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

Department of Energy - Office of Nuclear Physics

Contract # DE-SC0007659

Dr. Masoud Radparvar
HYPRES, Inc.
175 Clearbrook Rd.
Elmsford, NY 10523

August 7, 2014

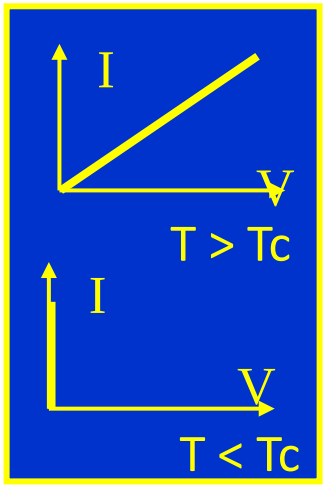
Outline

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

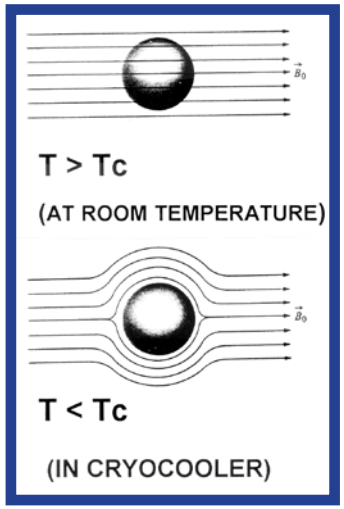
Superconductivity, Josephson Junctions, and SQUIDs

Superconductivity

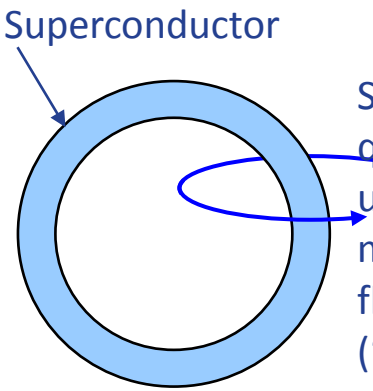
Zero Resistance



Expulsion of Magnetic Flux



Magnetic Flux Quantization



Single quantized unit of magnetic flux ("fluxon")

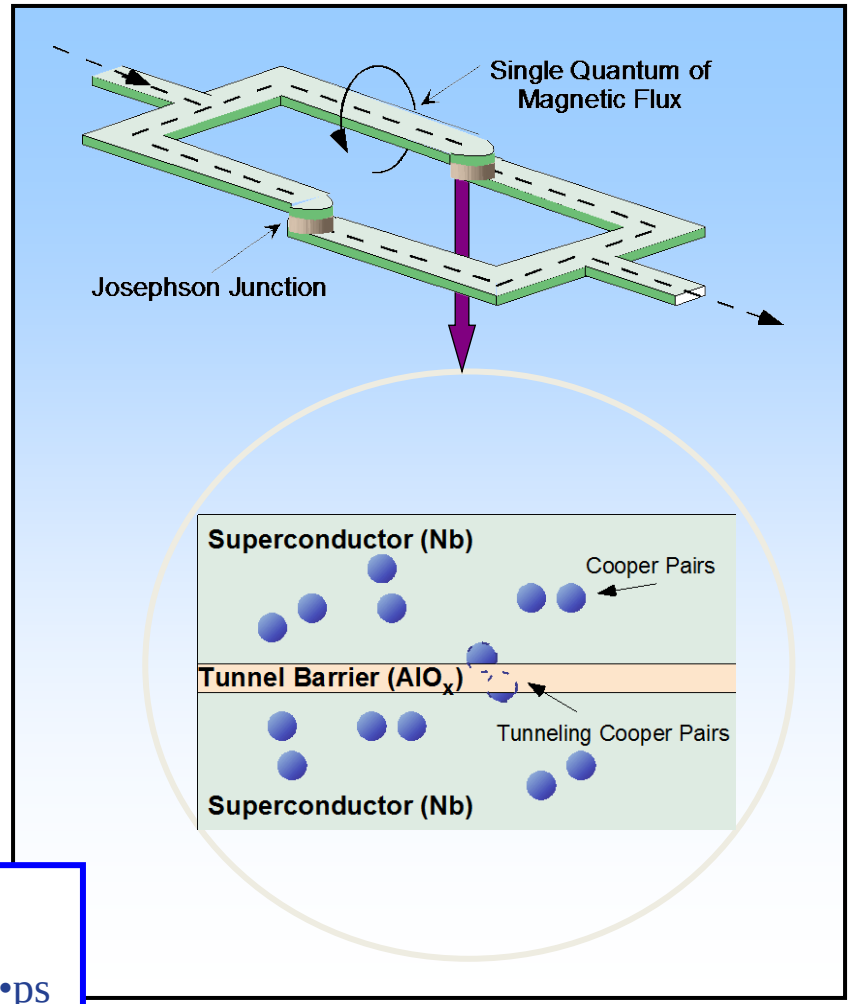
$$\Phi = \int B_n dA = n\,\Phi_0$$

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

$$= 2.07 \times 10^{-15}\ \text{Wb}$$

Single Flux Quantum (SFQ)

Josephson Junctions, and SQUIDs



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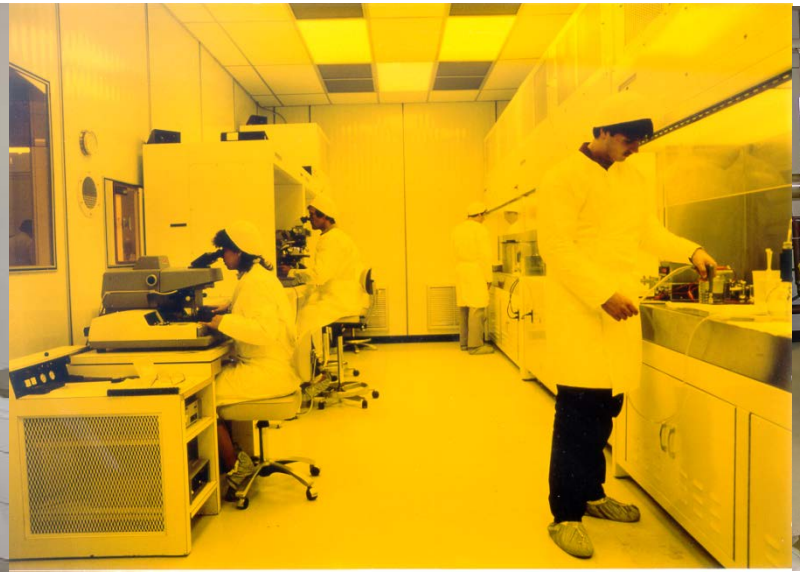
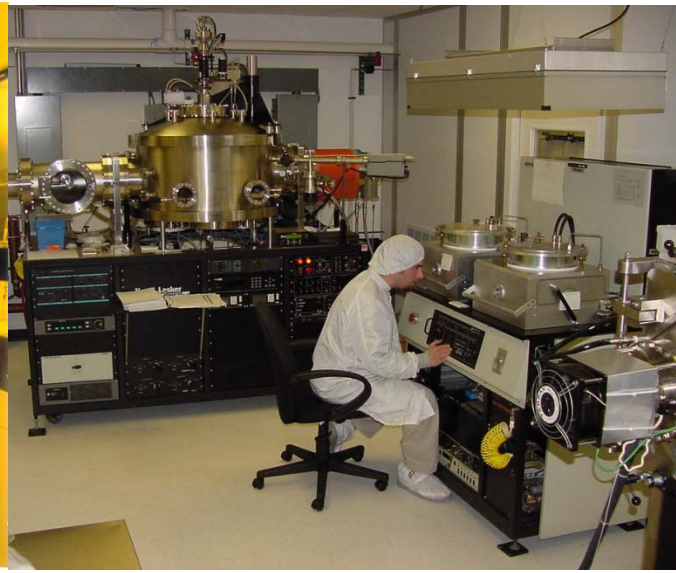
Superconductor Electronics Benefits

