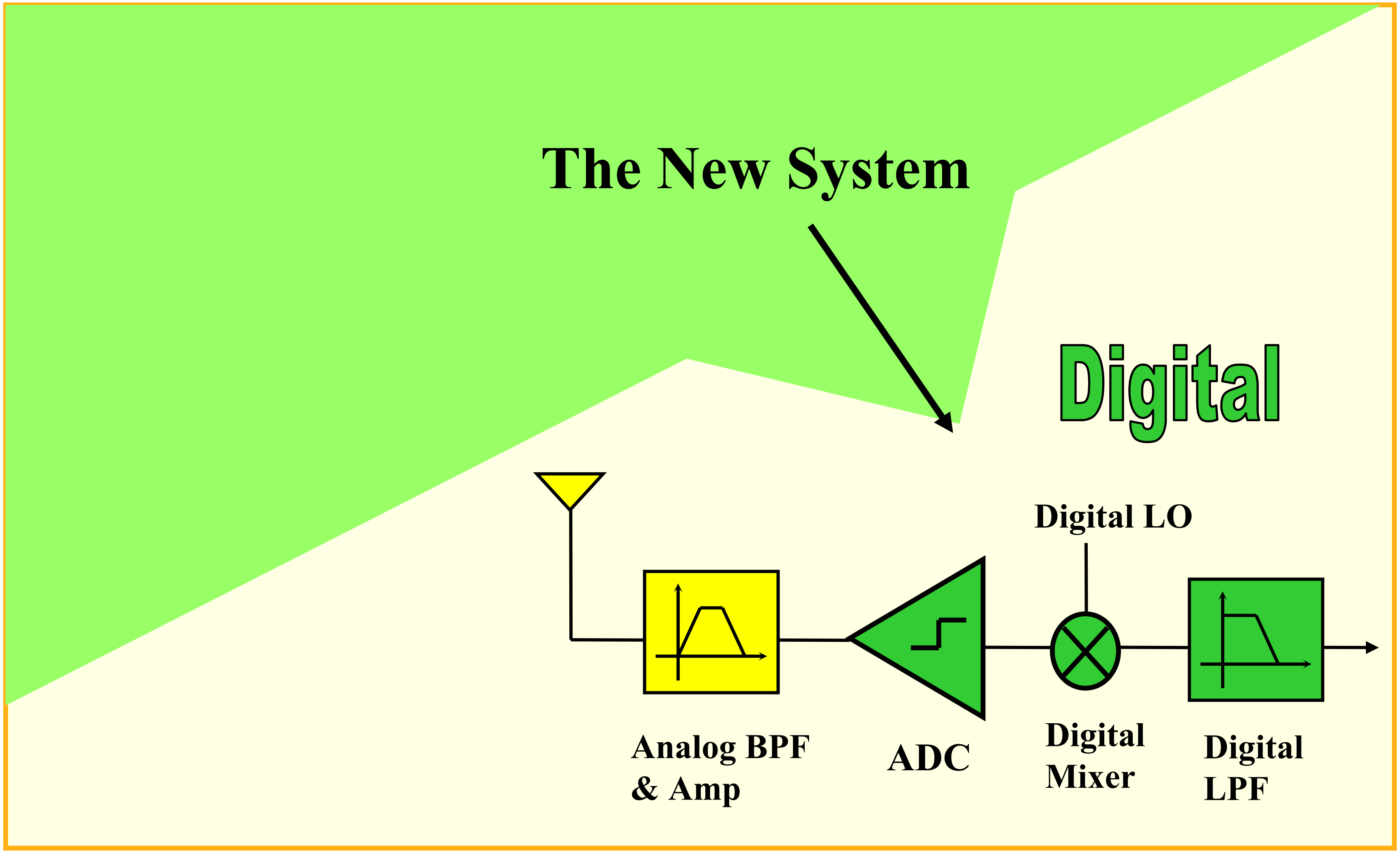
Analog-to Digital Converter

Application to digital radio

