Digital SQUID Magnetometers for Read-out of Detectors and Magnetic Particles

Department of Energy - Office of Nuclear Physics

Contract # DE-SC0007659

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Outline

- Superconducting Technology Overview
- Company Overview
- DOE Program Goals, Approach, and Accomplishments

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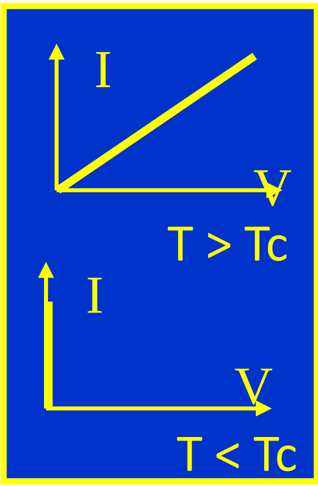
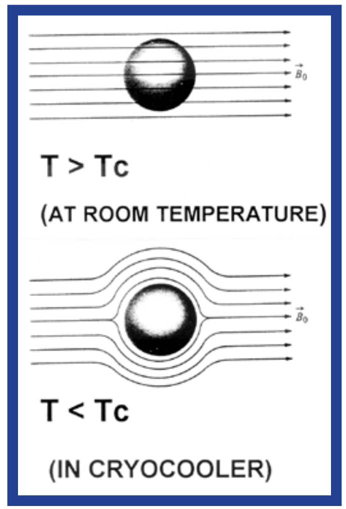
Superconductivity

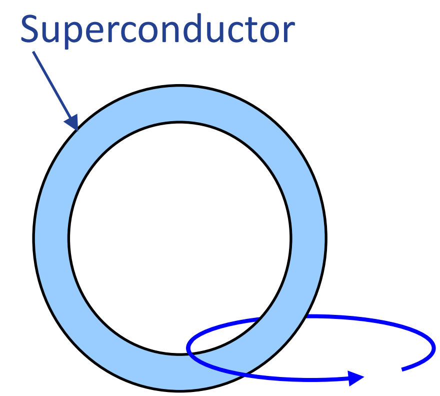
Zero Resistance



Expulsion of Magnetic Flux



Magnetic Flux Quantization



Single quantized unit of magnetic flux (“fluxon”)

Flux Quantization

$$\Phi_0 = h/2e = 2.07 \times 10^{-15}\ \text{Wb} = 2.07\ \text{mV}\bullet\text{ps}$$

h = Plank’s constant; e = Electron charge

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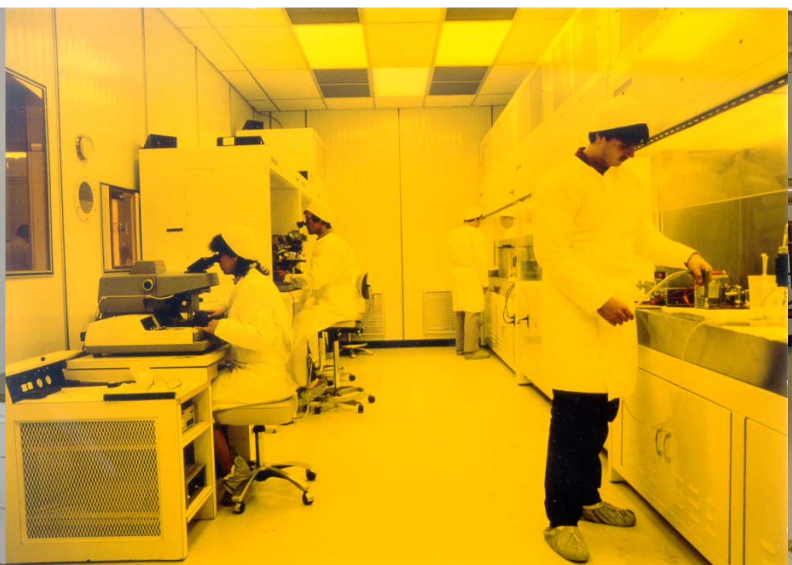
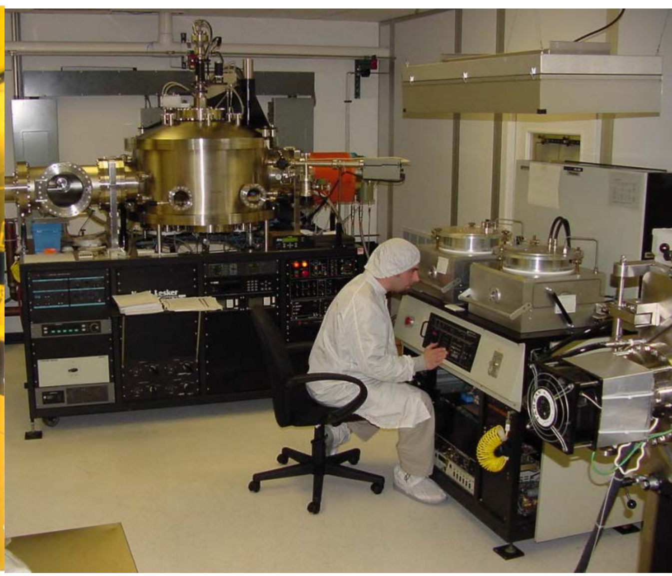
HYPRES, Inc. - Elmsford, NY

- Founded in 1983 as spin-off from IBM; 19,000 sq. ft. - 30 miles north of New York City
- US Privately held – 33 employees, primarily advanced degree engineers and scientists
- World leader in Superconductor Microelectronics technology producing high-end instrumentation equipment
- Pursuing applications and working on existing projects in DOD, DOE, NASA, and NIH
- The only commercial foundry service for superconducting electronics





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Mission and Strategic Focus

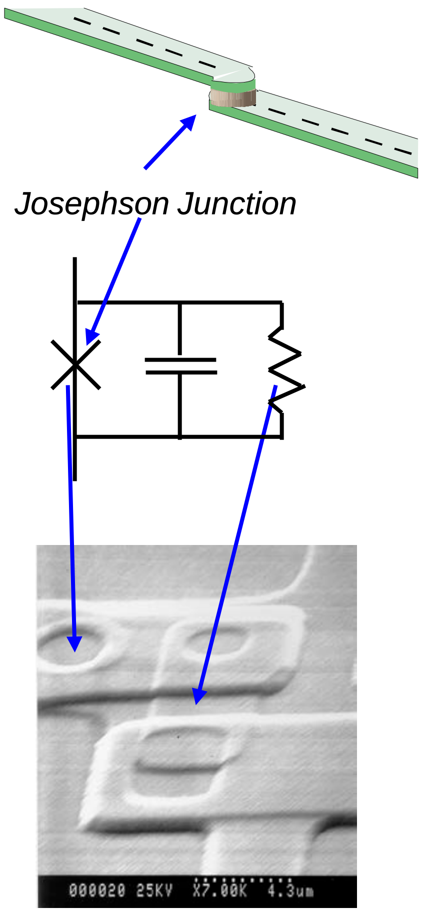
Mission

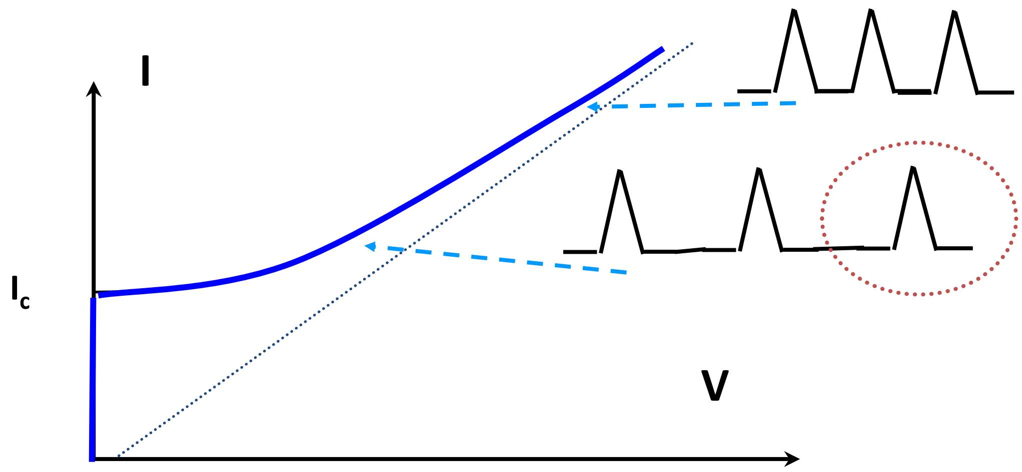
Develop and deploy innovative receivers, sensors, and high performance computing solutions based on superconducting circuits and cryoelectronics

Strategic Focus

- Wideband digital RF receivers based on analog to digital converters (ADCs)
- Superconducting QUantum Interference Device (SQUID)-based magnetic sensors for detectors and biomedical applications
- Custom chip and system design