- 100+ GHz speed
- Low-power Dissipation
- Digital and mixed-signal
- Ideal transmission lines
- Low-noise (Quantum limit)
- Quantum accuracy (voltage standard and ADC)
- Hybrid super/semi capability
- Simple fabrication

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

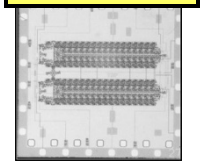
Strategic Focus

- 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

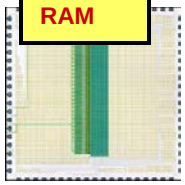
World Leader in Superconductor Electronics

PSP-1000: 70-GHz Sampling Oscilloscope

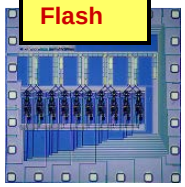
FFT Element

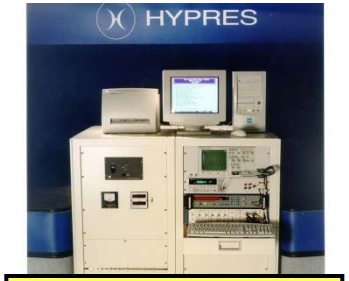


RAM

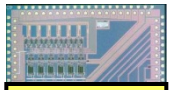


Flash



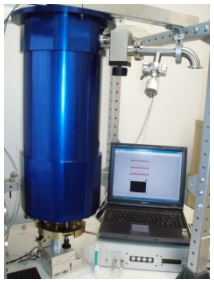


Primary Voltage Standard



Transient Digitizer

ADC+DDF



SQUID Microscope

All Digital Receiver

1983 1989 1995 2000

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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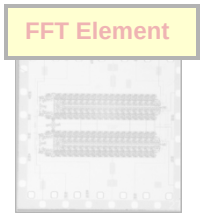
World Leader in Superconductor Electronics

PSP-1000: 70-GHz Sampling Oscilloscope



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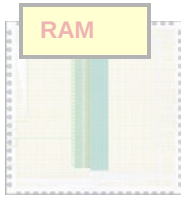
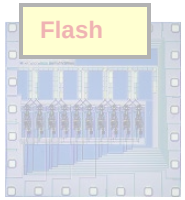


RAM



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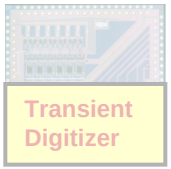
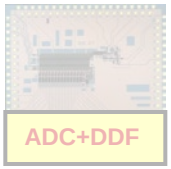
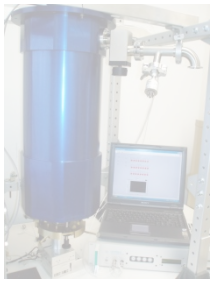
Primary Voltage Standard



Transient Digitizer



ADC+DDF



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- Voltage Standard

Focused Growth

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- SQUID Microscope

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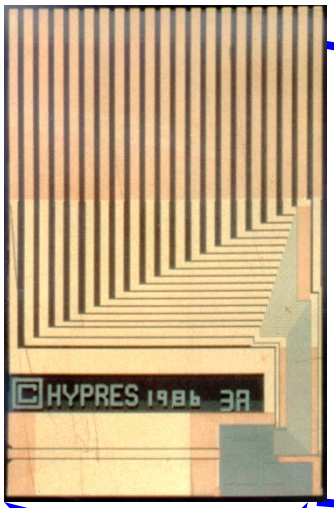
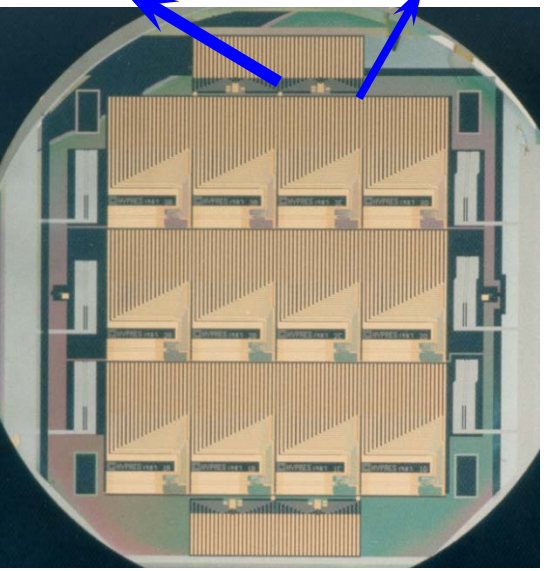
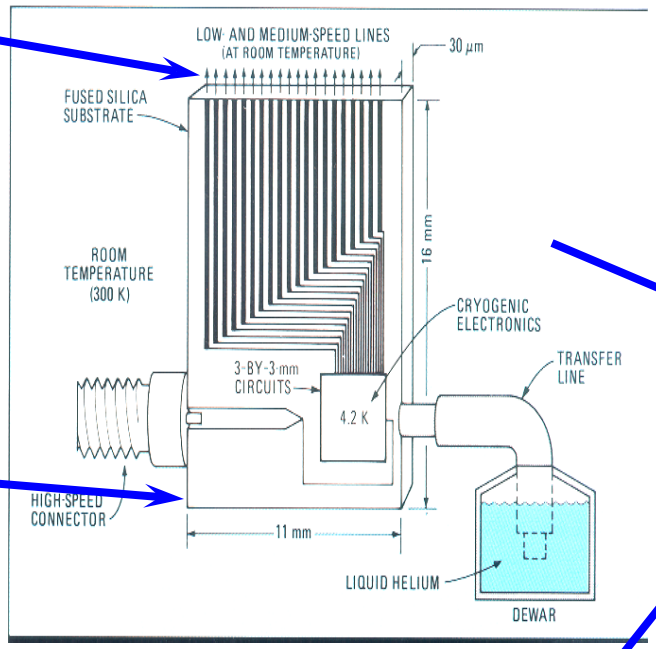
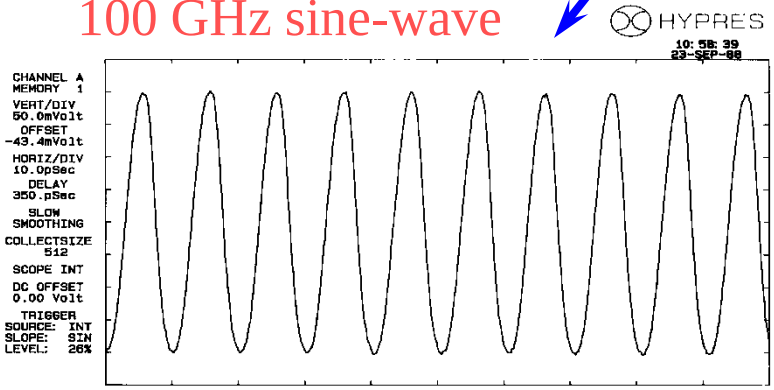
Sampling Oscilloscope







