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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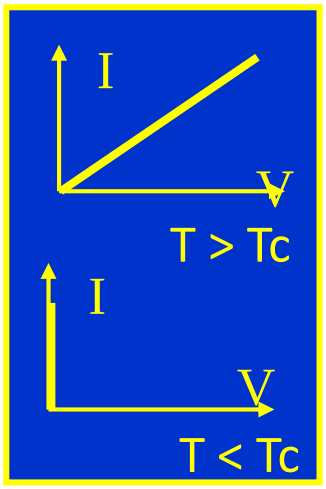
Outline

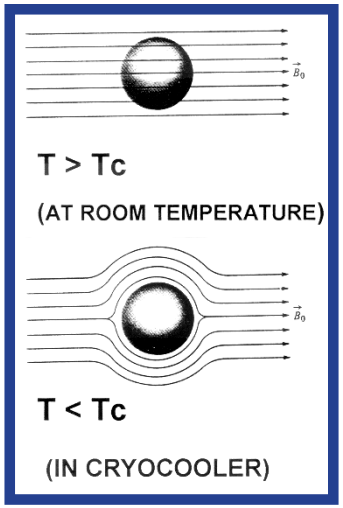
- Superconducting Technology Overview
- Company Overview
- DOE Program Goals, Approach, and Accomplishments
- Applications and Commercialization

Superconductivity

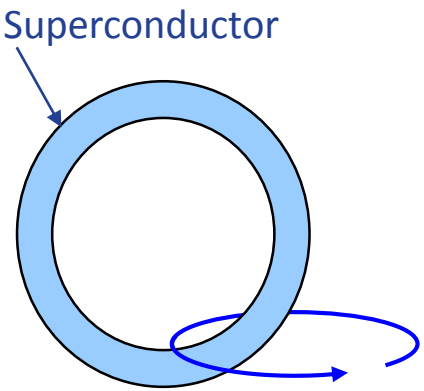
Zero Resistance



Expulsion of Magnetic Flux



Magnetic Flux Quantization



Single quantized unit of magnetic flux ("fluxon")

Flux Quantization

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

h = Plank's constant; e = Electron charge

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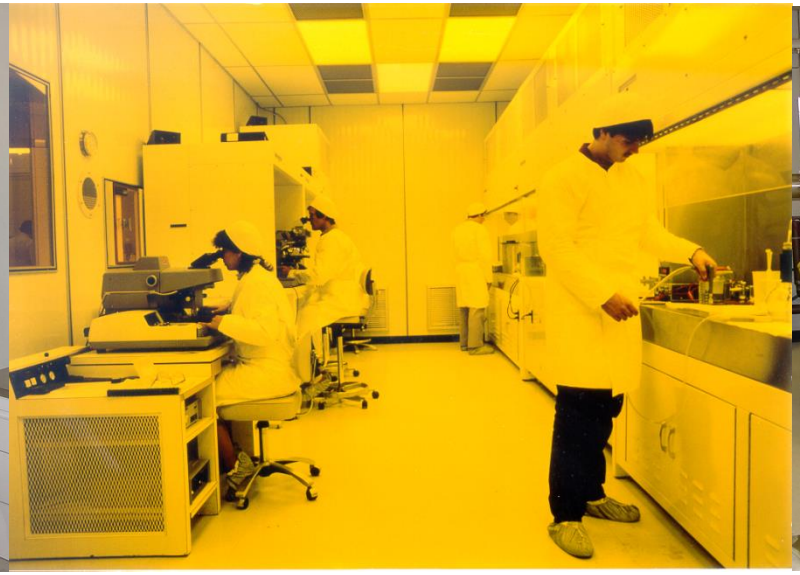
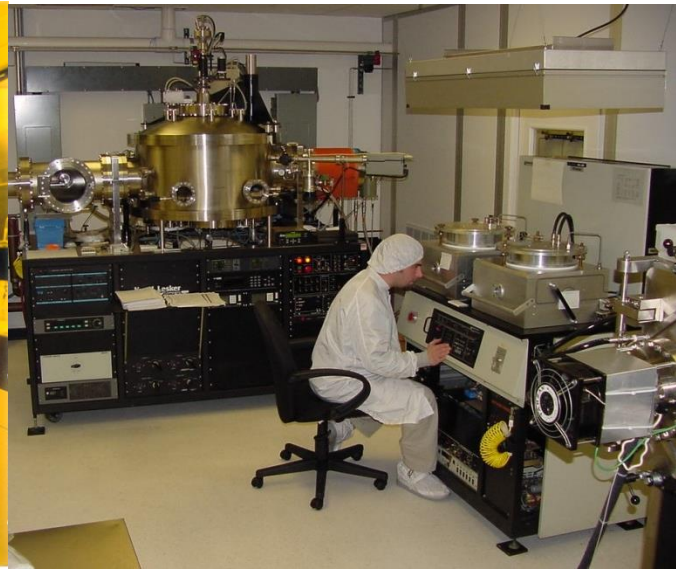
HYPRES, Inc. - Elmsford, NY

