Advanced SQUID Sensors and Readout Electronics in Support of the nEDM Experiment and Commercial Applications

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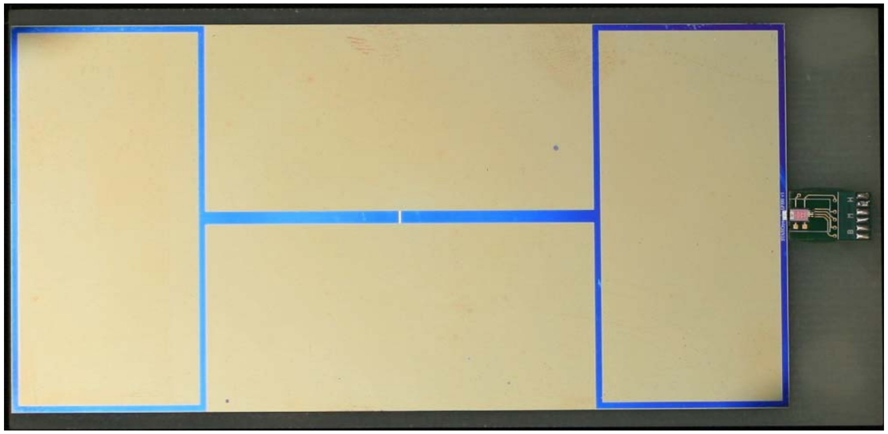
OUTLINE

- Company Overview
- SQUID Tutorial
- SQUID Sensor and Packaging Development
- Readout Electronics Development
- Commercial Applications



Prototype planar first-order SQUID gradiometer assembly designed for nEDM experiment

Work supported by DOE under Contract No. DE-FG02-08ER84990

Company Overview

- Founded April 1999
- Licensed magnetic sensing technology, acquired production inventory and thin-film manufacturing infrastructure from Conductus, Inc. (Sunnyvale, CA) in July 1999
- Acquired building in Santa Fe, NM in June, 2001
- 6,000 sq-ft of office, lab, cleanroom and warehouse space; additional 2,000 sq-ft recently acquired
- Total investments in infrastructure over $3,000,000
- 5 employees and 4 contract consultants

Products

- LTS and HTS dc SQUID sensors
- pcSQUID™ - Advanced PC-based SQUID readout electronics
- TES and STJ X-ray and alpha particle detectors
- Mr. SQUID® Educational Demonstration System
- Custom SQUID and thin-film foundry services
- Next-generation energy dispersive spectrometers based on TES microcalorimeter detectors for X-ray nanoanalysis and nuclear forensics
- High resolution spectrometers based on Ta STJ detectors for energy absorption spectroscopy at the synchrotron
- Cryogen-free ADR cryostats for R&D

Basic DC SQUID Operation

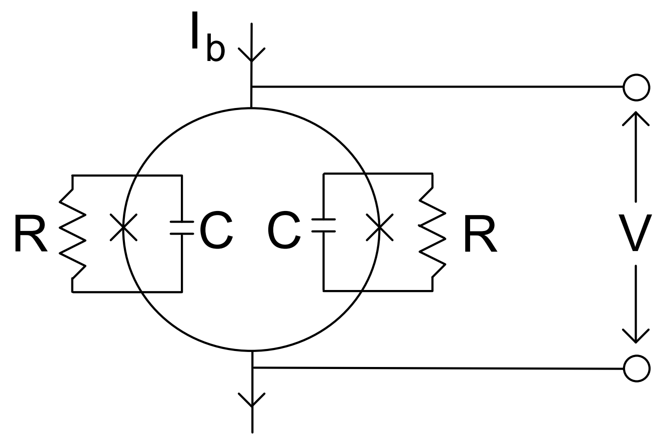
- Two Josephson junctions connected in parallel, represented by resistively shunted junction (RSJ) model
- **Optimal design parameters**:

  Stewart-McCumber parameter $\beta_c = \frac{2\pi}{\Phi_0} I_c R^2 C < 1$

  Modulation parameter $\beta = \frac{2LI_c}{\Phi_0} \approx 1$
- **Figure of merit**:

  Energy resolution $\varepsilon = \frac{S_\Phi}{2L} \approx 12 k_B T \sqrt{LC} \propto \sqrt{\frac{C_s}{J_c}}$
- **For lowest noise performance require**:

Low SQUID inductance L	~ 10 pH
Low capacitance C	< 1 pF
High critical current density J_c	> 1 kA/cm^2