Active Device: Josephson Junction (JJ)





$$I = I_c \, Sin[(\hbar/2e) \times (\int V dt)]$$

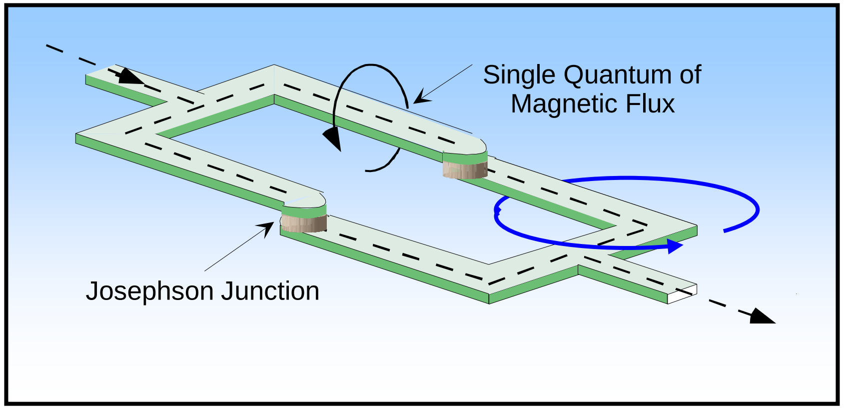
e = Electron charge; $\hbar = h$ (Plank's constant) $/2\pi$

$f = h/2e = 2.07 \times 10^{-15}$ Wb ~ 483.6 MHz/μV

Superconducting QUantum Interference Device (SQUID)

Magnetic Flux Quantization

Single quantized unit of magnetic flux ("fluxon")



$$\Phi = \int B_n dA = n\, \Phi_0$$

$$\Phi_0 = h/2e = 2.07\ \text{mV} \cdot \text{ps} = 2.07 \times 10^{-15}\ \text{Wb}$$

Single Flux Quantum (SFQ)

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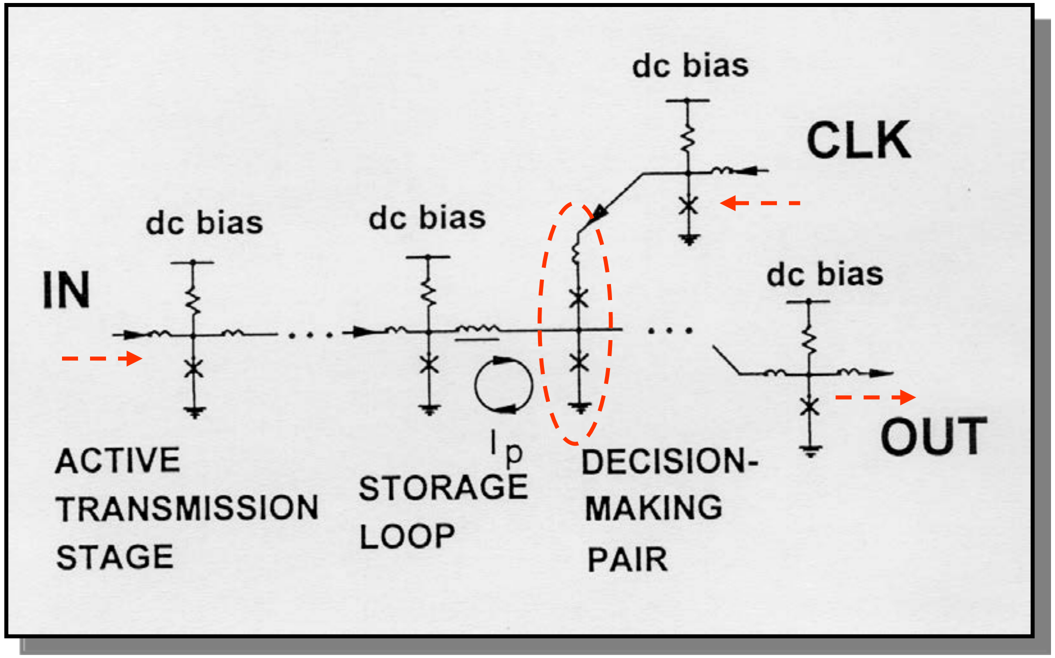
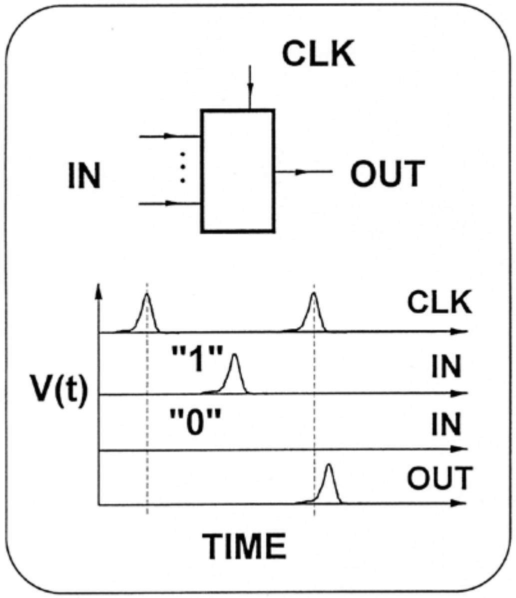
RSFQ (Rapid Single Flux Quantum) Logic Circuits



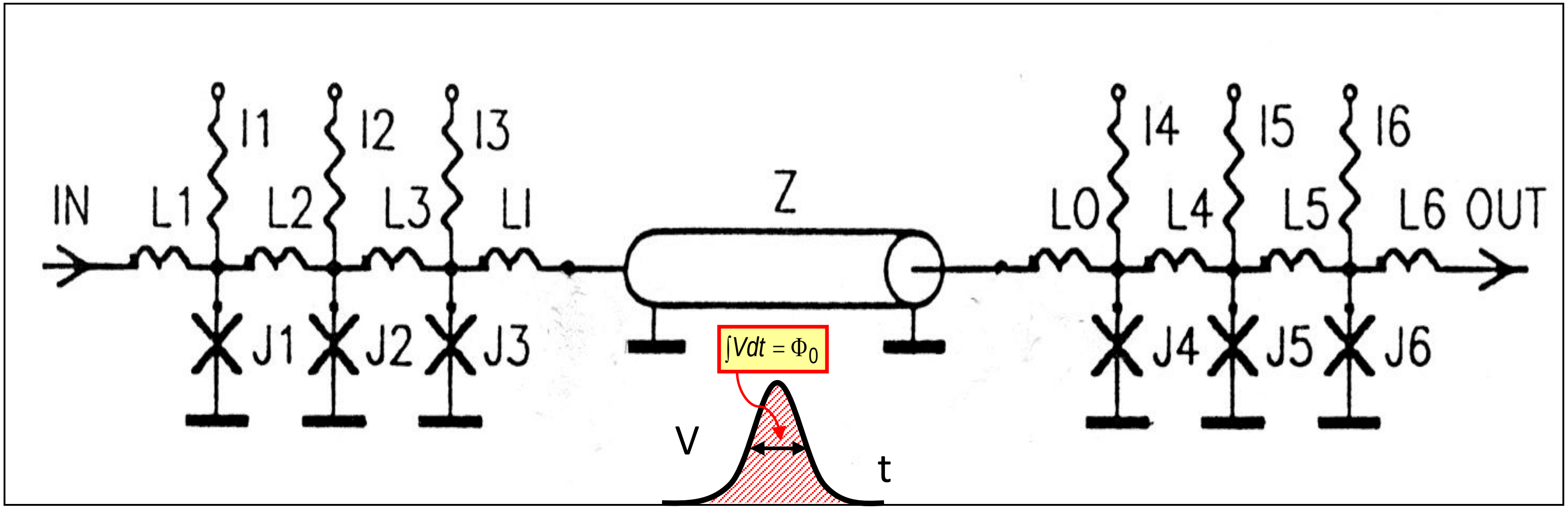


Both Data and Clock are SFQ voltage pulses V(t) with quantized areas

$$\int V dt = \Phi_0 = h/2e = 2.07 \text{ mV}\cdot\text{ps}$$

Transmission Lines

It is possible ballistically transfer SFQ pulses



- Semiconductor VLSI speed is limited by interconnect delays (RC-type charging)
- Superconductors have unique capability to transfer picosecond waveforms without distortions with speed approaching speed of light
- Crosstalk between neighboring transmission lines is very small
- Josephson junction impedance can be matched to that of microstrip lines

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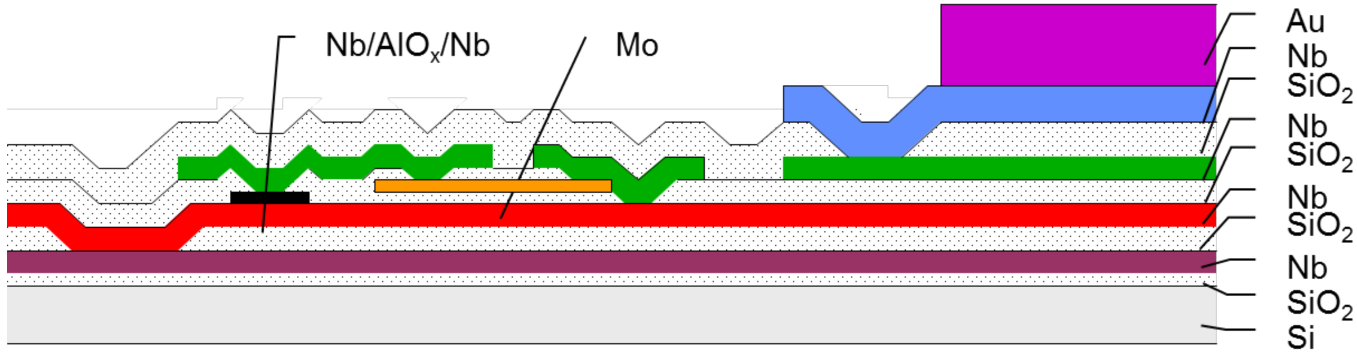
Superconductor Electronics Benefits