- 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

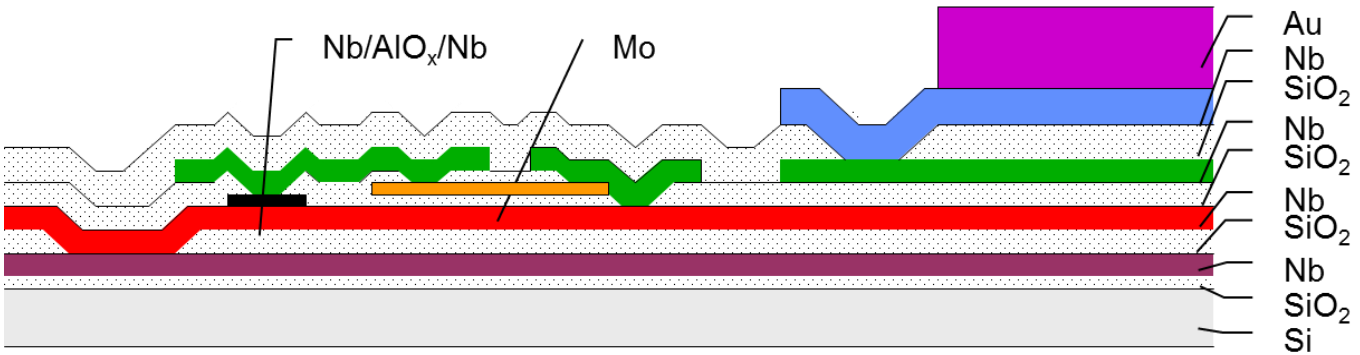
Develop and deploy innovative receivers, sensors, and high performance computing solutions based on superconducting circuits and cryoelectronics

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

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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Applications for Josephson Circuits