I_c: Critical current

J_c: Critical current density

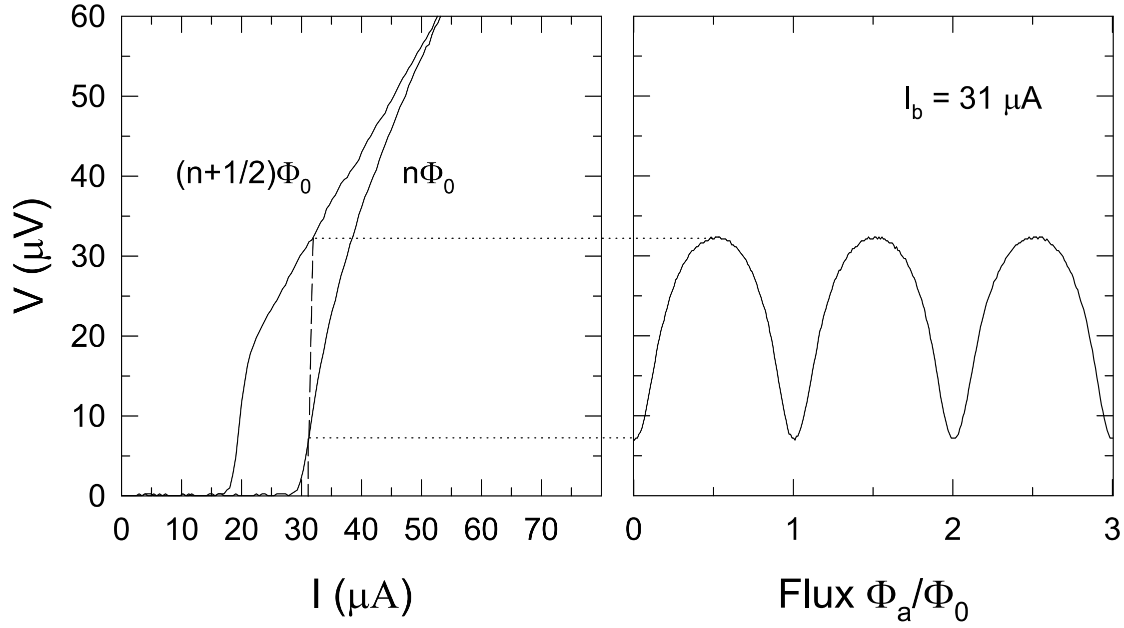
C_s: Specific capacitance

$\Phi_0 = 2.068 \times 10^{-15}$ Wb

Basic DC SQUID Operation

Operation with constant current bias I_b

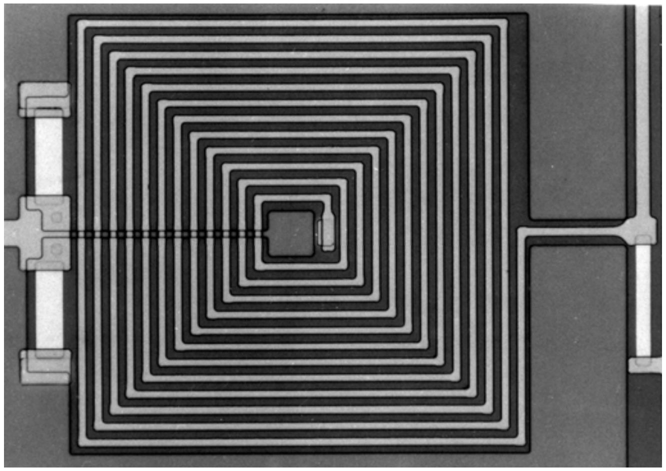
- Voltage output is a period function of applied flux
- Use flux-locked loop feedback electronics to linearize output



Basic DC SQUID Operation

Optimization for practical applications

- Improve flux capture area using pickup loop transformer-coupled to SQUID inductance
- Integrated magnetometers for magnetic field measurements
- Integrated gradiometers for magnetic field gradient measurements