- Ultra-high Sensitivity, low noise (on the order of *h*)
- High speed (~1ps time constant for 3um process)
- Low-power Dissipation (pW dissipation per gate)
- Digital and mixed-signal
- Ideal transmission lines (negligible loss, dispersion, and crosstalk)
- Quantum accuracy (voltage standard and ADC)
- Hybrid super/semi capability / Simple fabrication



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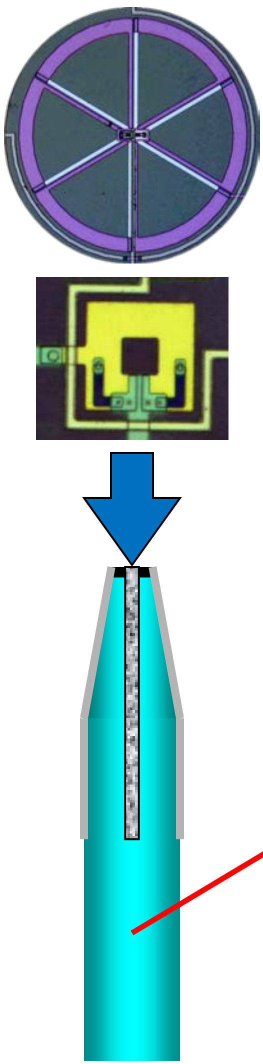
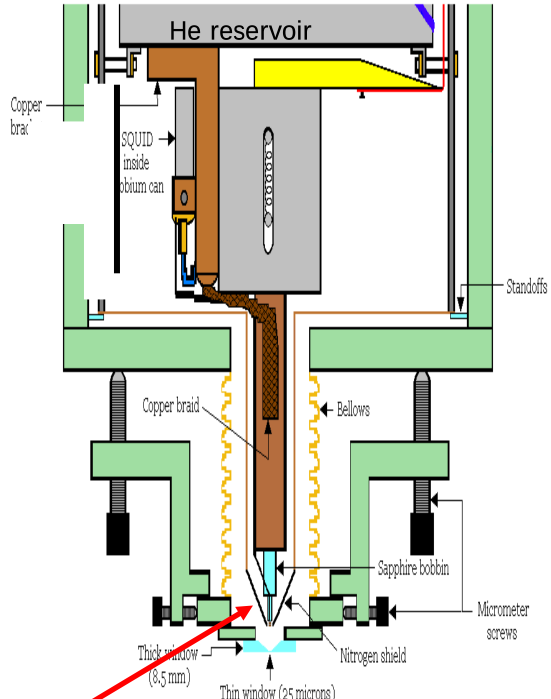
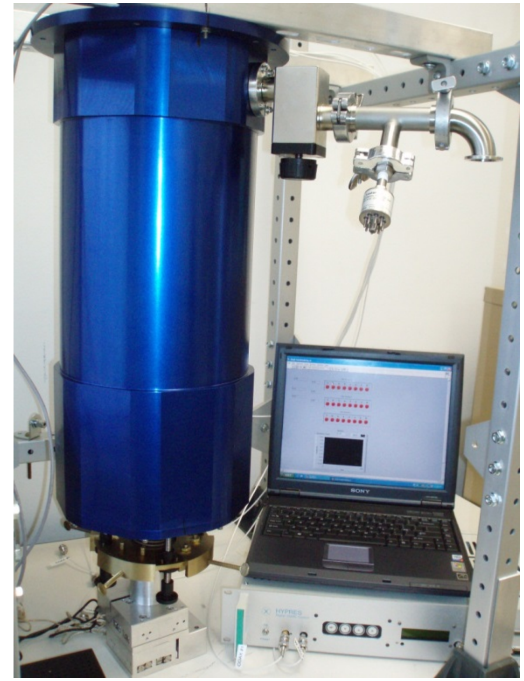
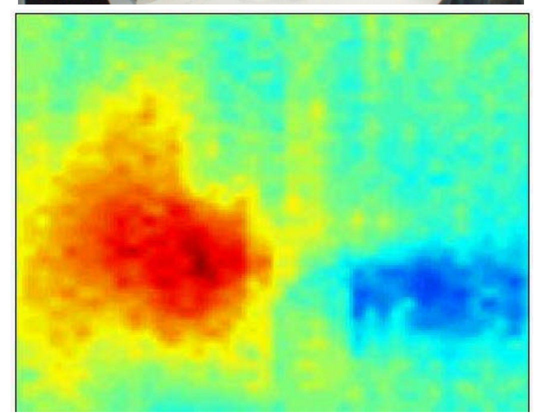
Magnetic Microscope

500 μm









Rabbit Heartbeat

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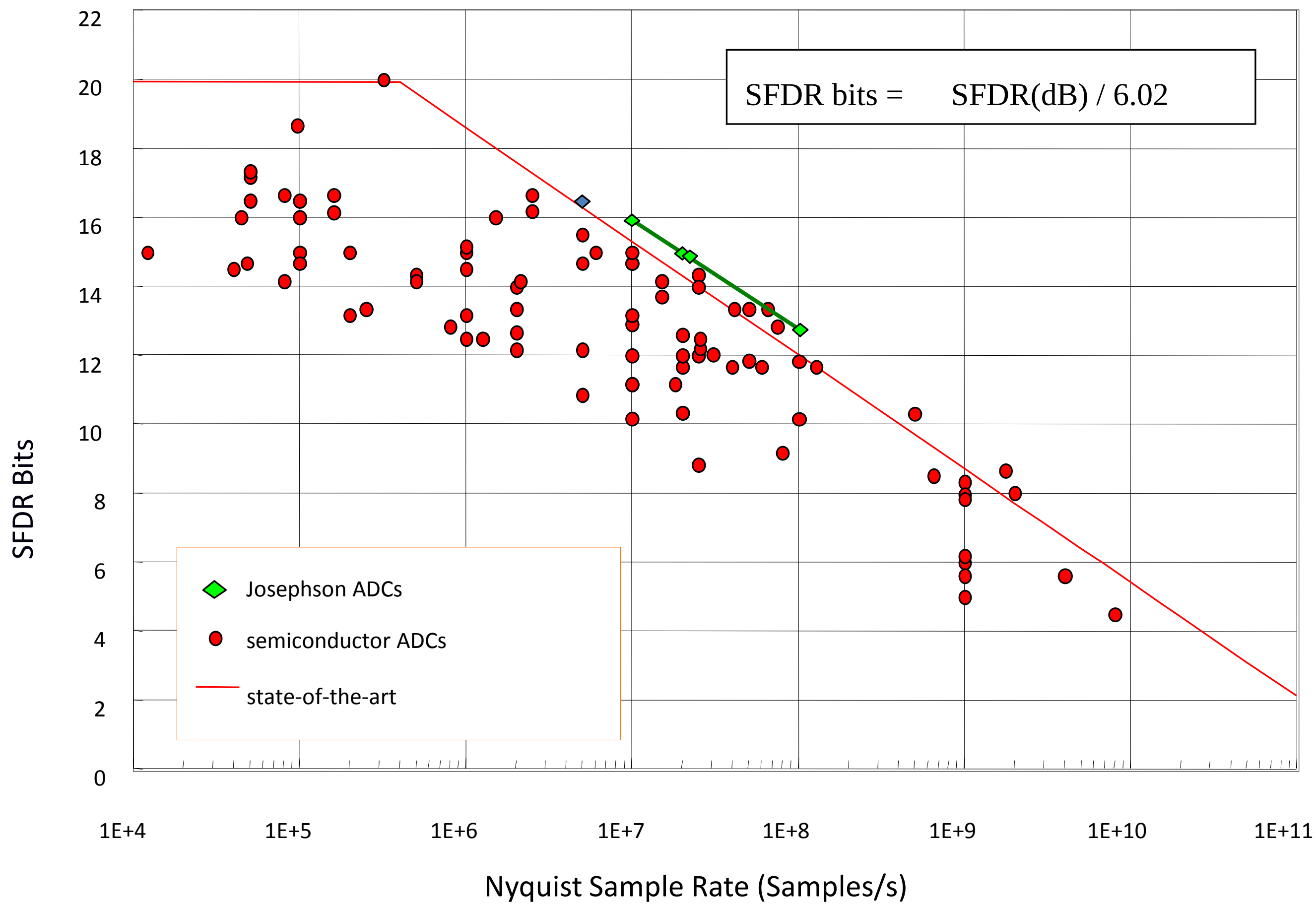
Analog to Digital Converter (ADC)