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

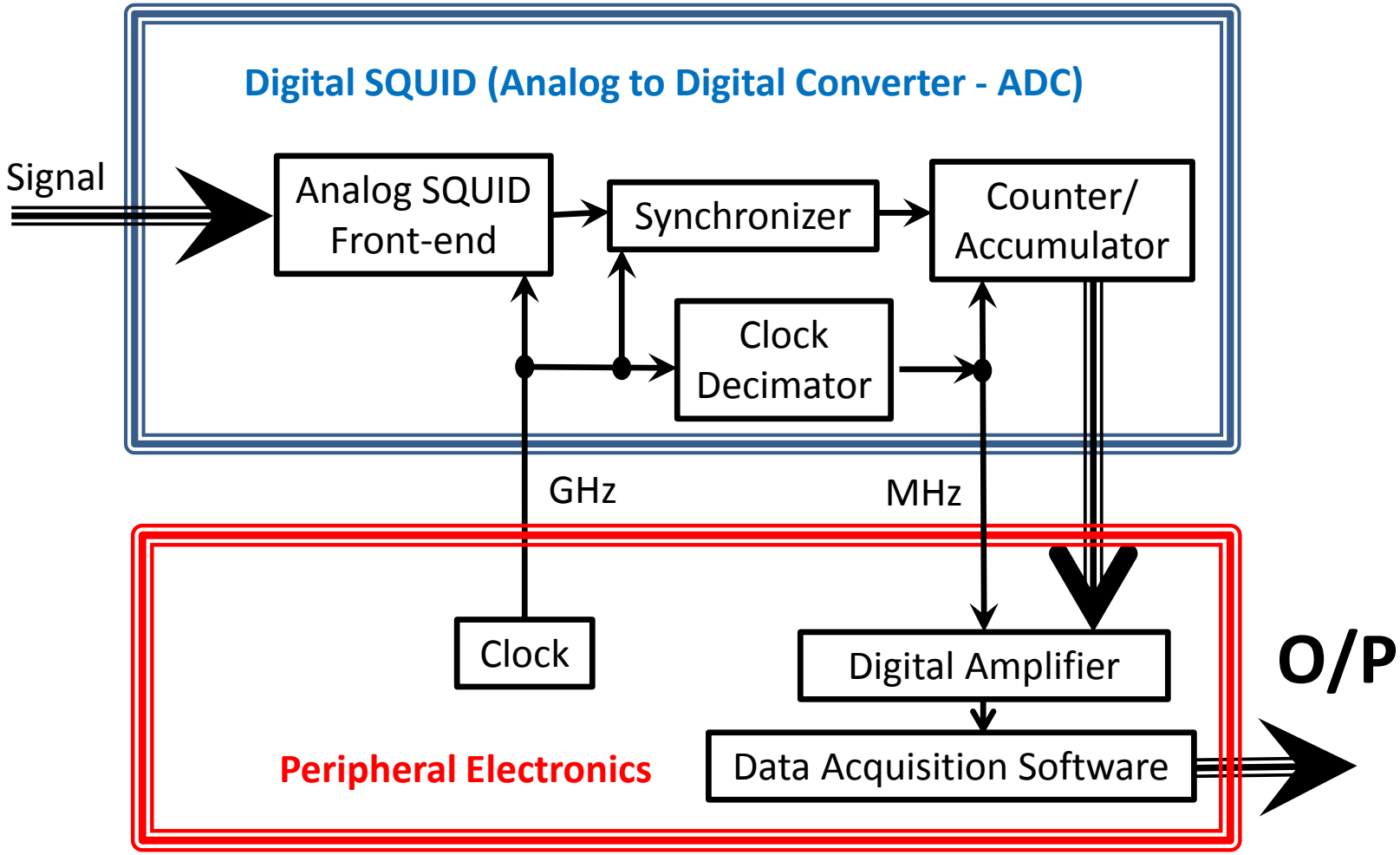
Digital SQUID Magnetometer / Amplifier

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