$$S_B^{1/2}(f) = B_\Phi \cdot S_\Phi^{1/2}(f)$$

$$B_\Phi = \Phi_0 \frac{L_p + L_{i,eff} + L_{par}}{M_i} \frac{1}{A_{eff}}$$

$$G_n^{1/2}(f) = S_B^{1/2}(f)/b$$

A_{eff}: Effective area of pickup loop

L_p: Pickup loop inductance

$L_{i,eff}$: Effective input coil inductance

L_{par}: Parasitic inductance

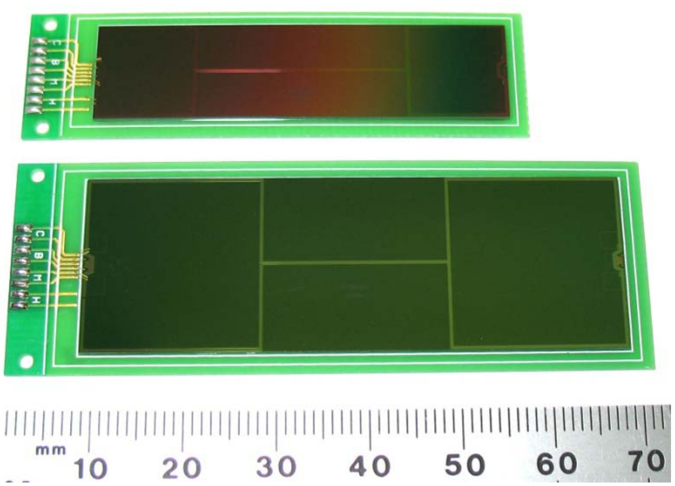
M_i: Mutual inductance of input coil

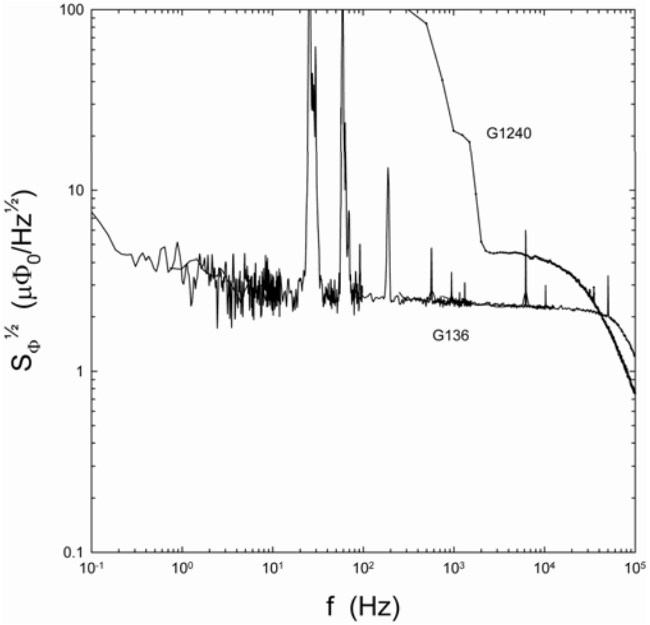
b: Gradiometer baseline

Integrated SQUID Gradiometer Development for nEDM

Long baseline first-order planar gradiometers

- G136 with 3.6 mm baseline
  - B_{Φ} = 0.63 nT/Φ_0, $S_B^{1/2}$ = 1.5 fT/Hz$^{1/2}$, G_n = 0.42 fT/cm-Hz$^{1/2}$
- G1240 with 4.0 mm baseline
  - B_{Φ} = 0. 3 nT/Φ_0, $S_B^{1/2}$ = 0.9 fT/Hz$^{1/2}$, G_n = 0.23 fT/cm-Hz$^{1/2}$ (estimated values)

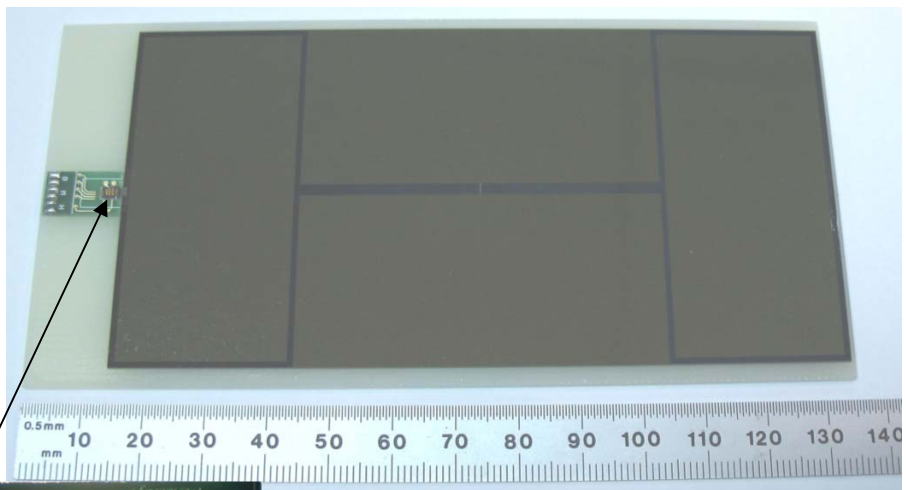


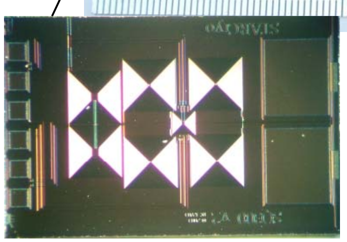


Ultra-Sensitive Gradiometer Development for nEDM

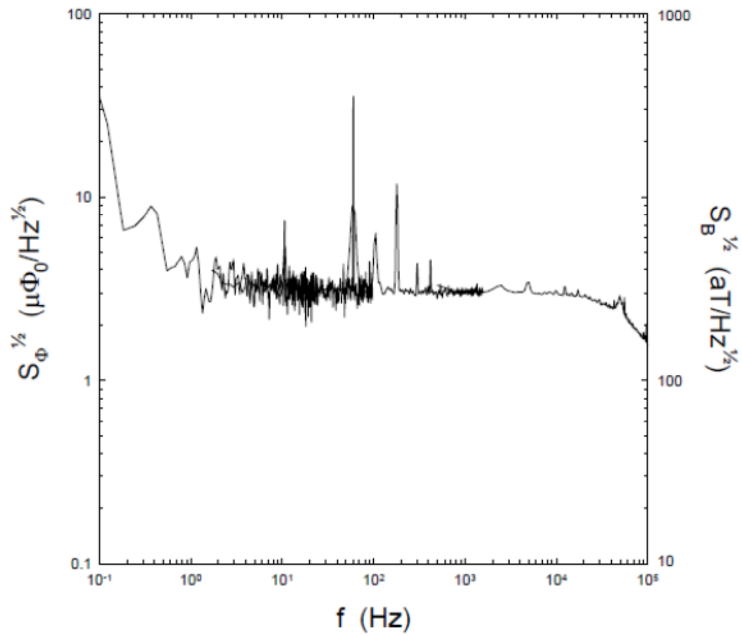
Multi-chip module with pickup loop chip and SQUID chip