100 GHz sine-wave



70 GHz bandwidth
50 μV sensitivity

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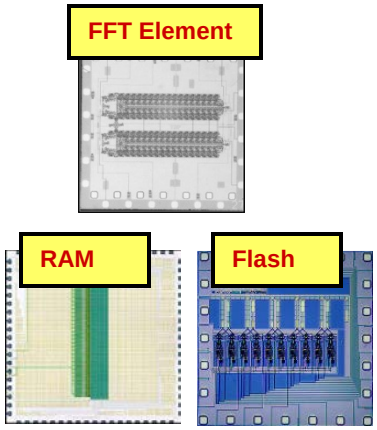
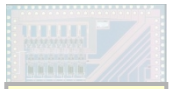
World Leader in Superconductor Electronics

PSP-1000: 70-GHz Sampling Oscilloscope

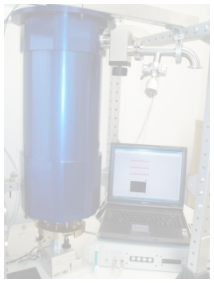


Primary Voltage Standard



Transient Digitizer

ADC+DDF



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Consolidation

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Focused Growth

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- SQUID Microscope

HYPRES

Customers, Collaborators, and Supporters

More than 75% of superconducting IC chips worldwide are produced by Hypres.

More than 80% of metrology labs worldwide utilize Hypres Voltage Standard Chips.

- BAE
- Raytheon
- Northrop/Grumman
- Argon ST
- Lockheed/Martin
- Cubic
- Titan
- ViaSat
- Boeing
- EADS Astrium
- Rockwell/Collins
- Harris
- SwRI
- STI
- L-3
- Thales
- Sarnoff Labs
- Ball Aerospace
- General Dynamics
- FMC/Selex
- DOC/NIST
- NIH
- NSF
- DOE
- NASA
- NSA
- Las Alamos
- Advantest
- National Measurement Service, Norway
- BIP – Russia
- National Physical Laboratory, UK
- BNM/LCIE -- France
- Netherlands Institute for Standards
- Bureau International Des Poids Mesures
- Centro Espanol de Metrologia, Spain
- NIMTT, PR China
- Danish Institute of Fundamental Metrology
- Dura, Inc.
- CSIRO Div. of Applied Physics, Australia
- Norfolk Naval Base
- Fluke Corporation
- Research & Manufacturing, Inc.(JEMIC)
- G&G, Japan (JEMIC)
- Research & Manufacturing, Inc.(Malaysia)
- Hong Kong
- Research & Manufacturing, Inc.(Mexico)
- IEN, Italy
- Research and Manufacturing, (Thailand)
- Industrial Research Limited – New Zealand
- Sandia Labs
- Industrial Technology Research Institute -- Taiwan
- Singapore Prod. & Stds. Bd.
- INMETRO (Brazil)
- Sirim -- Malaysia
- Inst. Nat. Meas., Canada
- Swiss Office of Federal Metrology
- INTA -- Spain
- Laz Representaciones, Spain (CEM)
- Metrology SA – Greece
- Stanford Univ.
- Univ. of California
- Stoney Brook Univ.
- Univ. of Rochester
- Colgate Univ.
- SIMIT
- Saitama Univ.
- Columbia Univ.
- Moscow State Univ.
- Univ. of Waterloo
- Univ. of Maryland
- Univ. of Southampton
- Chalmers Univ.
- Dynetics
- Tubigen Univ.
- Raytheon – BBN
- Univ. of North Carolina
- karlsruhe institute of technology
- MIT
- chalmers university of technology
- Paul Scherrer Institute
- Univ. of Wisconsin
- Max Planck Institute
- Univ. of Oxford
- Tech. Univ. Munchen
- Teratec Corp.
- Center for Astro. - Berkeley
- Niki Glass Co.
- European Space Agency
- Univ. of Heidelberg
- Univ. of Colorado
- Lawrence Livermore
- San Francisco State Univ.
- SRON
- Yale Univ.
- LETI

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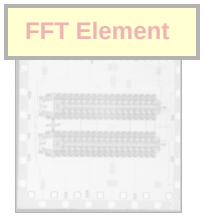
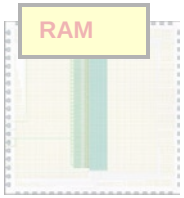
World Leader in Superconductor Electronics