ADC generating a stream of SFQ pulses at the rate exactly proportional to the input voltage by

$$f = h/2e = 2.07\text{x}10^{-15}\ \text{Wb} \sim 483.6\ \text{MHz}/\mu\text{V}$$



Noise Floor ~ -164 dBm/Hz ~ 2 x 10^{-21} T-$m^2/\sqrt{Hz}$

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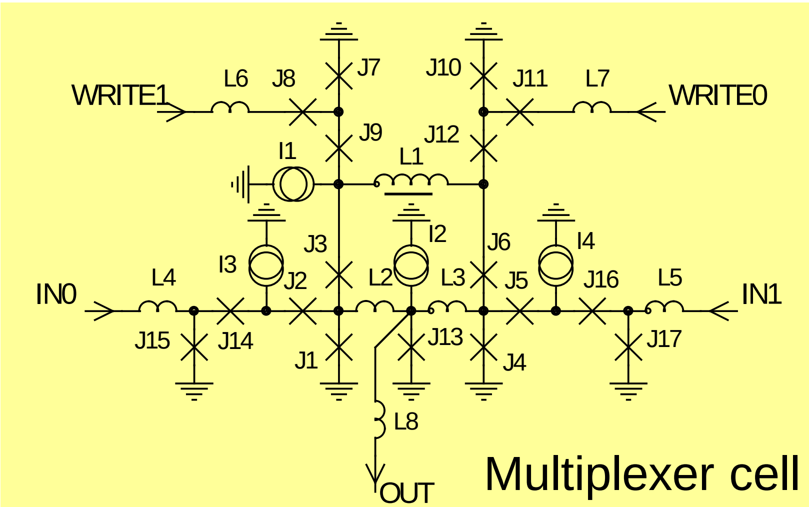
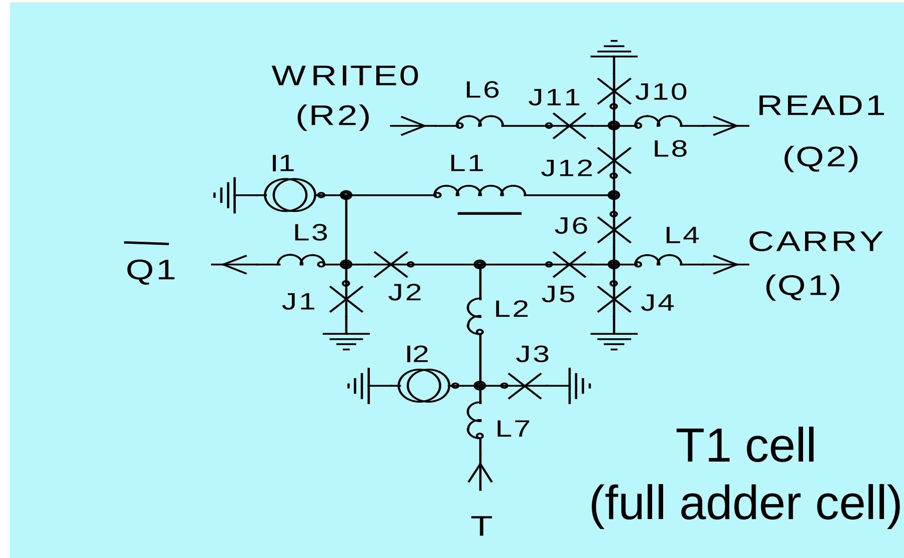
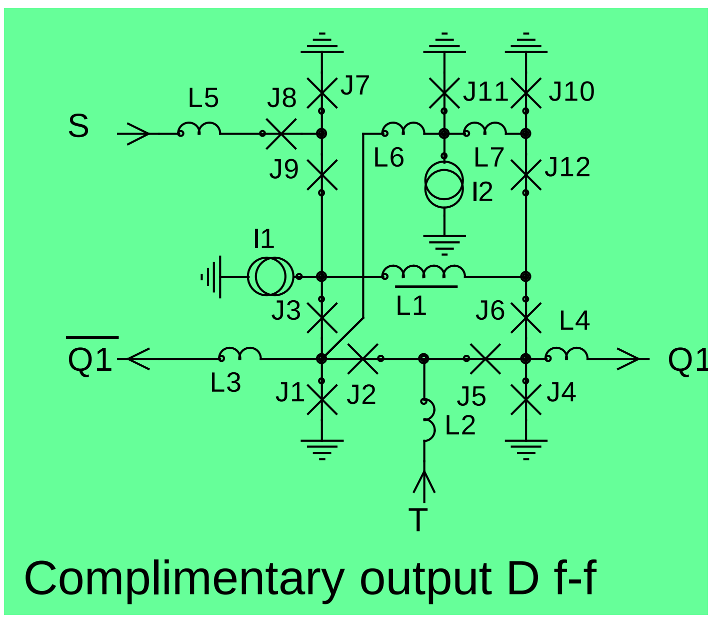
RSFQ Digital Logic, Counter, and Digital Filter



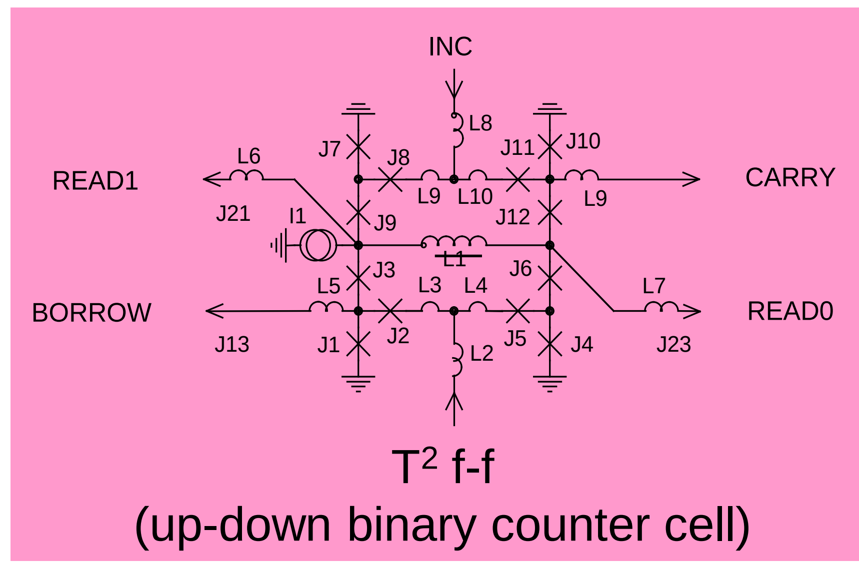
Multiplexer cell



T1 cell
(full adder cell)



Complimentary output D f-f



T^2 f-f
(up-down binary counter cell)

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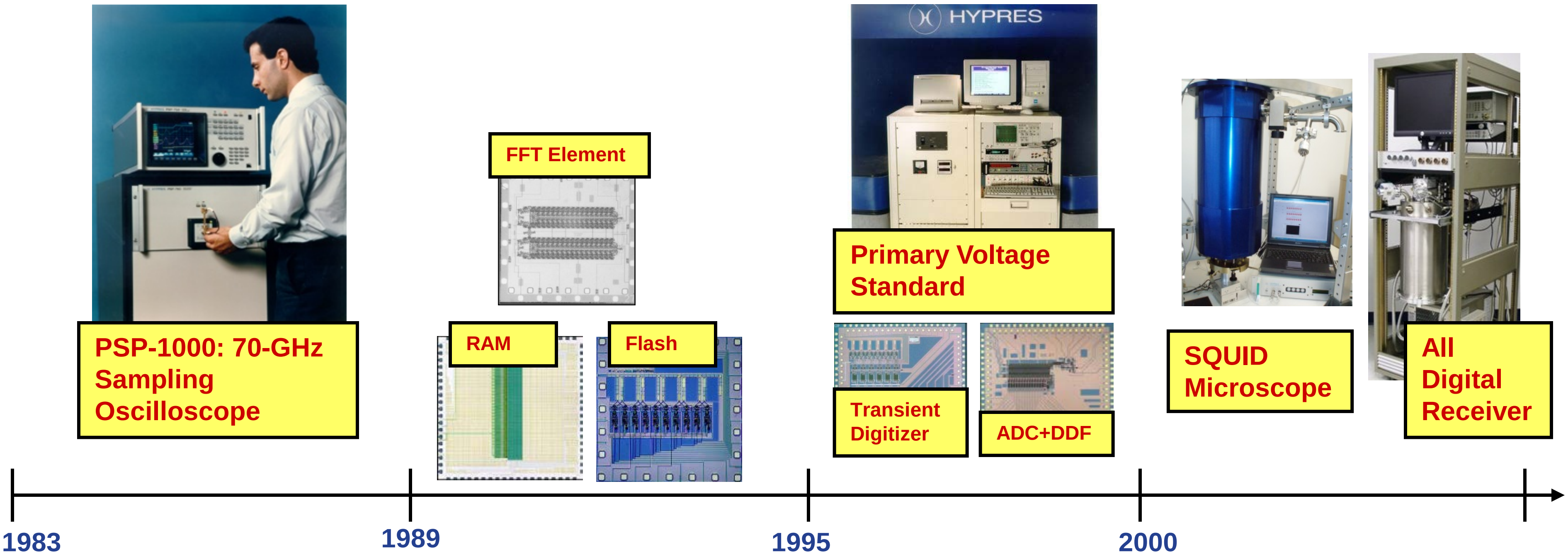
World Leader in Superconductor Electronics



The Beginning

- Developed technology for instrumentation markets
- 1st product commercialized
- Worlds fastest Scope

New Ideas

- Family of Superconductor Chips
- Analog to digital conversion
- Commercial foundry

Consolidation

- World leader in Superconducting Technology
- Voltage Standard

Focused Growth

- Dual Use Military and Commercial Technology
- SQUID Microscope

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Applications for Josephson Circuits

- Sensitive Magnetometer -- SQUID
- Analog-to-Digital Converters
- Digital Signal Processing

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Digital SQUID Magnetometer / Amplifier

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DOE SBIR Objectives

Develop a 4-channel digital SQUID (Superconducting QUantum Interference Device)-based amplifier system for read-out of detectors.