- Fabricate four-layer pickup loop with 90 mm baseline on 150 mm wafer
- Wire bond to input of separate SQ300 SQUID chip with Nb ribbon
- B_{Φ} = 0.105 nT/Φ_0, $S_B^{1/2}$ = 0.3 fT/Hz$^{1/2}$, G_n = 0.033 fT/cm-Hz$^{1/2}$ (est. noise values)





SQ300 chip, 2 mm × 3 mm



Typical rms flux noise of SQ300 with open input (left axis), projected field noise with pickup loop (right axis)

Ultra-Sensitive Gradiometer Development for nEDM

Options

- Need extremely robust fabrication to reduce risk of damage in strong *E*-field within experimental cell,

  \- or -

- Remotely located SQUIDs (outside of main experimental cell)

Issues

- Remotely locating SQUIDs requires high input inductance design with very high input coupling (M_i)

$$B_\Phi = \Phi_0 \frac{L_p + L_{i,eff} + L_{par}}{M_i} \frac{1}{A_{eff}}$$

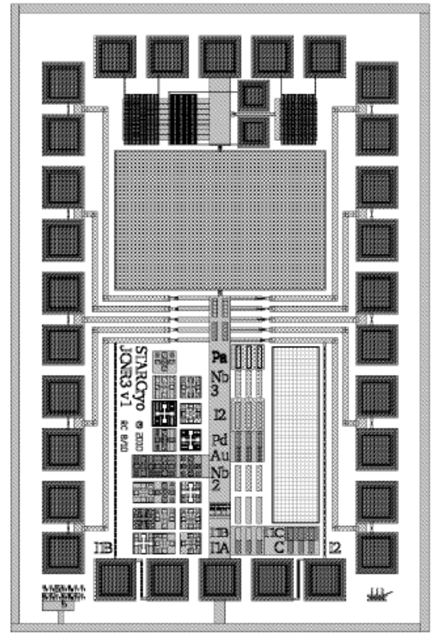
- Can be accomplished using large, multi-turn input coils
  - Introduces large parasitic capacitance that can degrade performance
  - Requires interlayer insulation with low dielectric constant

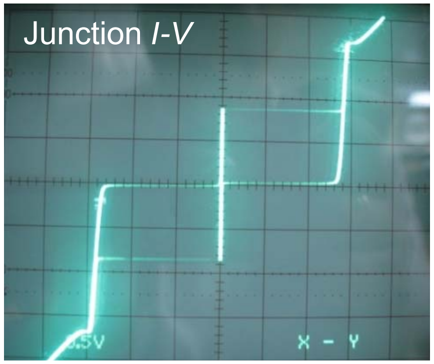
Improved SQUID Process Development

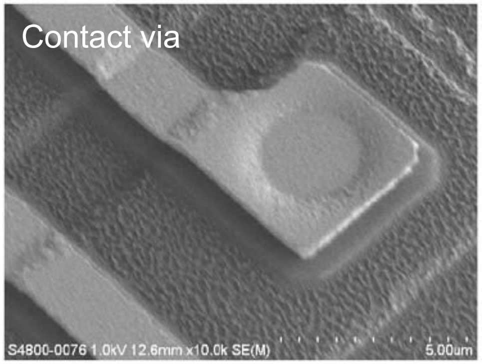
Key Improvements

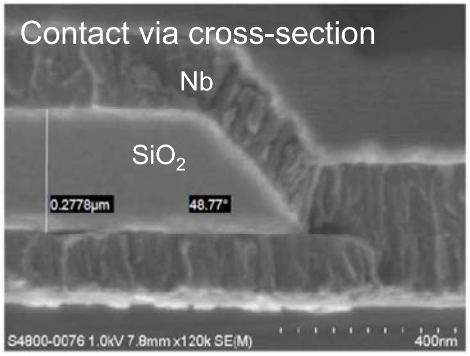
- Josephson junctions defined using dry etch (RIE) process
- PECVD SiO_2 used for all interlayer dielectrics
- New Nb and via RIE processes to improve cross-overs
- Dramatic results for via, cross-over critical current I_c
  - Junction vias (2 µm) ~ 40 mA
  - Wiring vias (2.5 µm) ~ 200 mA
  - Wiring cross-overs (3 µm) ~ 200 mA (~10 MA/cm^2)