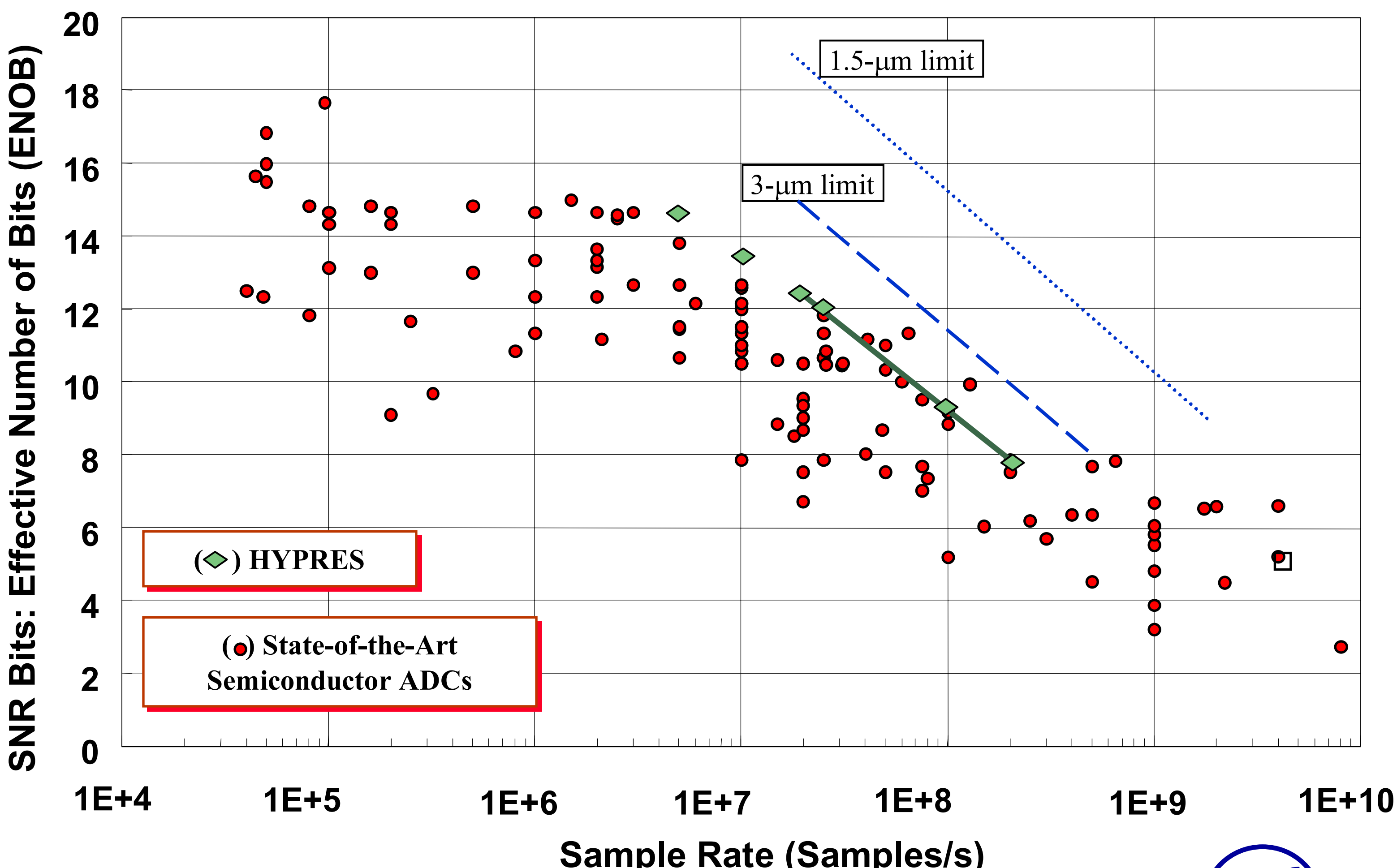
HYPRES


Analog LOs
Analog BPF
& Amps
Analog
Mixers
Analog LPFs
ADCs
Analog
Present System