- Front-end is an analog SQUID with magnetic field sensitivity of ~6 x 10^{-21} Wb/√Hz
- Analog SQUID is followed by ADCs (Analog to Digital Converters) and multiplexers for on-chip data streaming and coupling to slower data acquisition electronics
- On-chip processing of the 4-channel data at ~20 GHz allows multiplexing of 100s of channels

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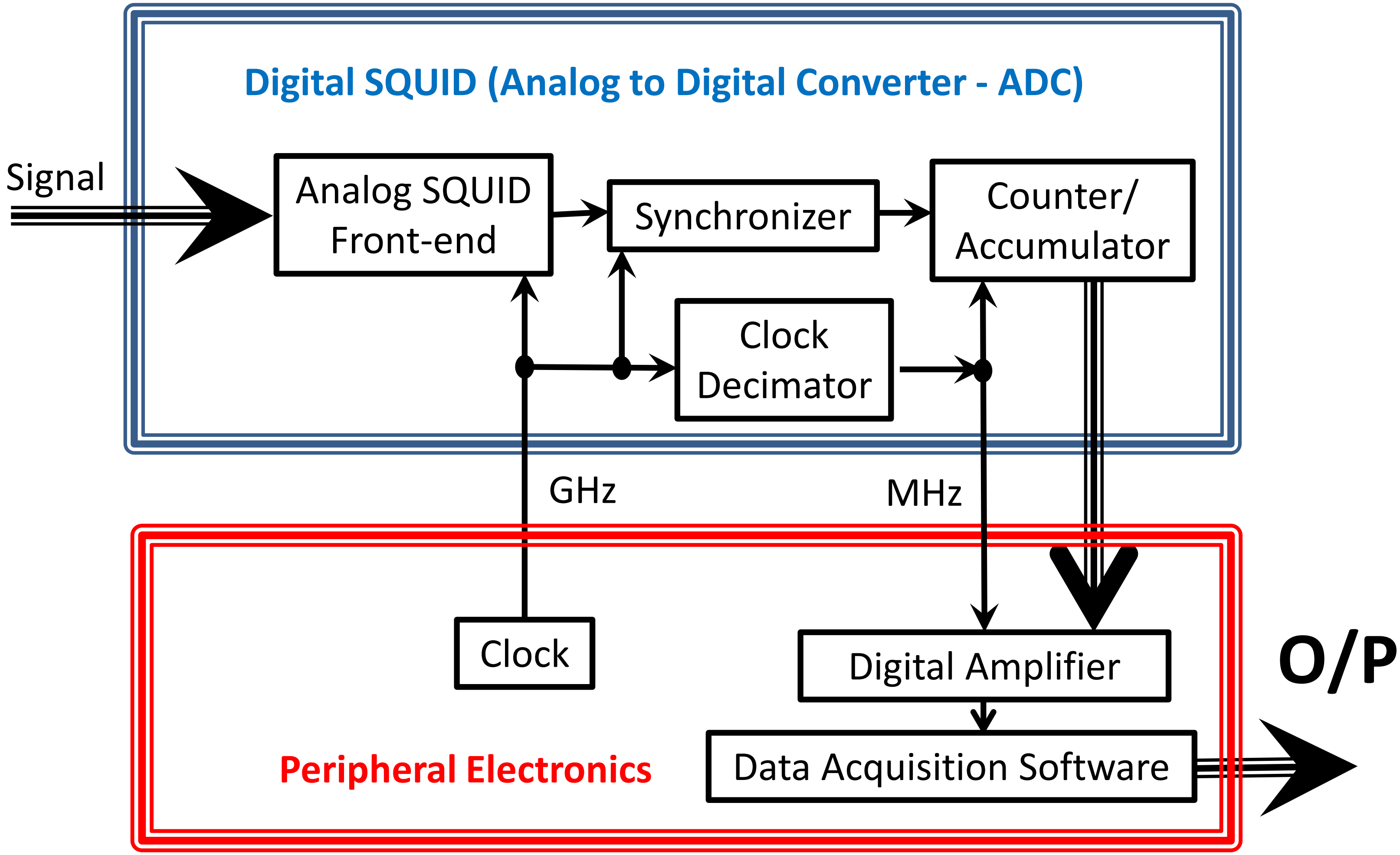
Single-Channel Read-out



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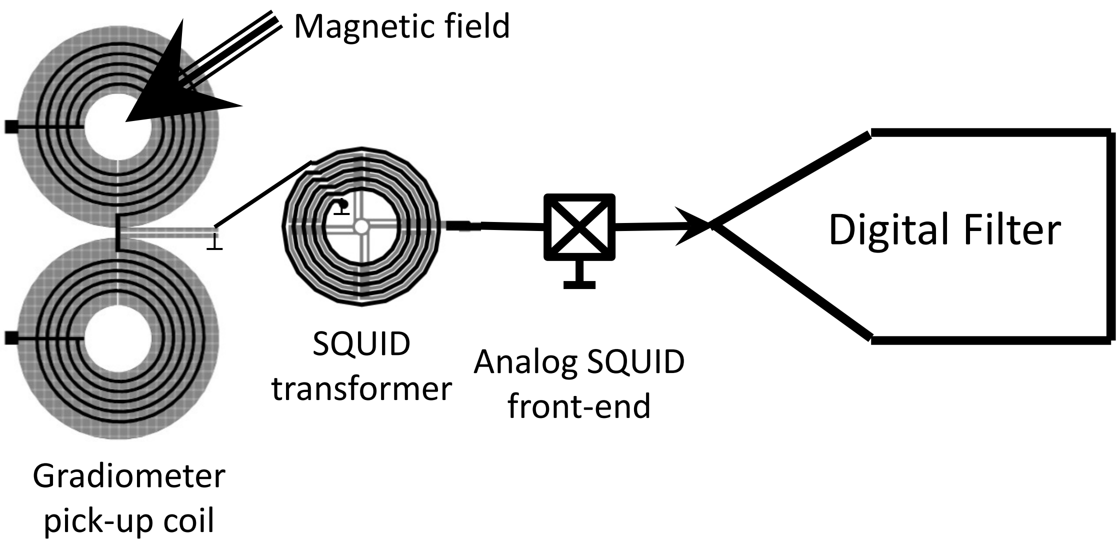
Single-Channel Schematic



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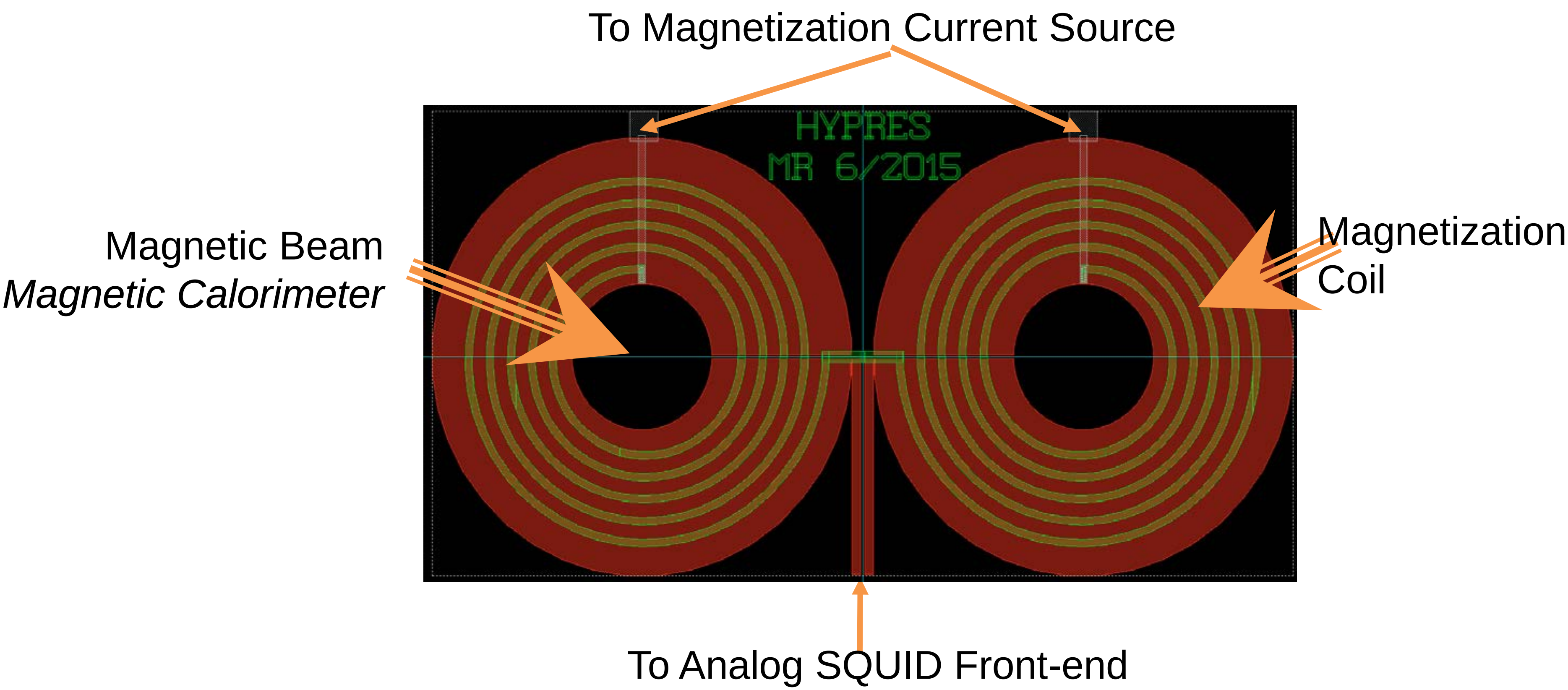
Pick-up Coil