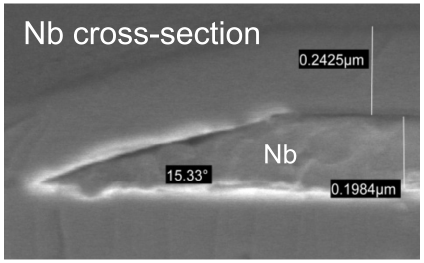
Process Test Chip, 2 × 3 mm









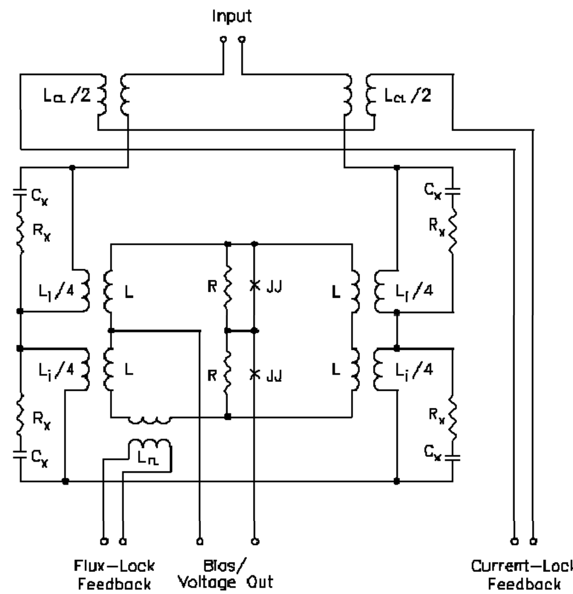


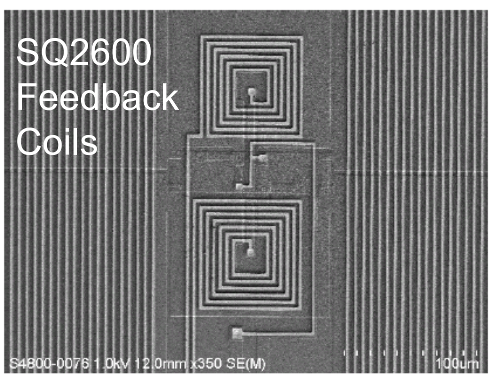
SQUIDs for High Inductance Loads

Two successful candidate designs:

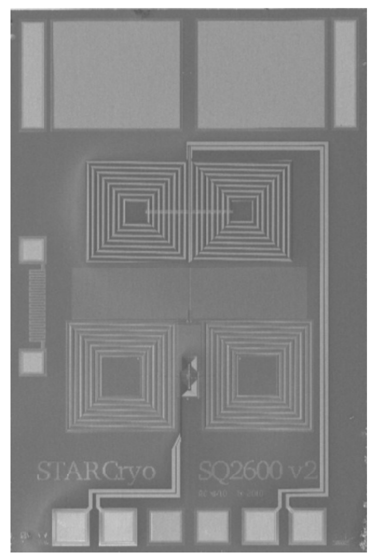
- ► **SQ1200** (four-washer series-parallel, symmetric feedback)
  - – 1200 nH input, 0.13 $\mu A/\Phi_0$ input coupling
  - – ~4 $\mu\Phi_0/Hz^{1/2}$ flux noise with matched load (~500 fA/Hz$^{1/2}$ current noise)
- ► **SQ2600** (two-washer parallel, symmetric feedback)
  - – 2600 nH input, 0.096 $\mu A/\Phi_0$ input coupling
  - – ~2.5 - 4 $\mu\Phi_0/Hz^{1/2}$ flux noise (~250 to 400 fA/Hz$^{1/2}$ current noise; lowest noise commercially available)