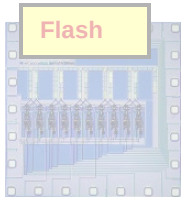
PSP-1000: 70-GHz Sampling Oscilloscope



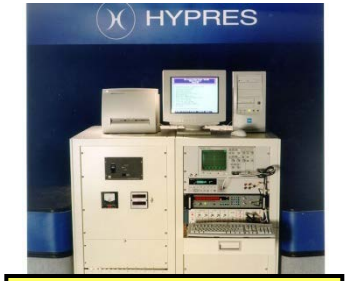
FFT Element



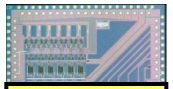
RAM



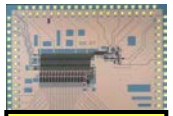
Flash



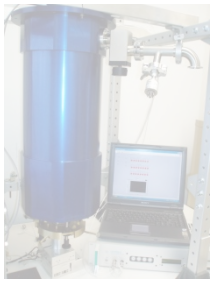
Primary Voltage Standard



Transient Digitizer



ADC+DDF



SQUID Microscope

All Digital Receiver

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Consolidation

- **World leader in Superconducting Technology**
- **Voltage Standard**

Focused Growth

- Dual Use Military and Commercial Technology
- SQUID Microscope

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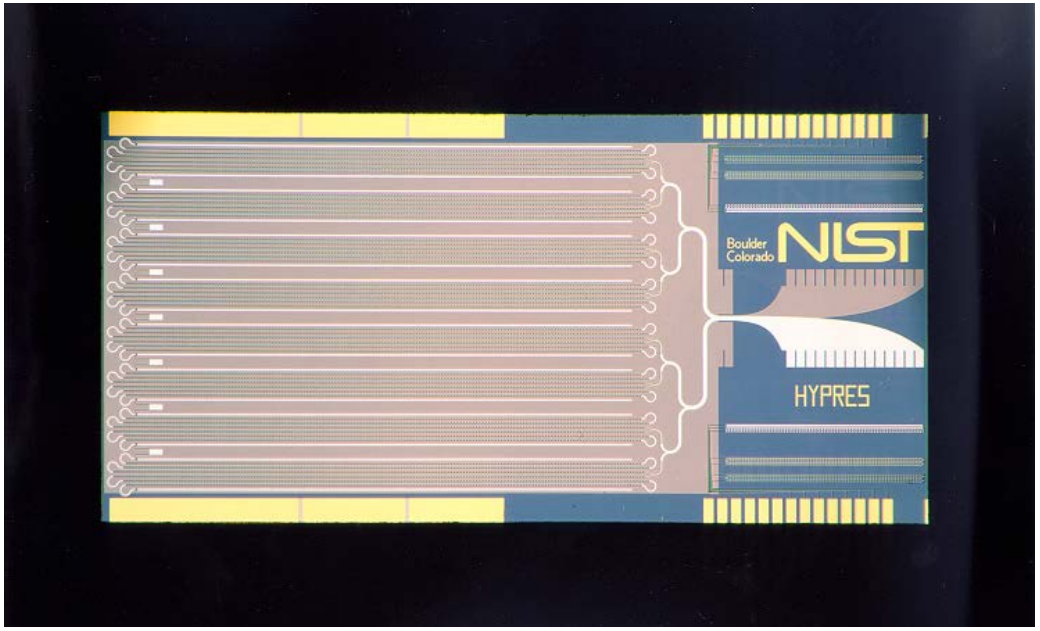
Primary Voltage Standard System

- Commercial Primary Voltage Standard for Metrology Markets Developed with DoD Dual use Resources
- This application cannot be done using any other technology



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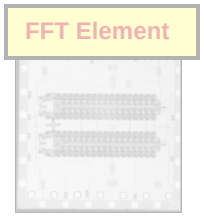

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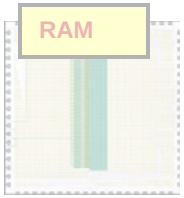

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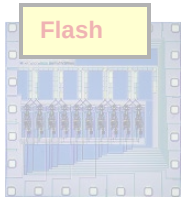

Flash

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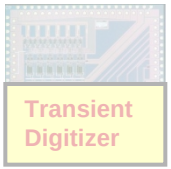

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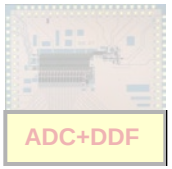

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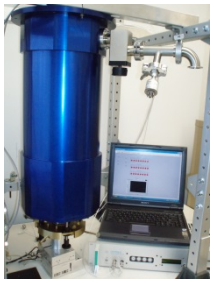

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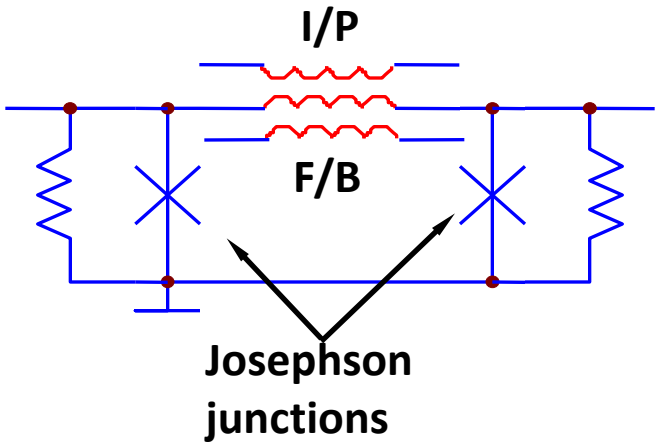
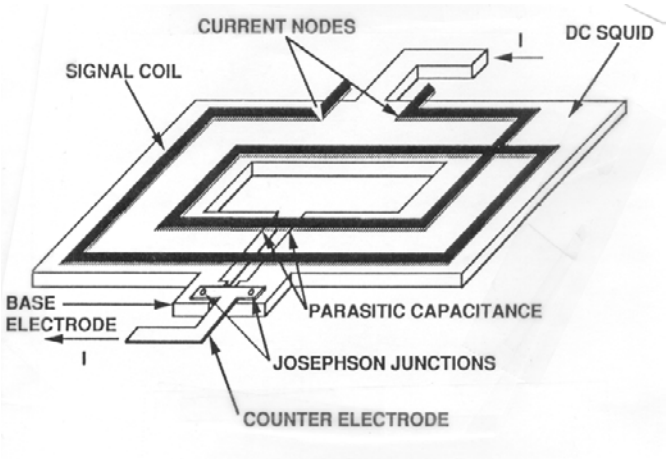
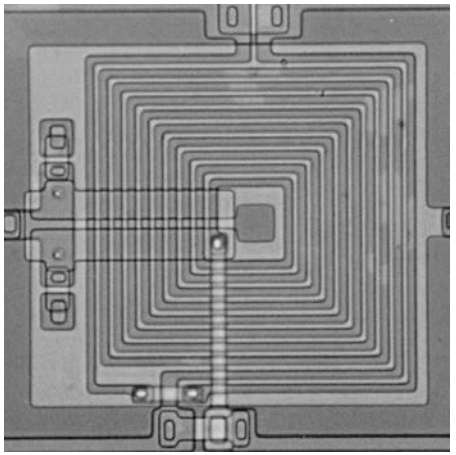
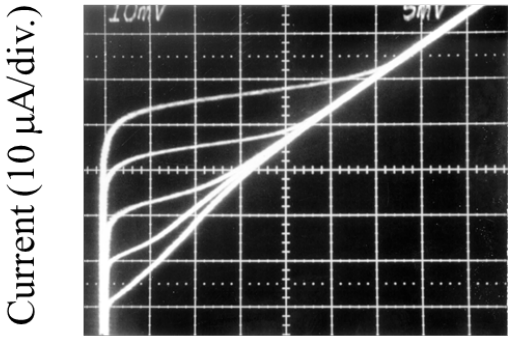
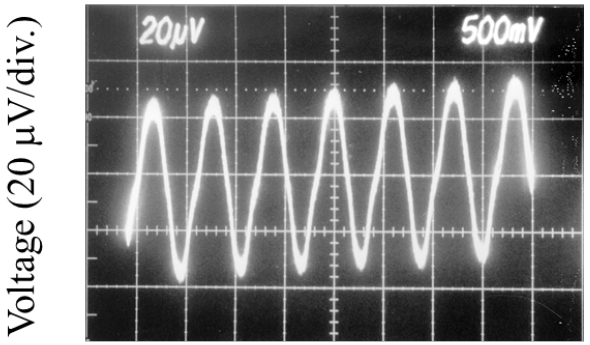
SQUID (Superconducting QUantum Interference Device)