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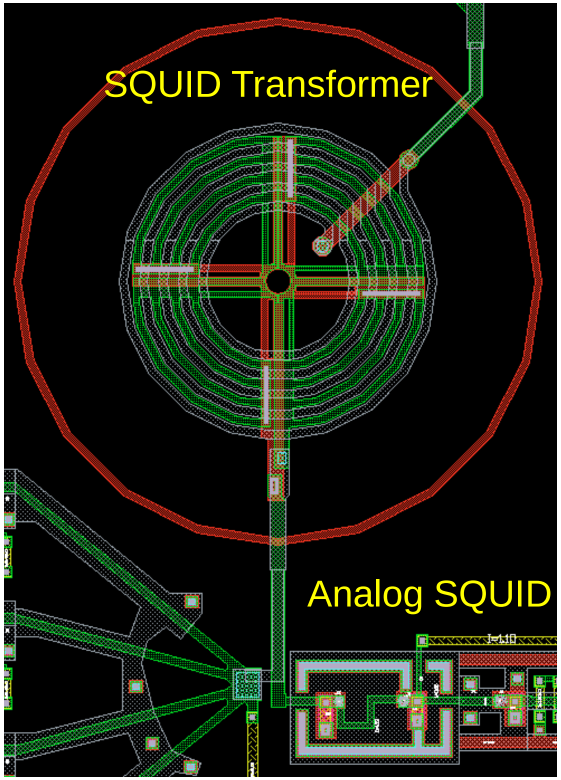
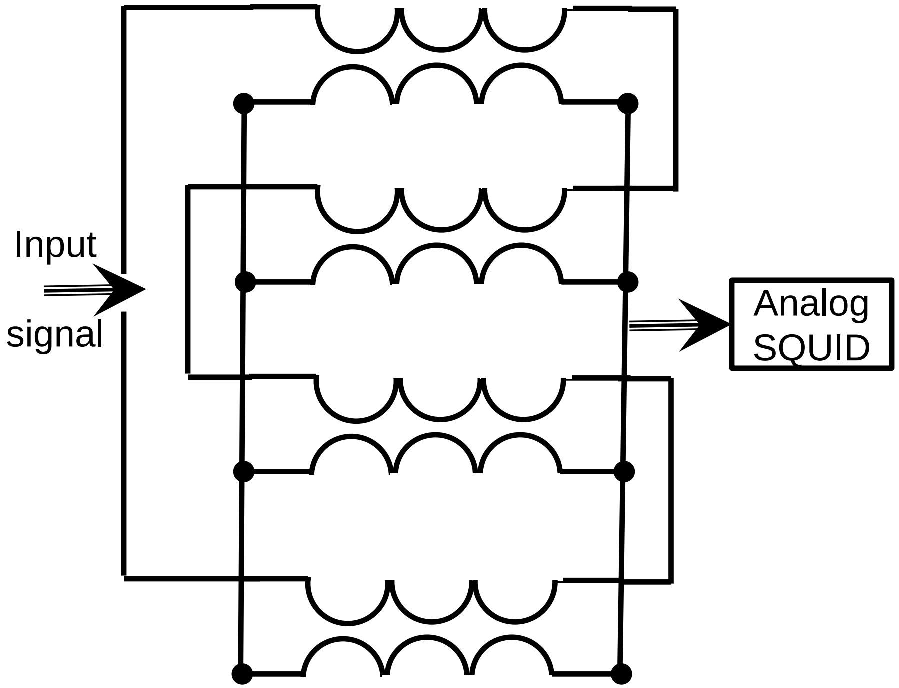
Front-end Analog SQUID Magnetometer





Multi-turn Transformer Coupled to 4 Analog SQUID Inductors

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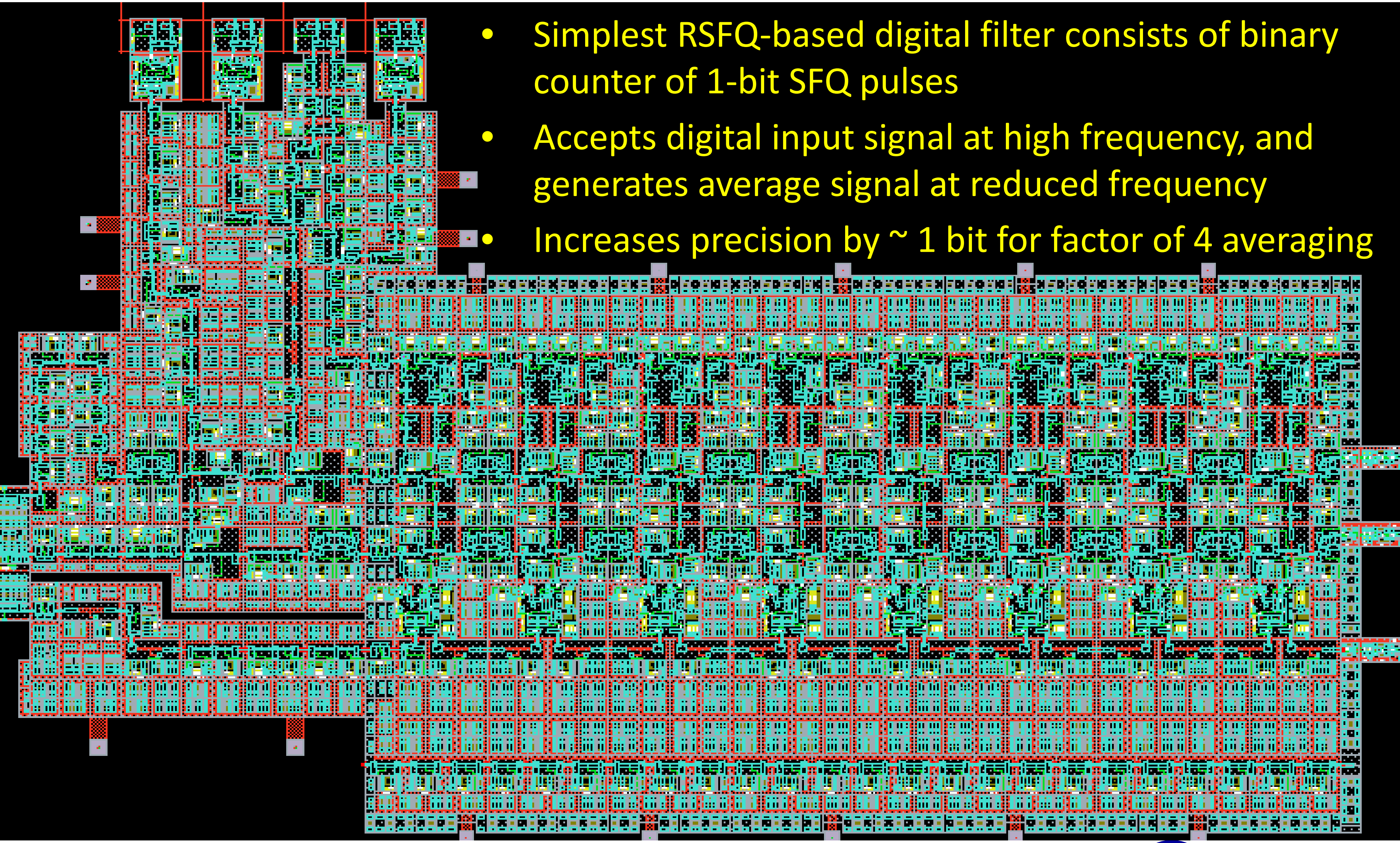
Counter/Accumulator (Digital Filter)

- Simplest RSFQ-based digital filter consists of binary counter of 1-bit SFQ pulses
- Accepts digital input signal at high frequency, and generates average signal at reduced frequency
- Increases precision by ~ 1 bit for factor of 4 averaging