SQ1200 Schematic

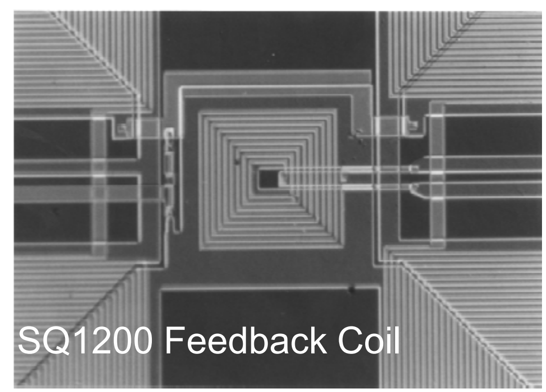




SQ2600 Feedback Coils



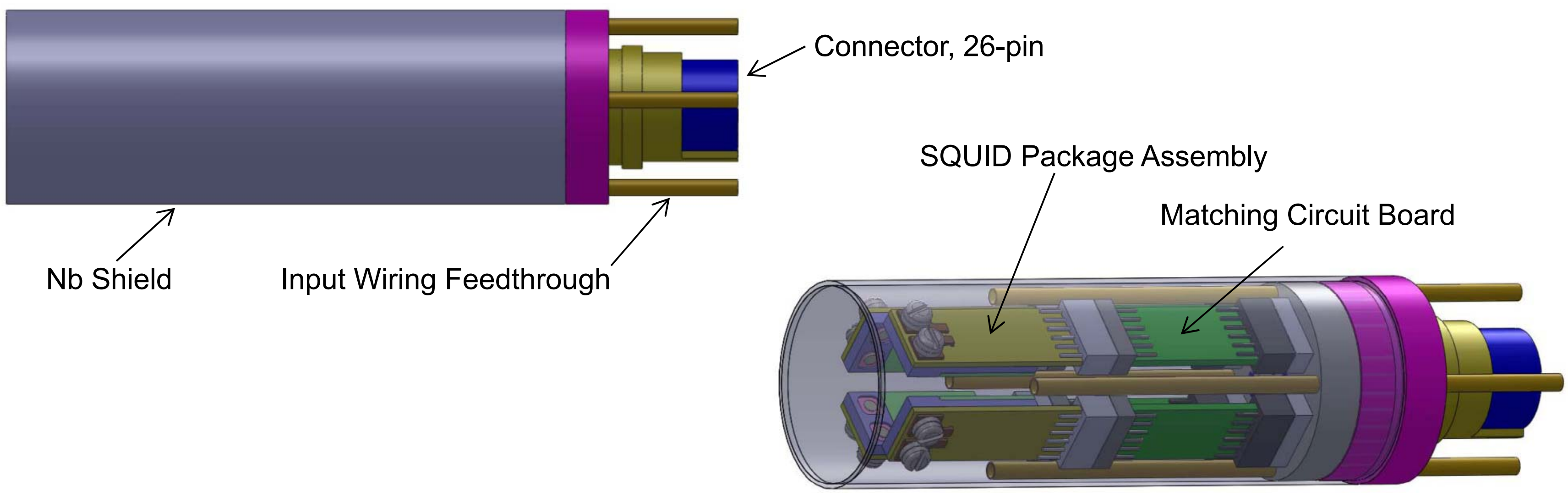
SQ2600 Chip


SQ1200 Feedback Coil

SQUID Package Development for nEDM

Key Features

- Four SQUID channels per assembly
- Reliable connector interface based on LEMO 26-pin connectors
- Optional cooled matching transformer circuit board for each channel
- Modular sensor package with connectorized interface

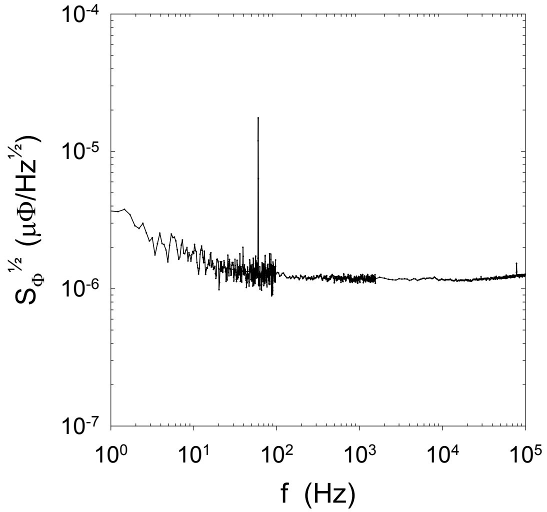


SQUID Readout Electronics Development for nEDM

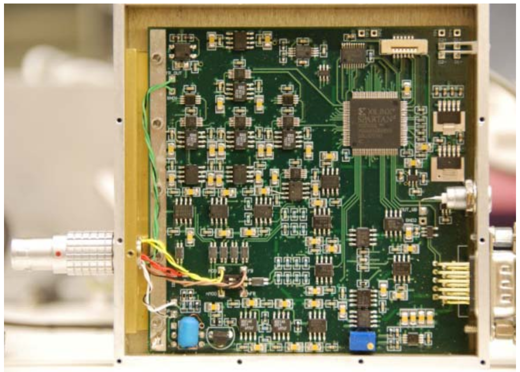
Overview

- Robust design based on flux modulation technique
- Useable bandwidth extended from 100 kHz to ~1 MHz
- All drive signals and feedback loop parameters configurable via software
- Single-channel design successfully completed, eight-channel design underway

Current single- and eight-channel feedback loops



Measured rms white flux noise of a STAR Cryoelectronics SQ100 SQUID, recorded using second revision of prototype feedback loop design



Prototype single-channel feedback loop assembly

Commercial Developments

Commercial products that leverage core technologies developed as part of the nEDM SBIR project include:

- Advanced SQUID sensors and related packaging
- High-speed, multi-channel, PC-based dc SQUID readout electronics

Applications and markets include:

