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
Zero Resistance

Expulsion of Magnetic Flux

\[ \Phi = \int B \, dA = n \Phi_0 \]

\[ \Phi_0 = \frac{\hbar}{2e} = 2.07 \text{ mV \cdot ps} \]

Single Flux Quantum (SFQ)

Magnetic Flux Quantization

Superconductivity

Josephson Junctions, and SQUIDs
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
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

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

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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All Digital Receiver

HYPRES
Sampling Oscilloscope

- 100 GHz sine-wave
- 70 GHz bandwidth
- 50 µV sensitivity

PSP 750
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- PSP-1000: 70-GHz Sampling Oscilloscope
- FFT Element
- RAM
- Flash
- Transient Digitizer
- ADC+DDF
- SQUID Microscope
- All Digital Receiver

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. & Stdts. 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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All Digital Receiver
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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All Digital Receiver

HYPRES
SQUID (Superconducting QUantum Interference Device)

Josephson junctions

Current (10 μA/div.)

Voltage (10 μV/div.)

Voltage (20 μV/div.)

I/P Current (1 μA/div.)
SQUID Magnetometer/Amplifier

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

SQUID array Magnetometer/amplifier
SQUID Microscope

500 µm

Rabbit Heartbeat
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 $\sim 6 \times 10^{-21} \text{ Wb/√Hz}$
- 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 $\sim 20 \text{ GHz}$ allows multiplexing of 100s of channels
Layout of 4-Channel Read-out Circuit
Cryogenic Package / Peripheral Electronics

Chip (@3K)
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.
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.
4-Channel Read-out Circuit

Experimental Results: Digital bits

Digital data output for input line 3.

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