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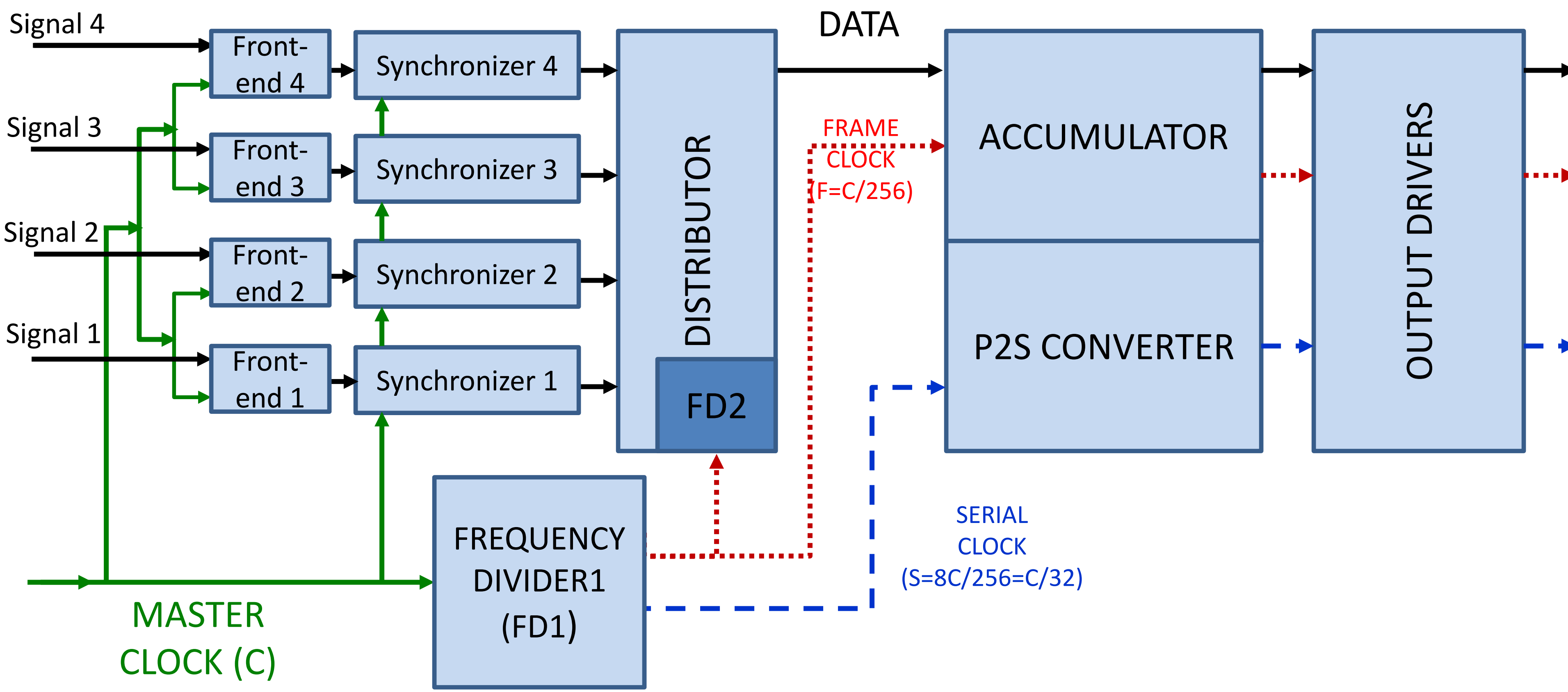
Schematic of 4-Channel Read-out Circuit



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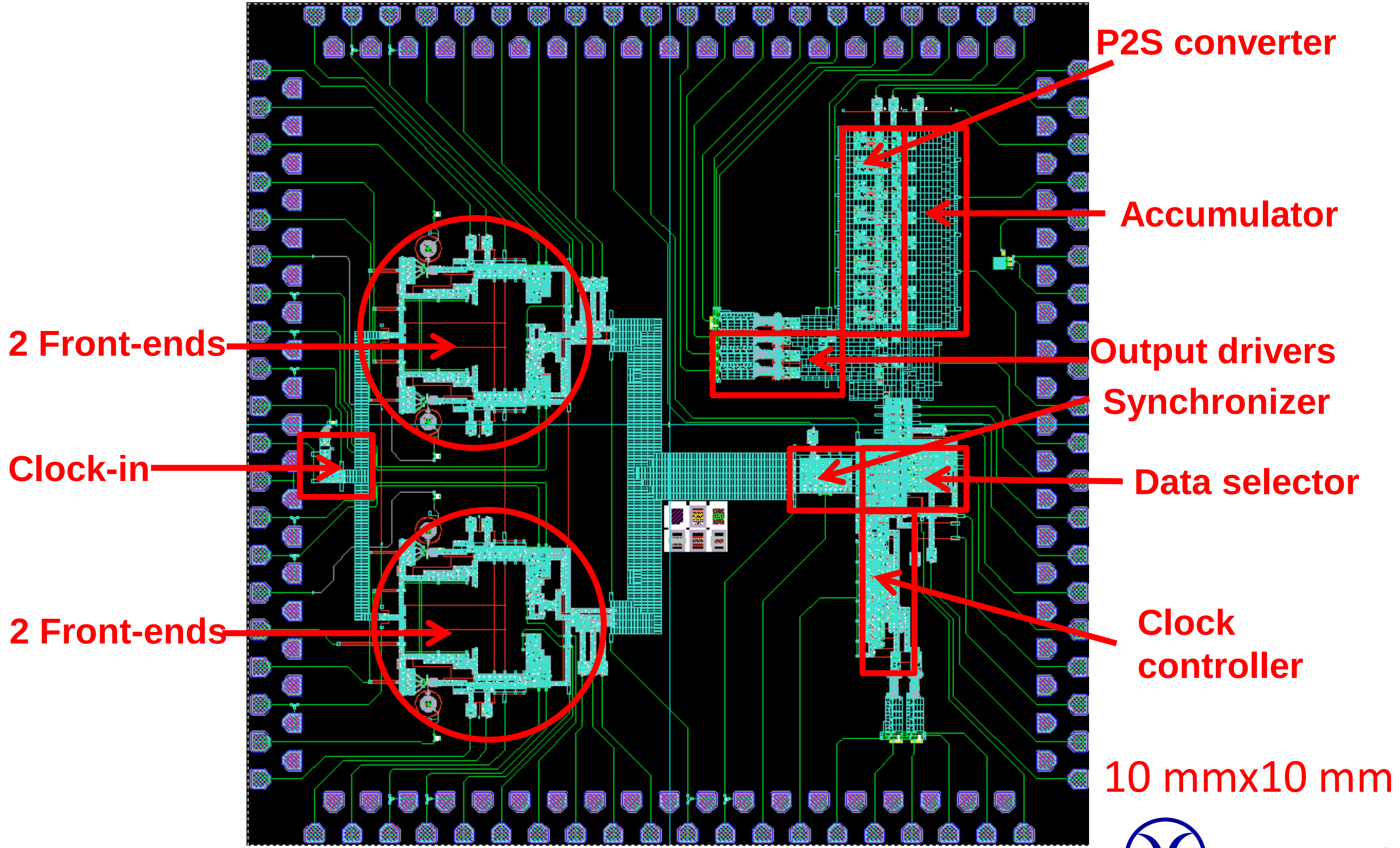
Layout of 4-Channel Read-out Circuit



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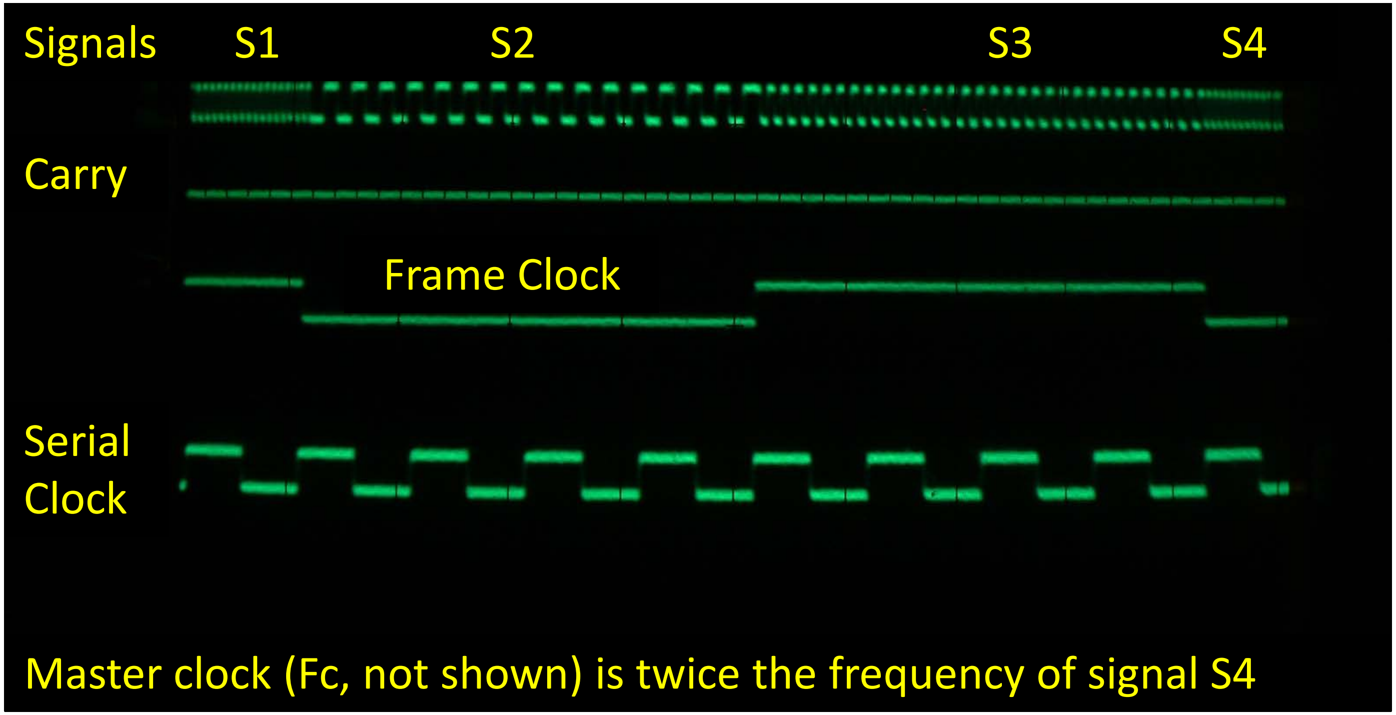
Low Frequency Test