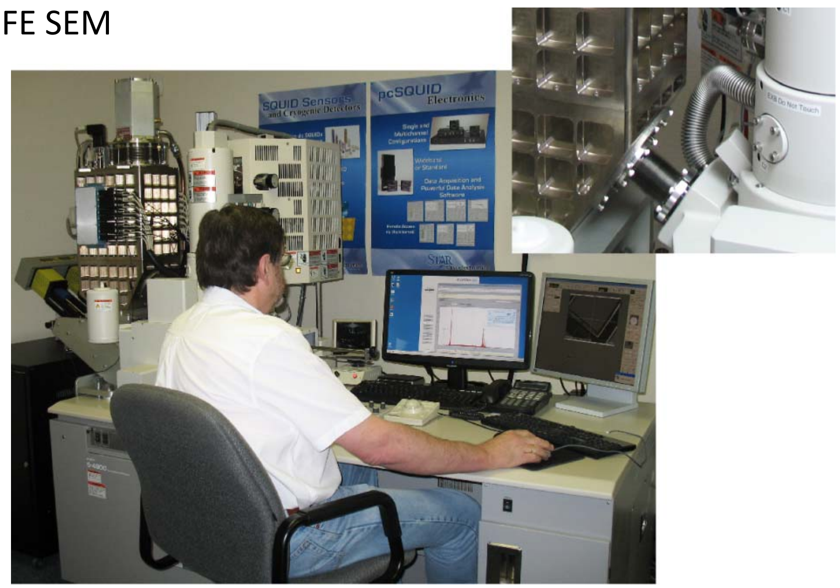
- Biomedical imaging
  - Magnetoencephalography (MEG) and magnetocardiography (MCG)
- Advanced, cryogen-free spectrometers
  - X-ray nanoanalysis
  - Alpha particle spectroscopy
  - X-ray absorption spectroscopy at the synchrotron

Spectrometer Development

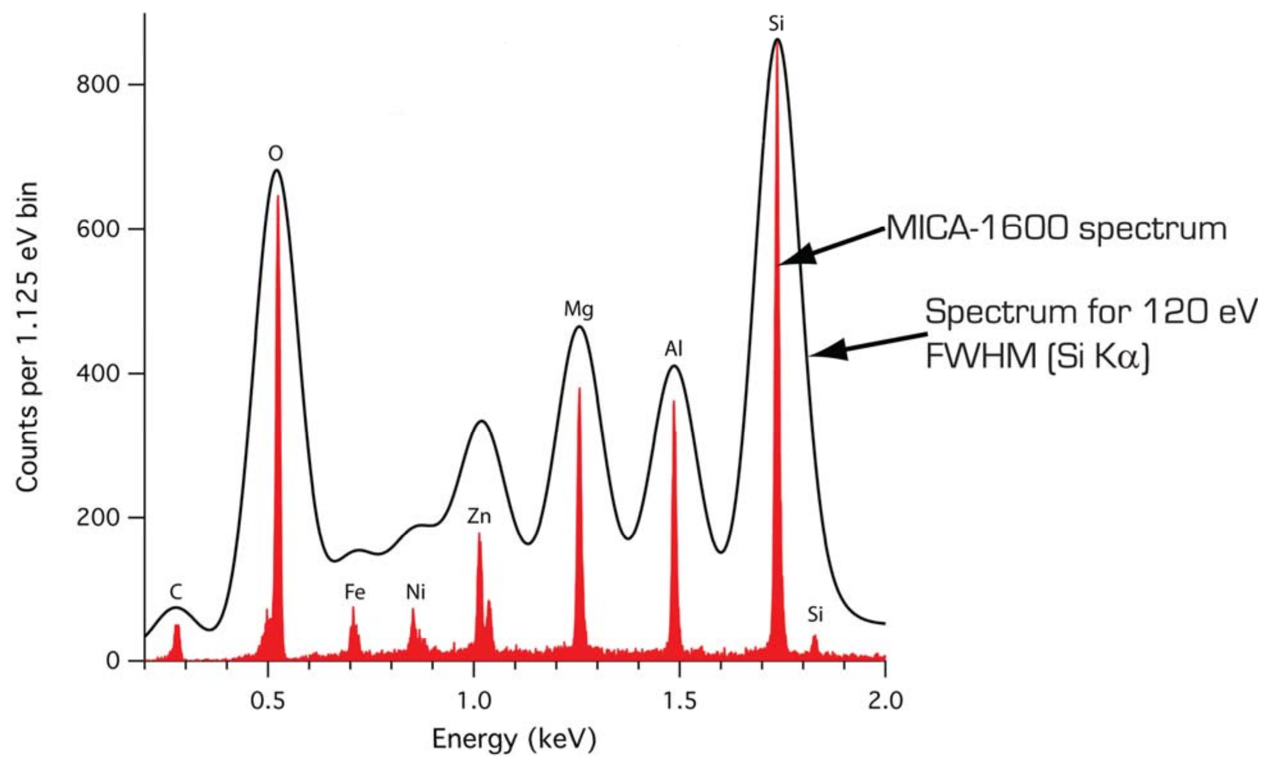
MICA-1600 Spectrometer for X-Ray Nano-Analysis

A next-generation, cryogen-free energy-dispersive X-ray spectrometer with the energy resolution of a wavelength dispersive spectrometer (WDS)

MICA-1600 X-ray spectrometer with Bruker pulse processor and Quantax EDS analysis software mounted on a Hitachi S-4800 FE SEM