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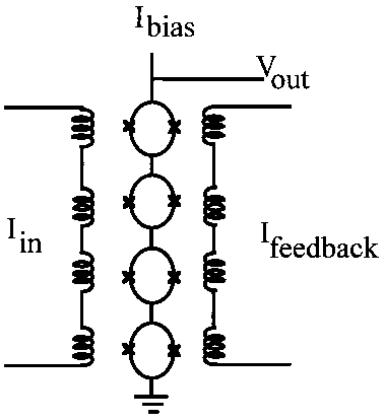
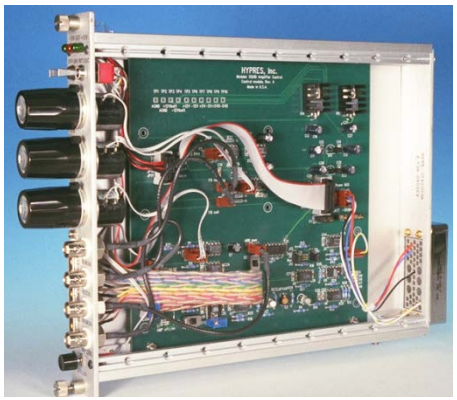
SQUID Magnetometer/Amplifier



- Simple peripheral electronics
- Wide bandwidth amplifier
- Extremely low power dissipation
- Multi-channel