4 Signals of frequencies (Fc/2, Fc/8, Fc/4, and Fc/2) are applied to the 4 input channels. The first trace is the multiplexed data on the output line.

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High Frequency Test (4 GHz Clock)

Frame 1
S1 = Fc/4

Frame 2
S2 = Fc/2

Frame 3
S3 = Fc/2

Frame 4
S4 = Fc/8

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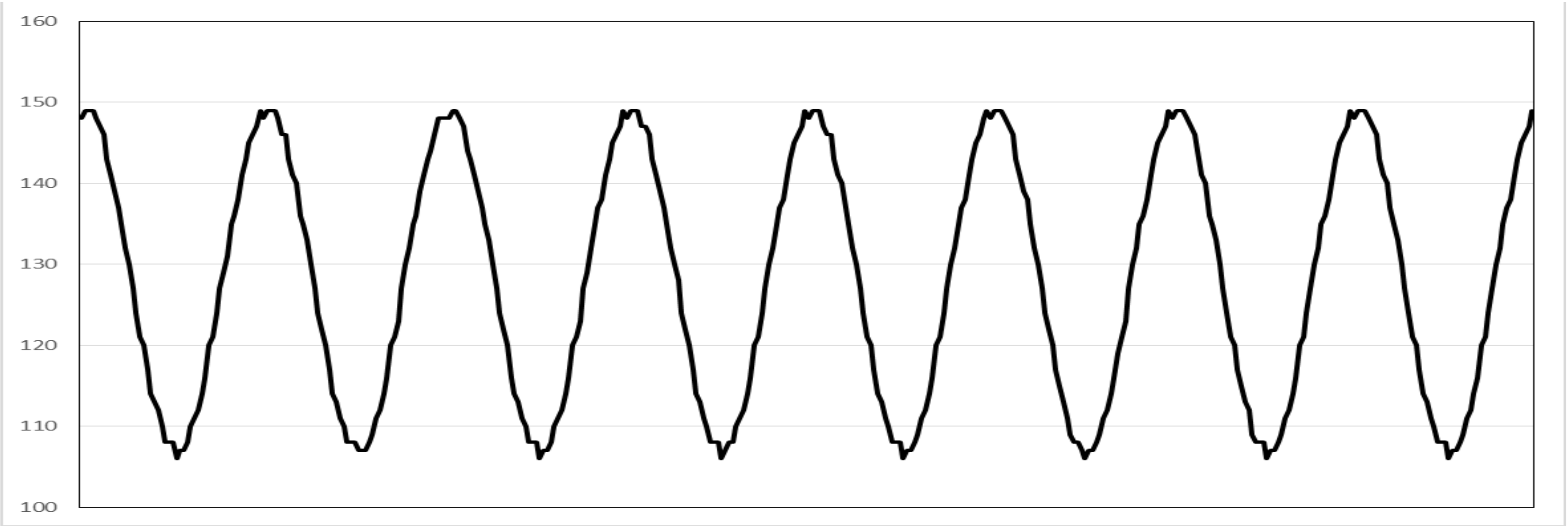
Signal Reconstruction



Clock frequency = 8 GHz

Channel 1 Signal Frequency = 156.25 KHz

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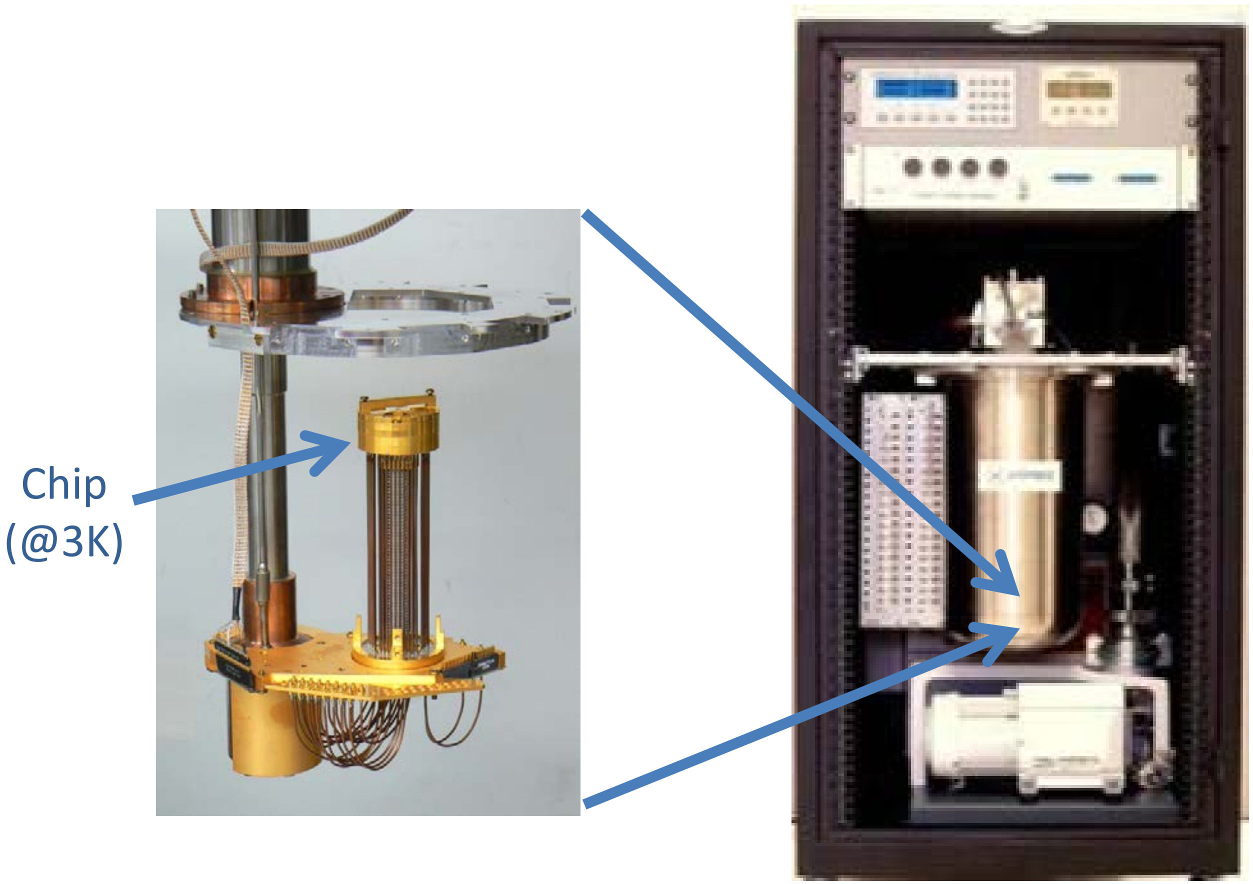
Cryogenic Package / Peripheral Electronics



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Collaborators (Past & Present)

- Prof. Daniel Prober, Yale University
- Prof. Blas Cabrera, Stanford University
- Dr. Stephan Friedrich, Lawrence Livermore National Laboratory
- Dr. Peter Shirron, Goddard Space Flight Center, NASA

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Accomplishments

- Completed the design, simulation, fabrication of two iterations of the 4-channel digital SQUID amplifier chip as well as two of its diagnostic chips.

- Diagnostic chips were fully characterized. All components of the amplifier chip (pickup coil, front-end SQUID, analog to digital converter, multiplexer, etc.) successfully passed all tests.

- First and second iterations of the 4-channel digital SQUID amplifier were evaluated. Full functionality was demonstrated. The final 4-channel version with better margin and sensitivity is currently being optimized and is expected to become available by November 2015.