MICA-1600 Application Data

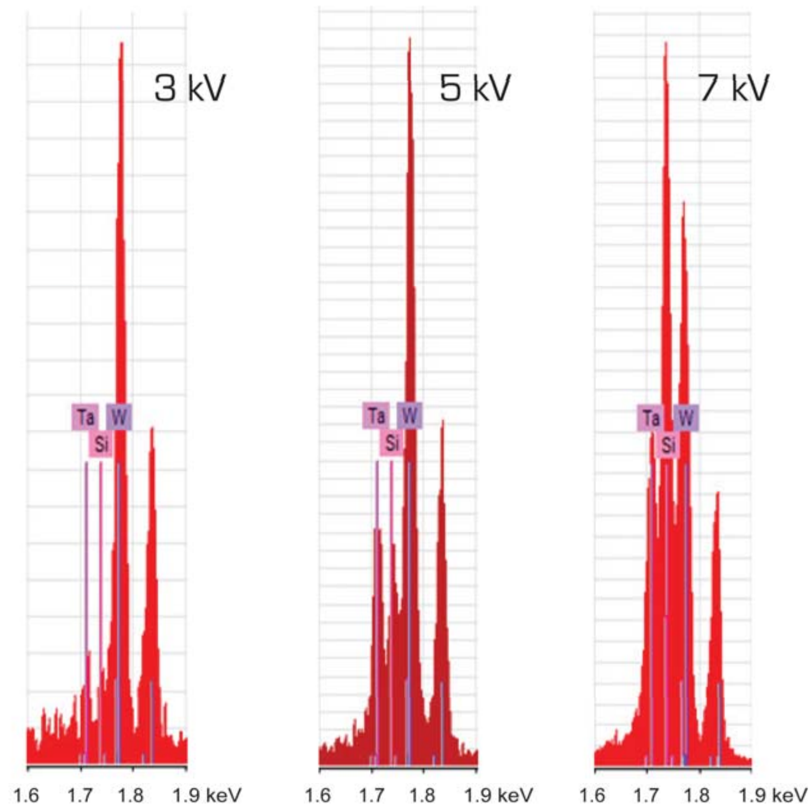


Sample: NIST K3670 reference glass, Vacc = 7 kV (red spectrum). All peaks clearly resolved, including Zn Lα (1.012 keV) and (Zn Lβ (1.034 keV) peaks. The equivalent spectrum that would be measured with 120 eV resolution (FWHM at Si Kα) typical for a conventional EDS spectrometer is shown for comparison (black spectrum).

MICA-1600 Application Data

MICA-1600 clearly resolves Ta, Si, and W peaks around 1.75 keV and enables surface analysis of nanometer-scale films.

Spectra on the right illustrate the effect of the increasing X-ray excitation volume with increasing beam voltage.

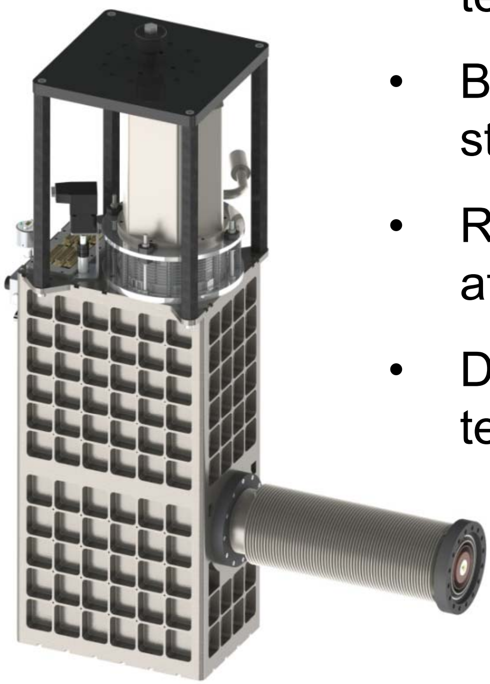


Sample: W (20 nm) over Ta (20 nm) on Si

Spectrometer Development

Alpha Particle and X-Ray Absorption (EAS) Spectroscopy

- Cryogen-free ADR design with 0.7 W pulse tube cooler
- Fully automated ADR control and temperature regulation
- Base temperature <50 mK, stability <10 µK rms at 100 mK
- Remote rotary valve and vibration isolation at 300 K, 60 K, and 3 K
- Detectors and SQUID readouts leverage technologies developed for nEDM project



DRC-102 Ta-based STJ Cryostat Configured for Synchrotron Science Applications

DRC-201 Alpha TES Microcalorimeter Cryostat Configured with Load Lock for Nuclear Forensics Applications

Summary

SQUID Gradiometer Development

- Ultra-sensitive integrated SQUID gradiometers and magnetometers successfully developed
- New robust SQUID fabrication process implemented
- Successfully developed new high input inductance SQUIDs

SQUID Readout Electronics Development

- Developed next-generation designs for single-channel and multi-channel applications
- Bandwidth extended by an order of magnitude
- Flexible design architecture with PC-based software control