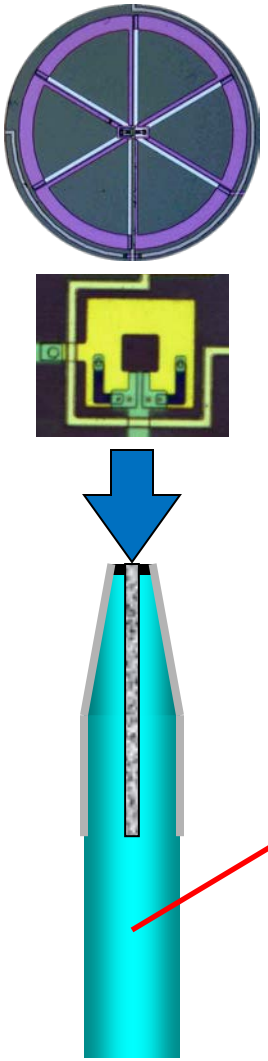


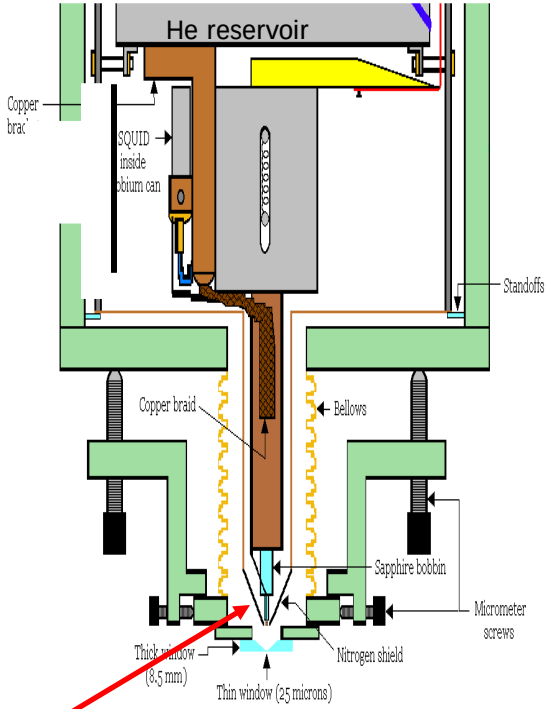
SQUID array Magnetometer/amplifier

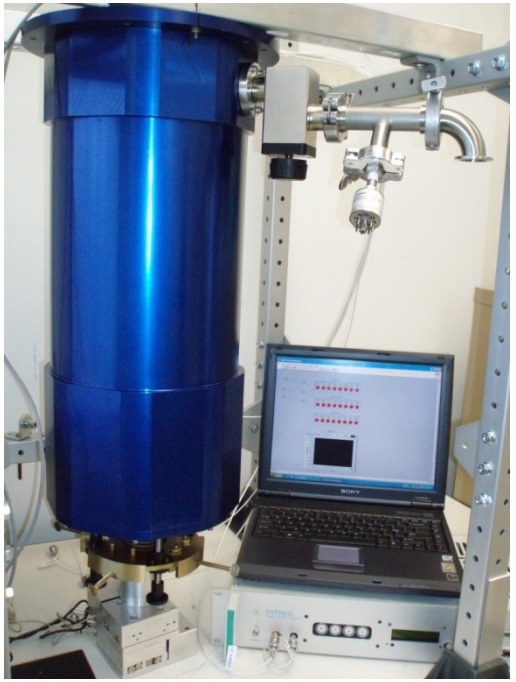
HYPRES

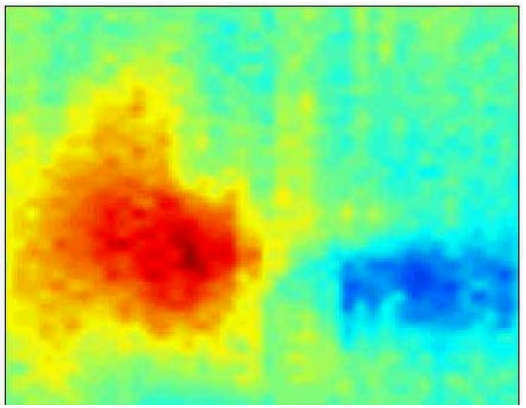
SQUID Microscope

500 μm









Rabbit Heartbeat

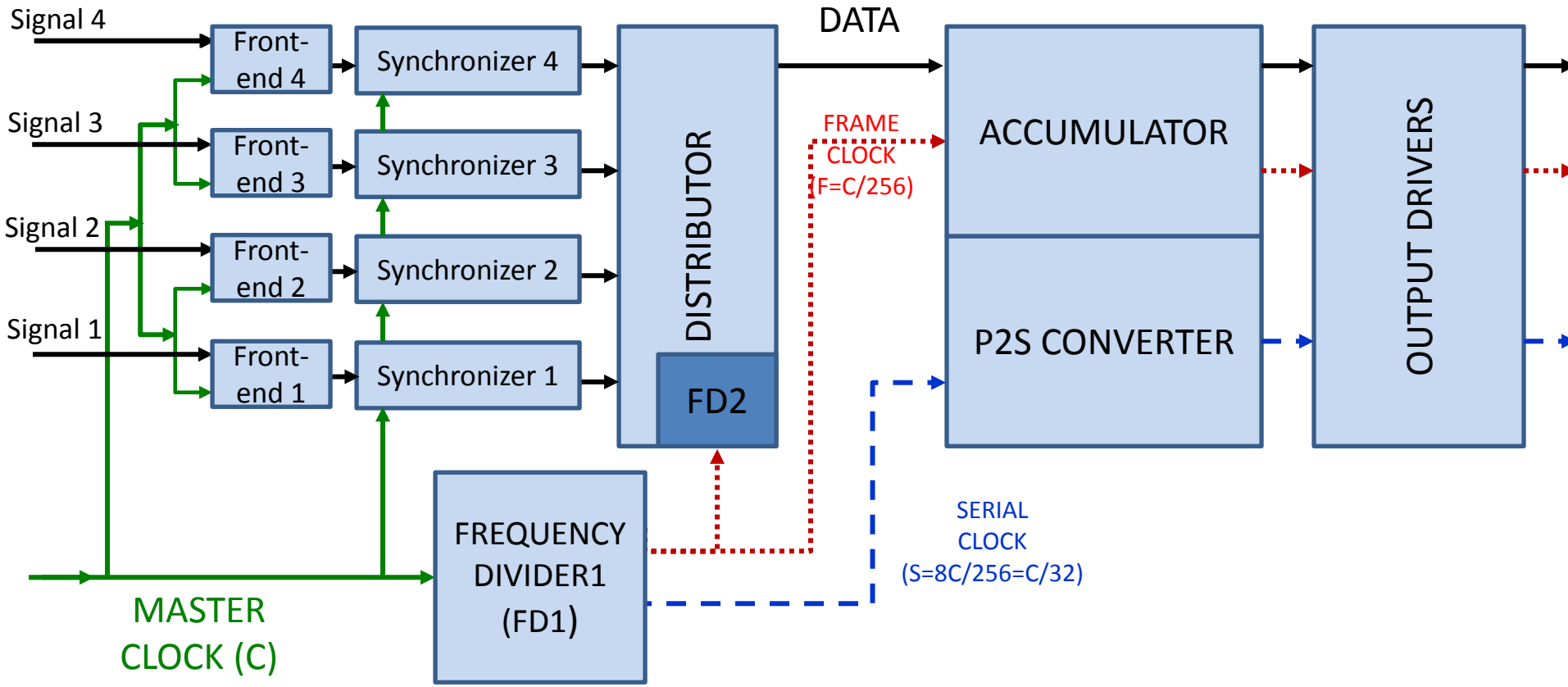
HYPRES

Objective

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

Schematic of 4-Channel Read-out Circuit



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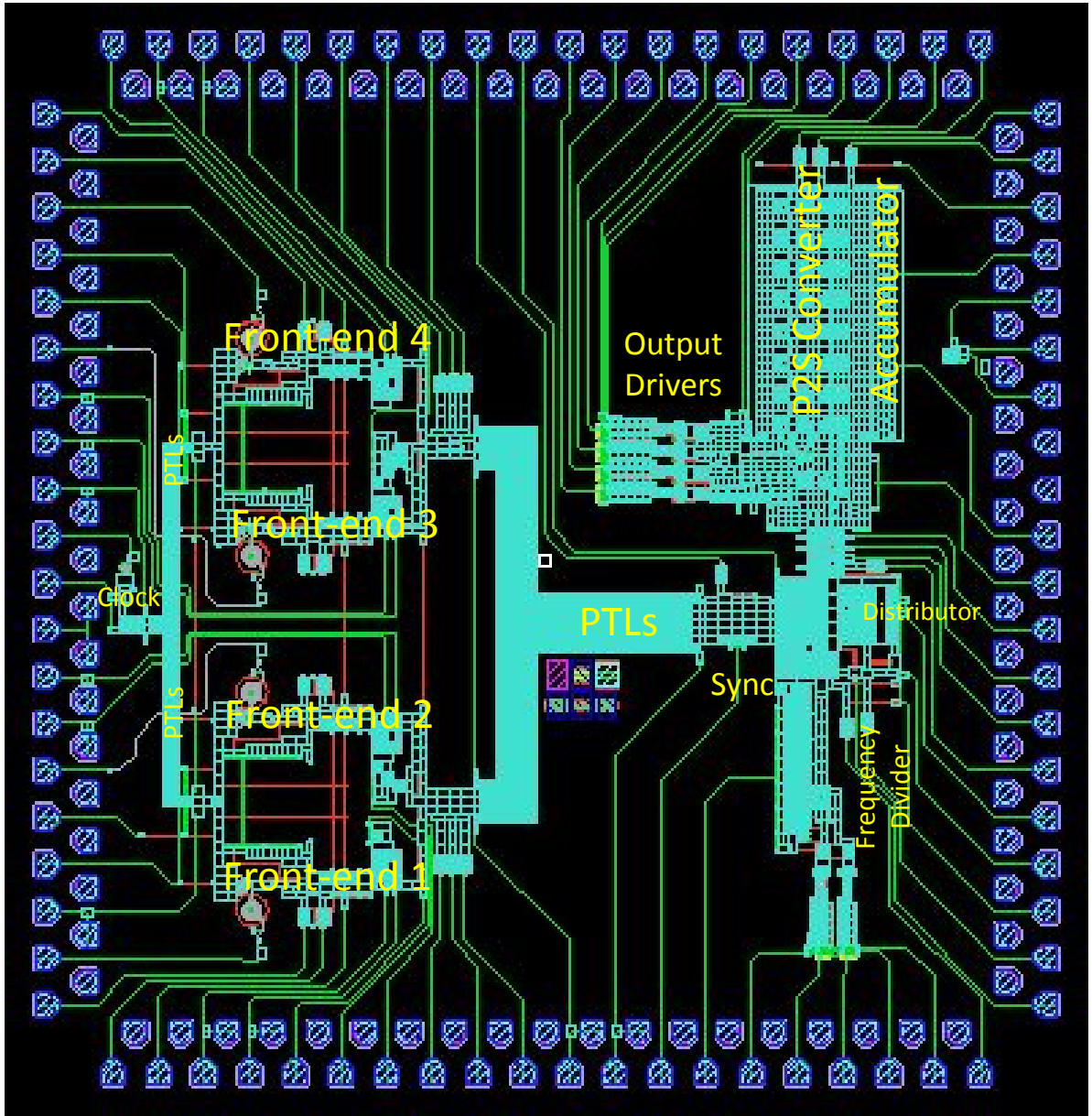
Layout of 4-Channel Read-out Circuit