Objective: *Digital RF*



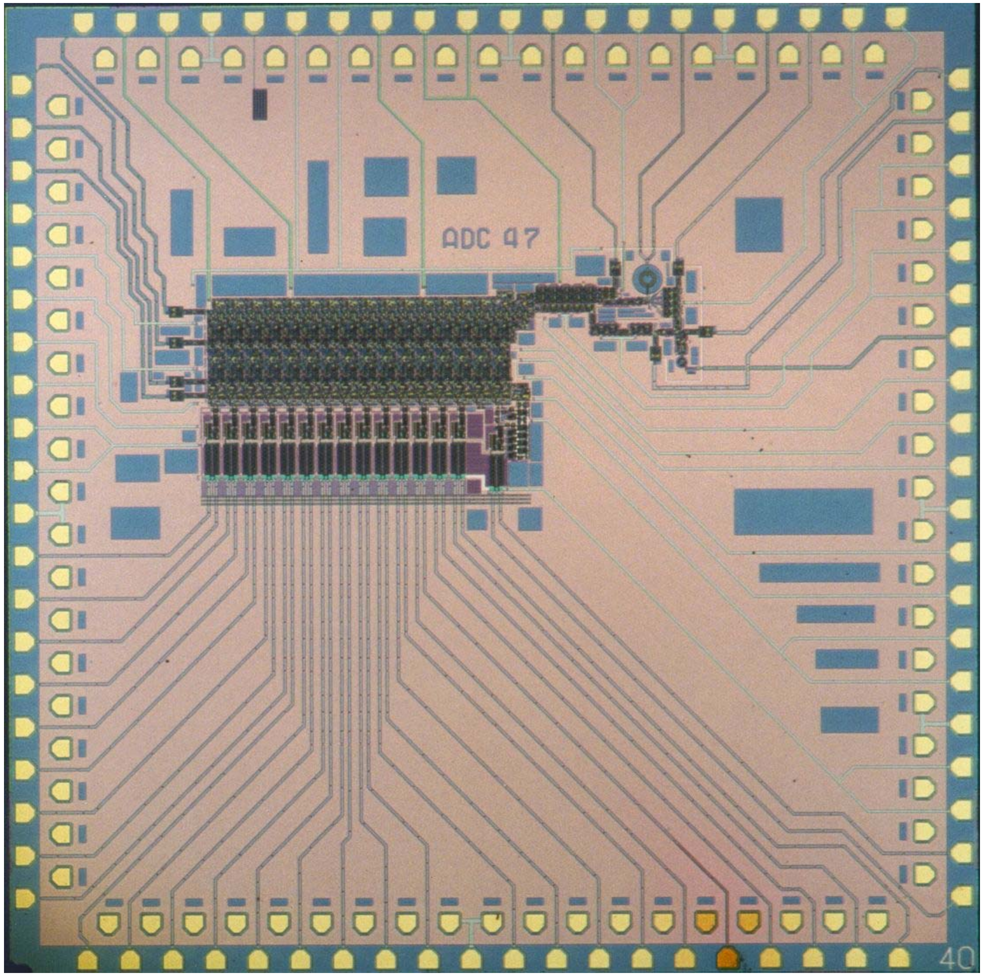
SNR (SINAD) Performance



Data used with permission of Bob Walden, HRL / (310) 317-5895 / walden@hrl.com

HYPRES

ADC Chip (2G Design)



Standard 3.5-um JJ process

1 kA/cm^2

1 cm x 1 cm chip

HYPRES

SQUID Qubit for Quantum Computing

Reason for interest in QC:
Factoring and encription

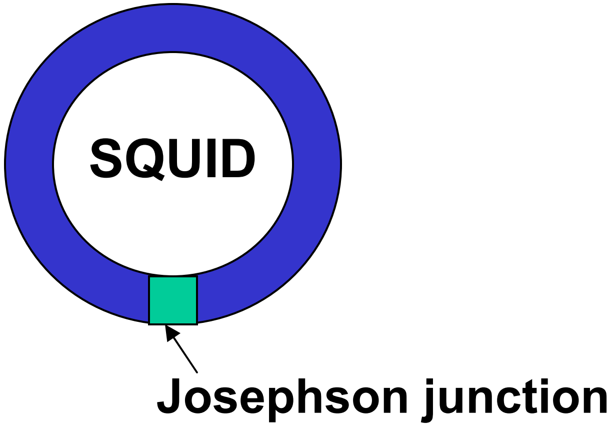
Goal: large number of qubits all entangled quantum mechanically

States must stay coherent for 10^4 x clock period

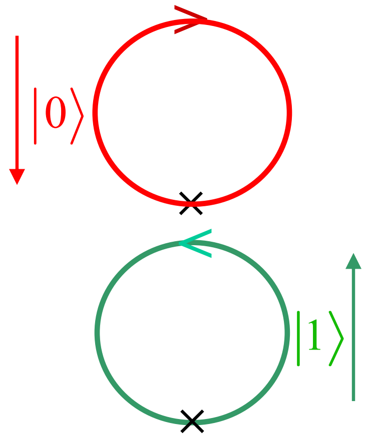
Decoherence by noise and coupling to external modes

Superconductor advantage:
Large energy separation of s-c state from dissipative state

Possible qubit



TWO STATES



$$|\Psi> = \alpha\ |0> + \beta\ |1>$$

Forefront Research Directions

Materials and Devices

MgB_2 films (and junctions) for 20 K operation
LTS internally shunted Josephson junctions
LTS micron and submicron junctions with high J_c
HTS Josephson junctions
Components for quantum computing

Circuits and Systems

Improve unshielded SQUIDs
Improve sensitivity of HTS SQUIDs
Small HTS digital circuits
Raise SNR of A/D converters
Develop software radio application
Demonstrate 50 GHz (and higher) RSFQ circuits
Demonstrate large digital processor, switches