Single-Channel Read-out



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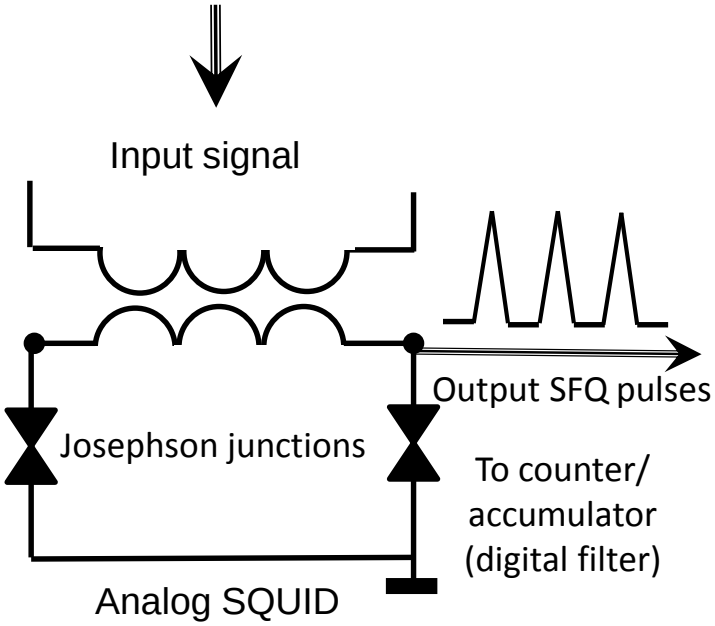
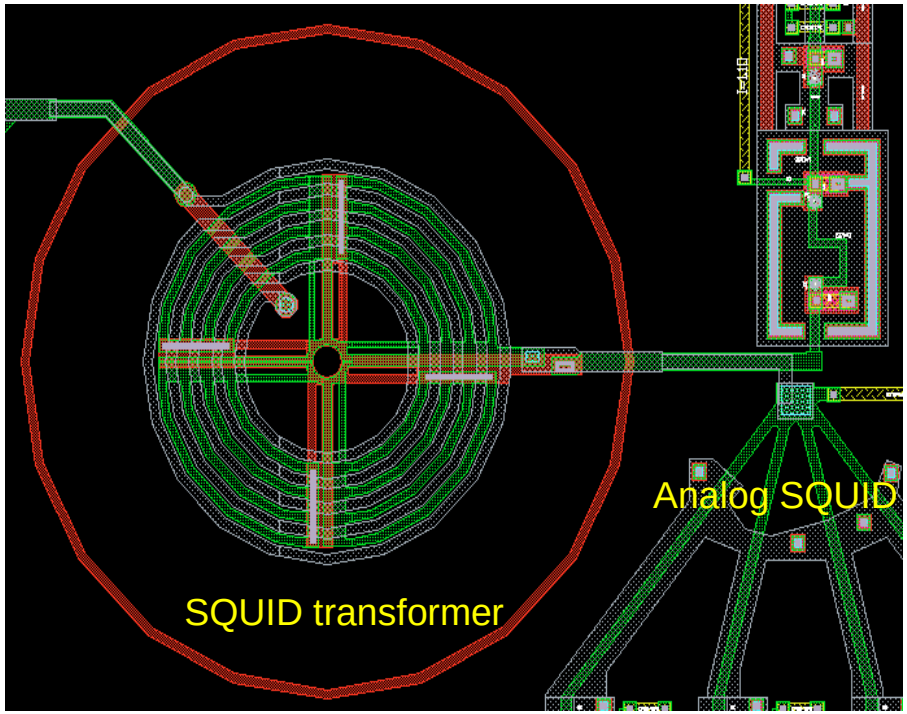
Front-end Analog SQUID