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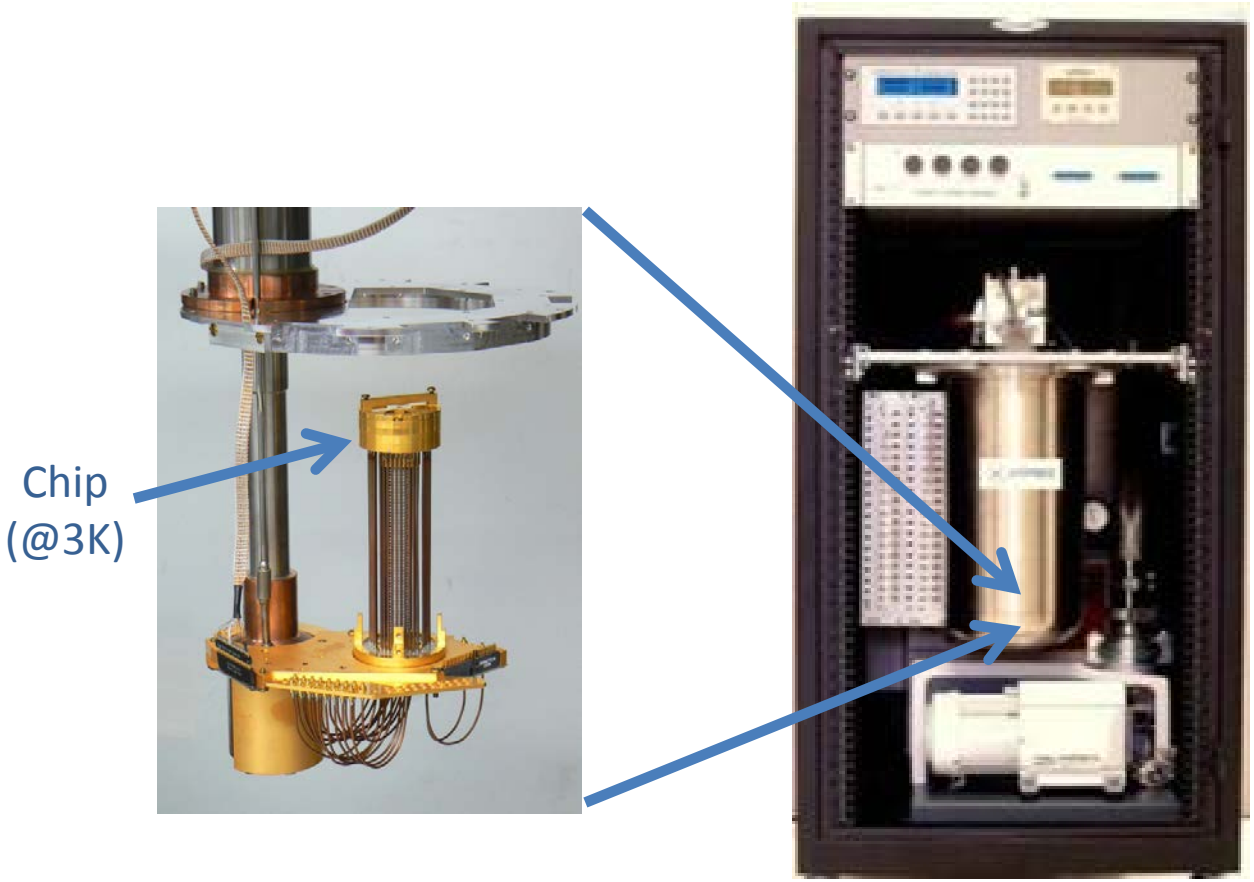
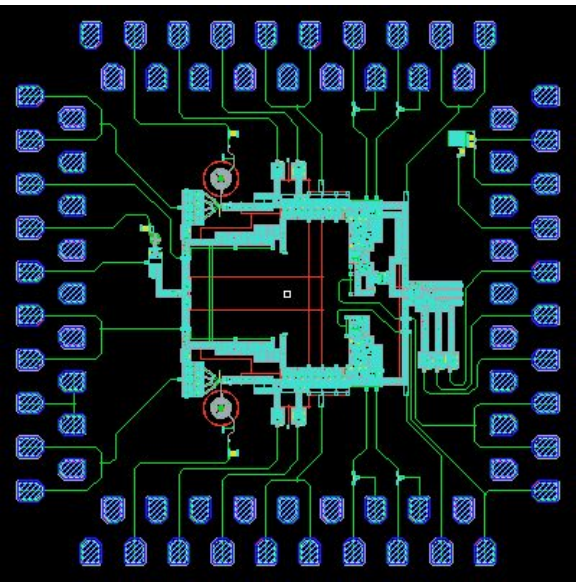
Cryogenic Package / Peripheral Electronics

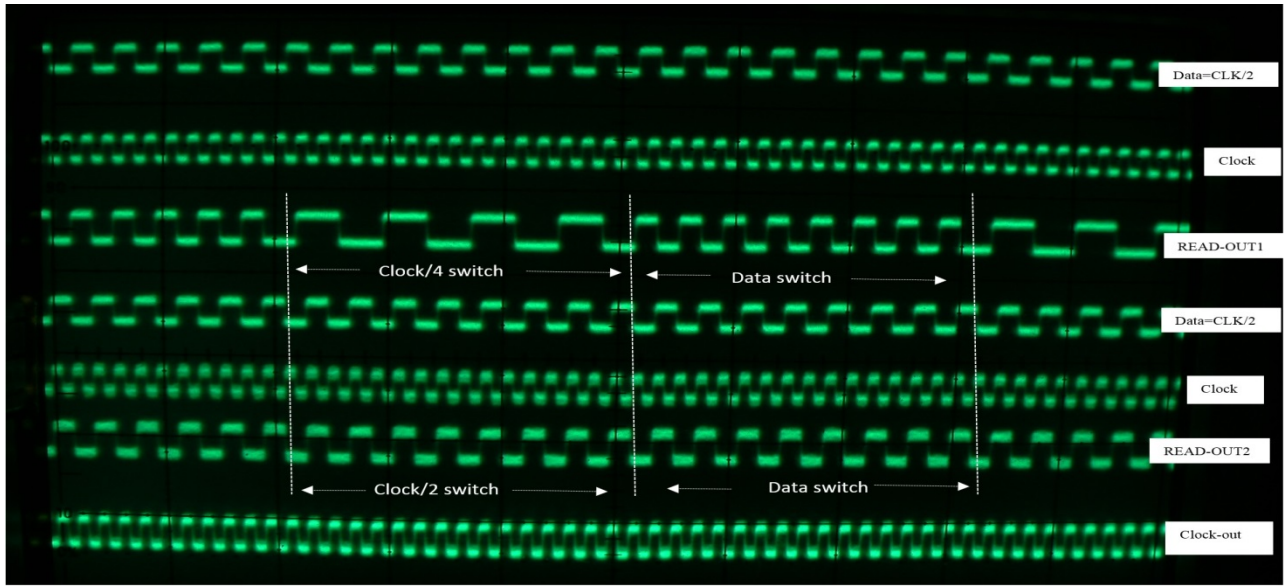


HYPRES

Diagnostic Circuits: Front-ends

Experimental Results





Test result of two-input front-end. The first three waveforms correspond to signal at Front-end 1 and next three waveforms correspond to signal at Front-end 2. The last waveform is clock-out propagation. Readout is generated by applying two square wave at 5 KHz and 180 degree phase difference to two switches of the each circuit. Switch 1 of Circuit 1 will allow propagation of Clock divided by 4 pulses, while Switch 1 of Circuit 2 allows propagation of Clock divided by 2 pulses. Switch 2 in both circuits allow Data propagation.