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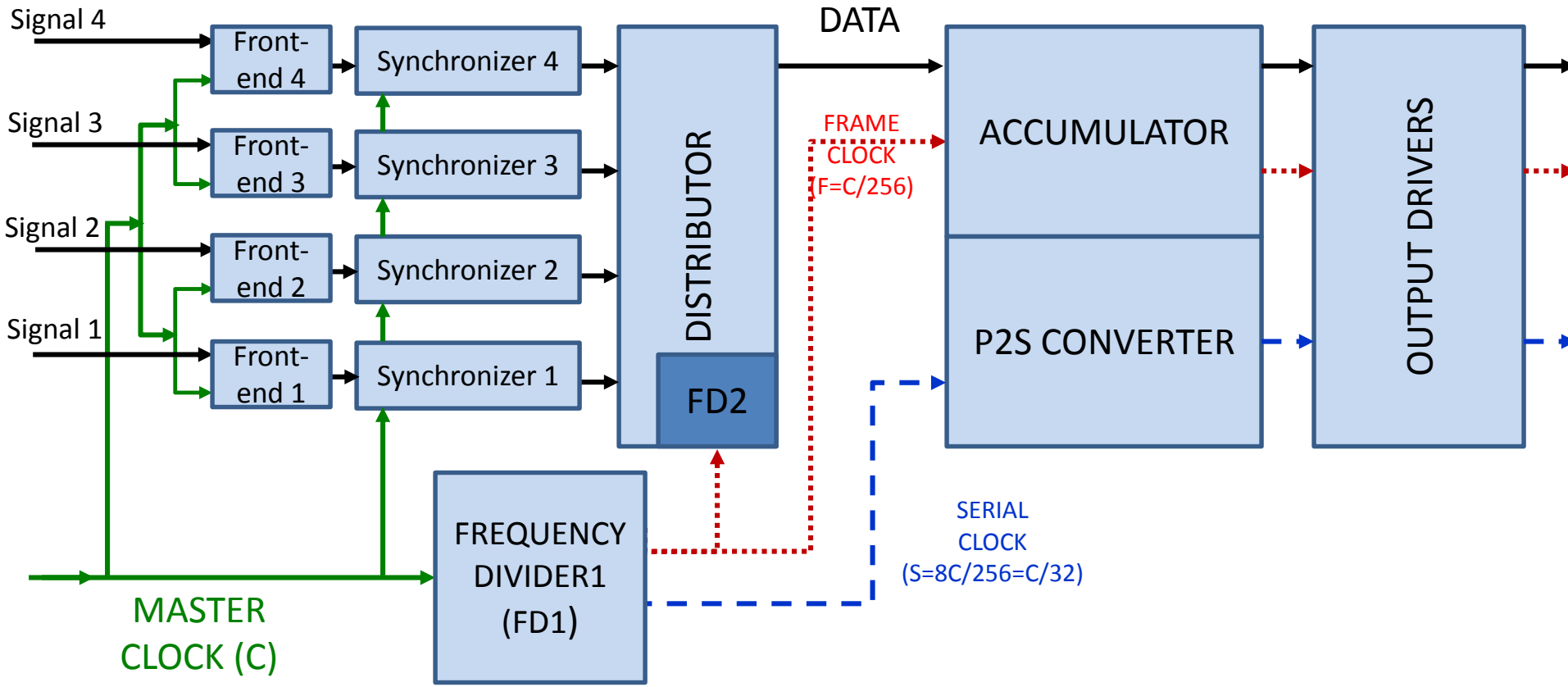
Schematic of 4-Channel Read-out Circuit



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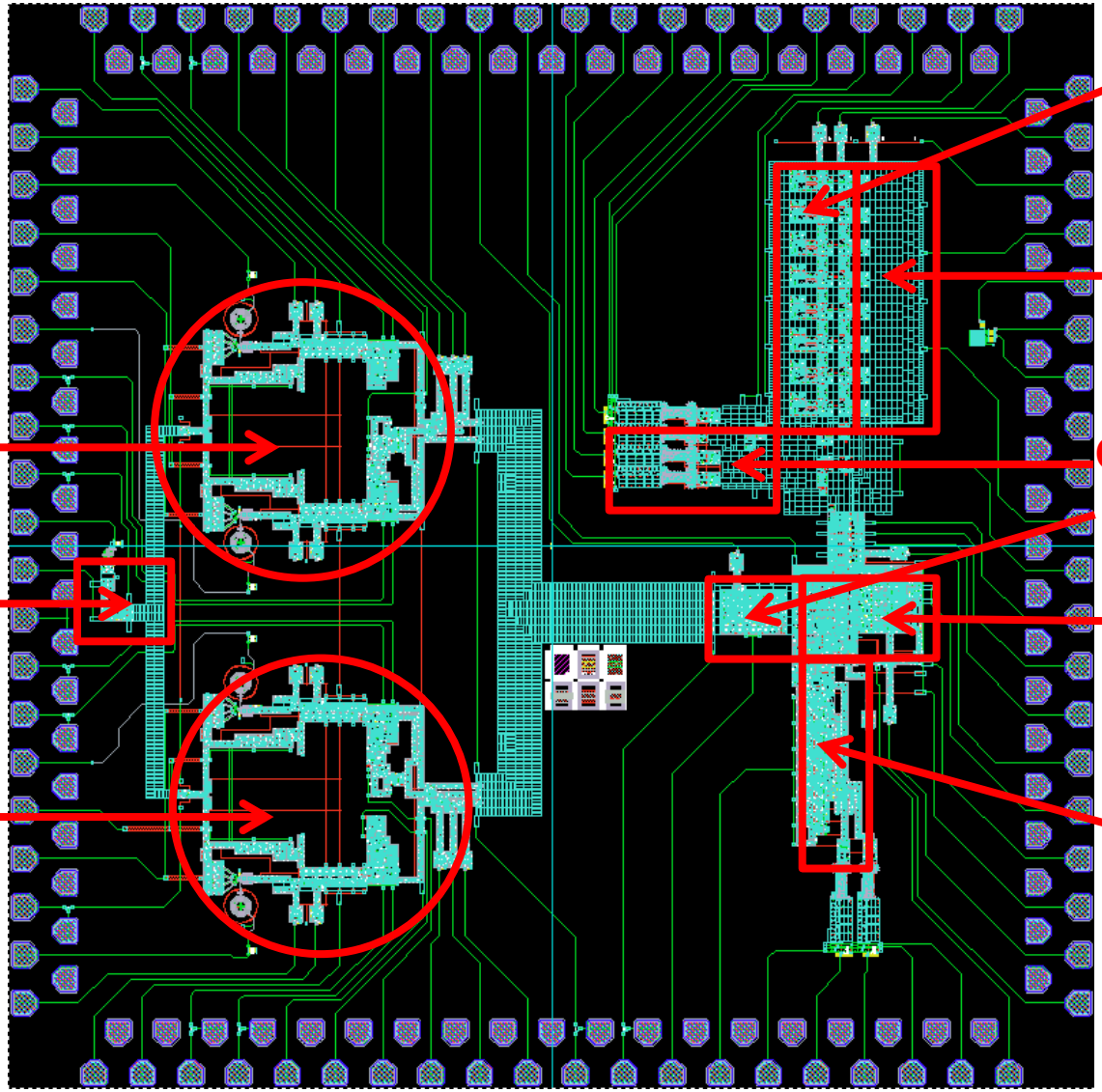
Layout of 4-Channel Read-out Circuit



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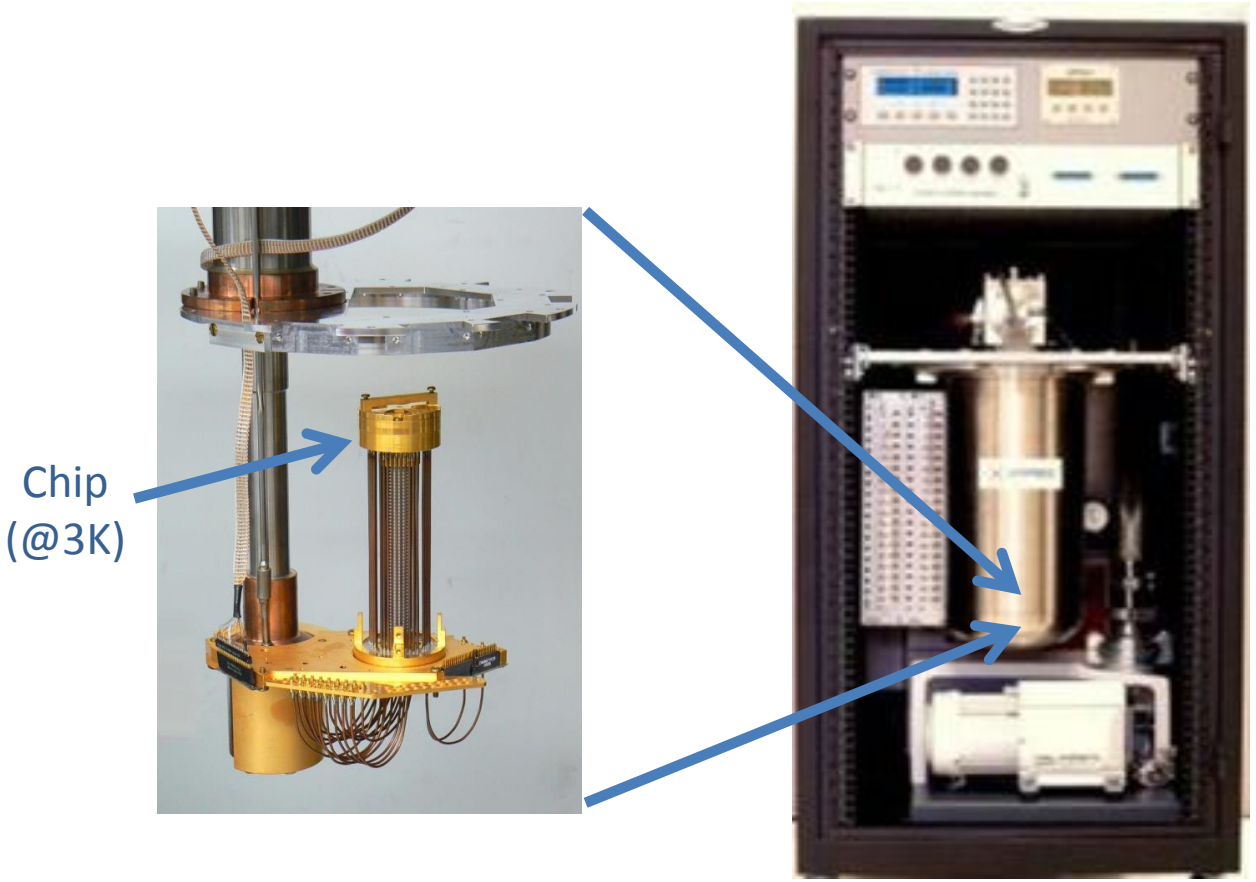
Cryogenic Package / Peripheral Electronics