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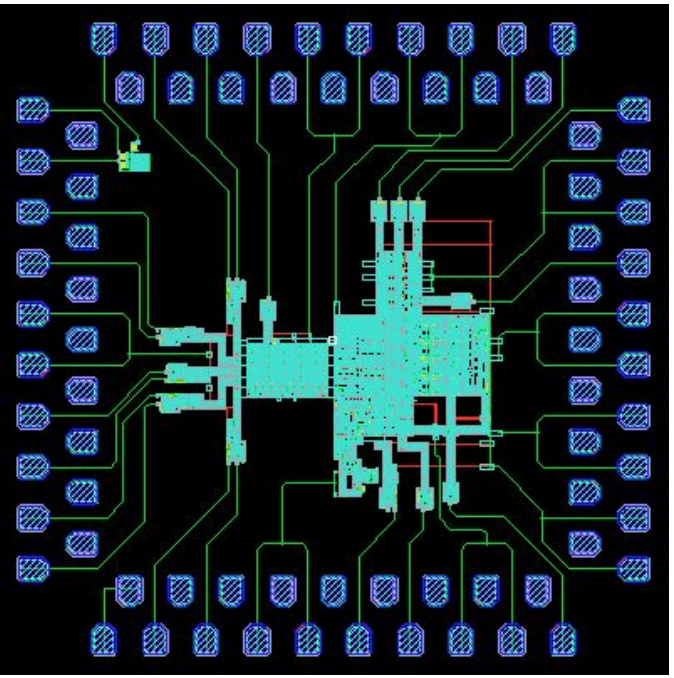
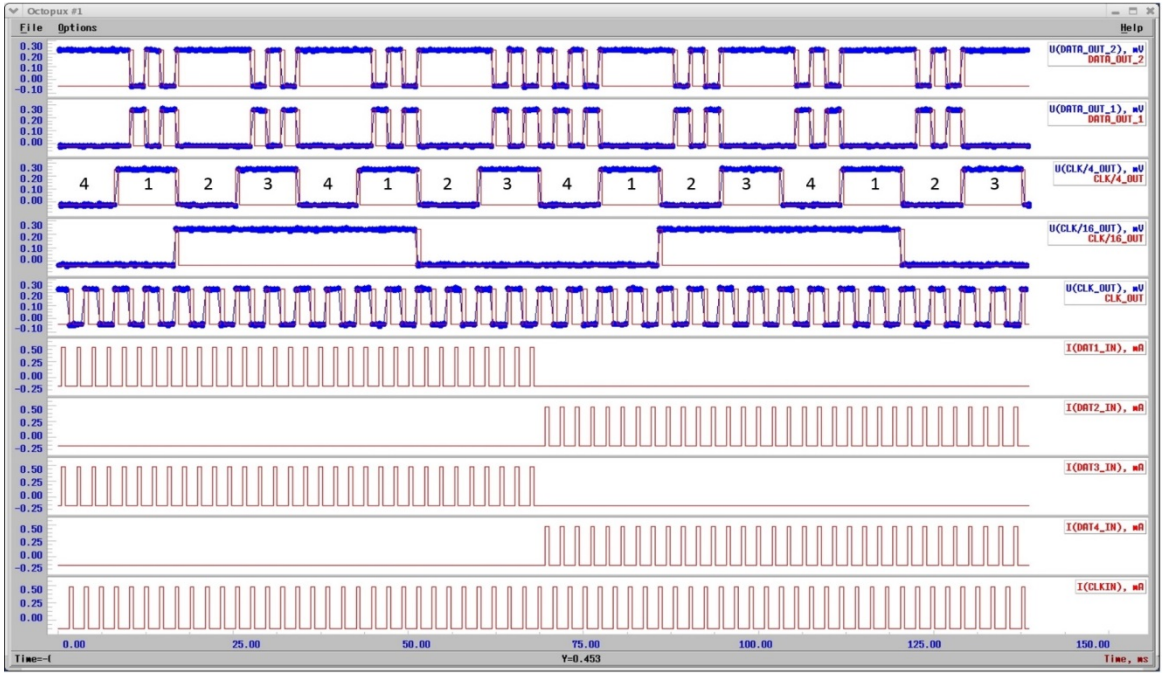
Diagnostic Circuit: Multiplexer

Experimental Results





Low frequency functional test of the 4-to-1 multiplexer. The inputs are applied through channel Dat1_in, Dat2_in, Dat3_in and Dat4_in while CLK/4_OUT represents the selected channel as shown in the figure. The output replicates as Data_out_1 and Data_out_2.

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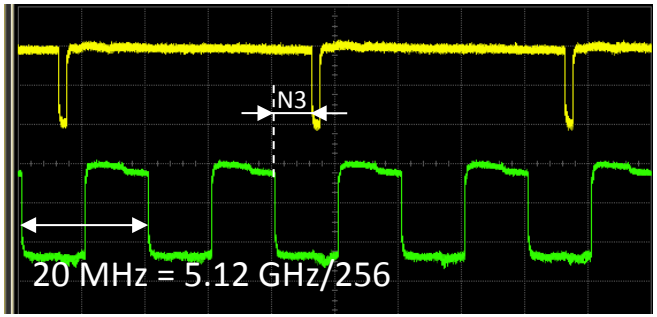
4-Channel Read-out Circuit

Experimental Results: Digital bits

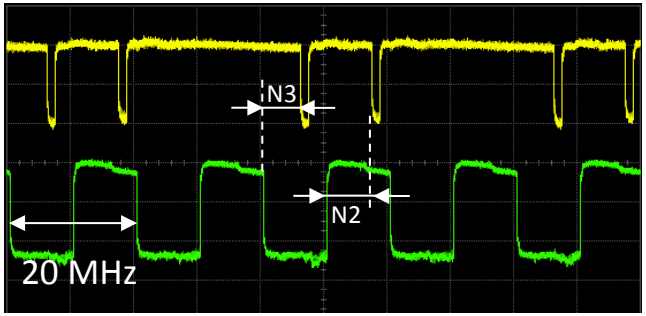


Data Output 3

Frame Output

Digital data output for input line 3.

N2>N3



Data Output 2 & 3

Frame Output

Digital data outputs for input lines 2 & 3. The timing of the signals after transition in frame output identifies the input.

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Accomplishments

- Completed the design, simulation, fabrication of the first iteration 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 iteration of the 4-channel digital SQUID amplifier was evaluated. The optimized 4-channel amplifier is currently being fabricated and is expected to become available by October 2014.