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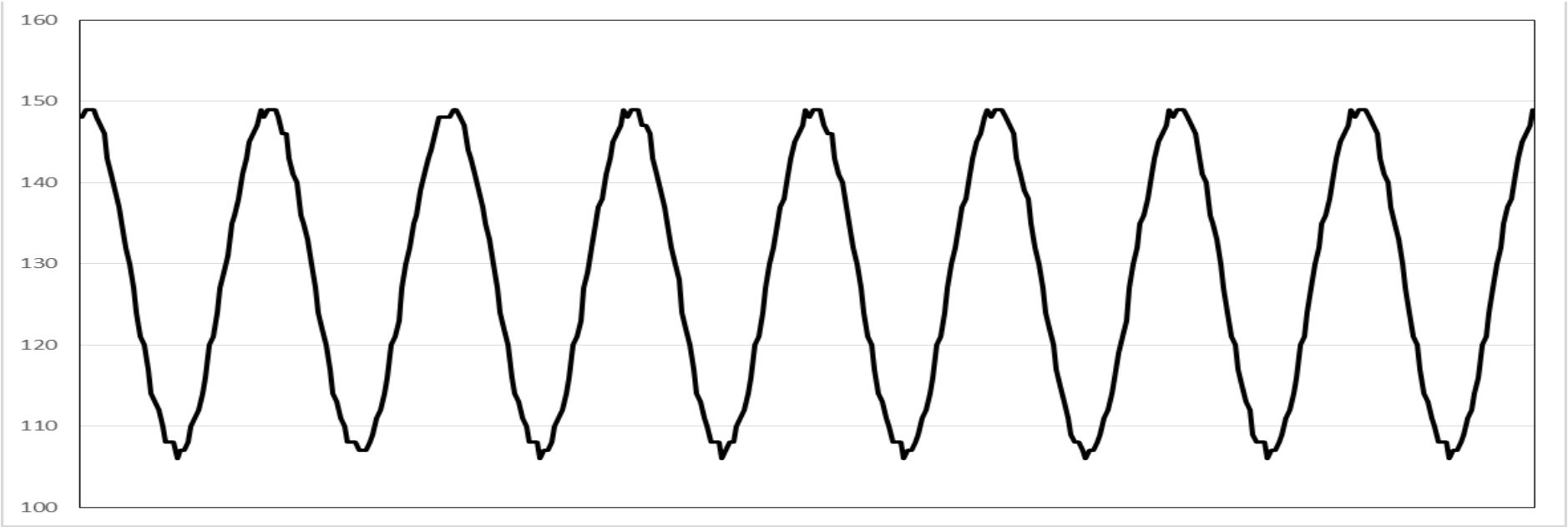
Signal Reconstruction



Clock frequency = 8 GHz

Channel 1 Signal Frequency = 156.25 KHz

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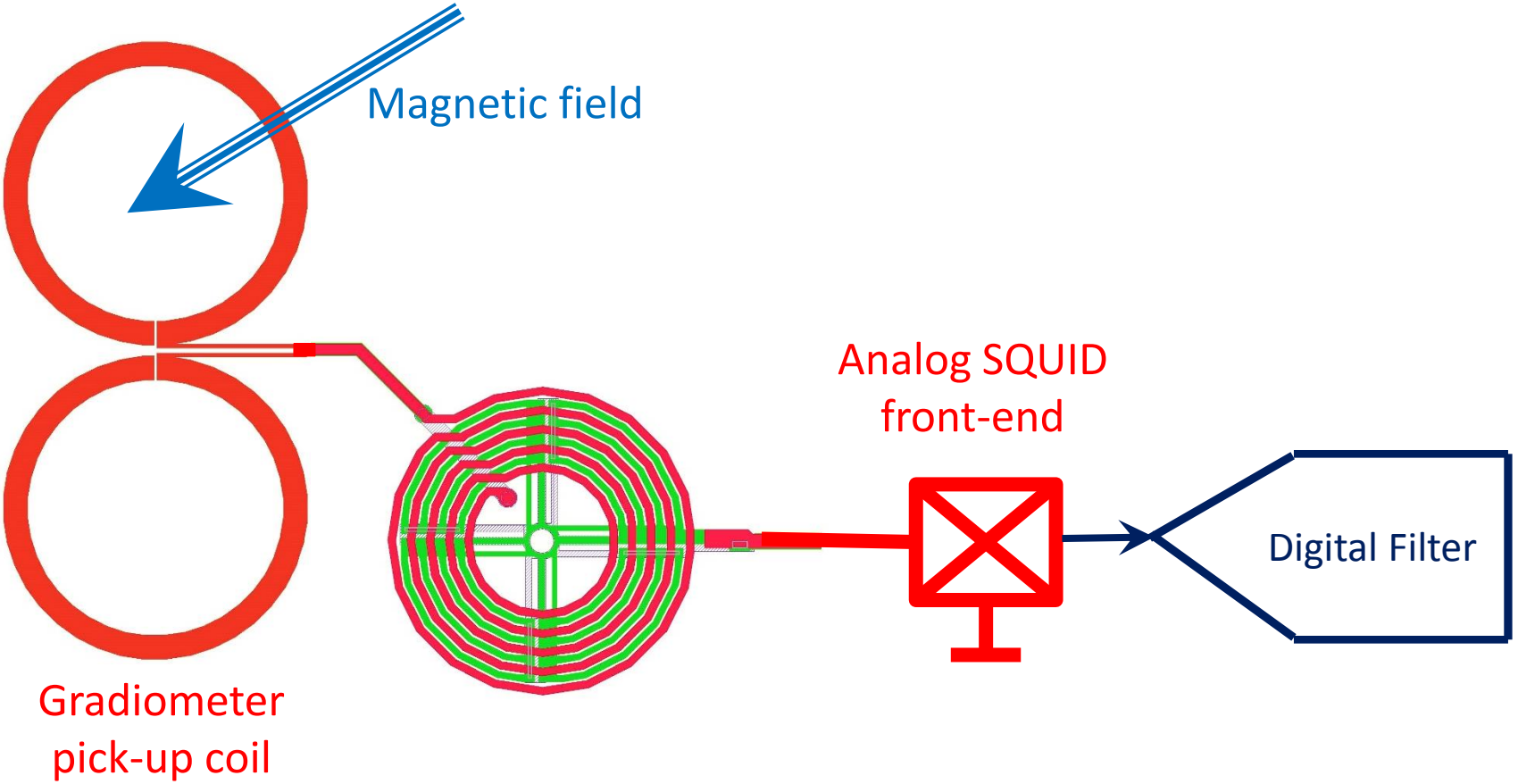
Front-end Analog SQUID / Pickup Coil



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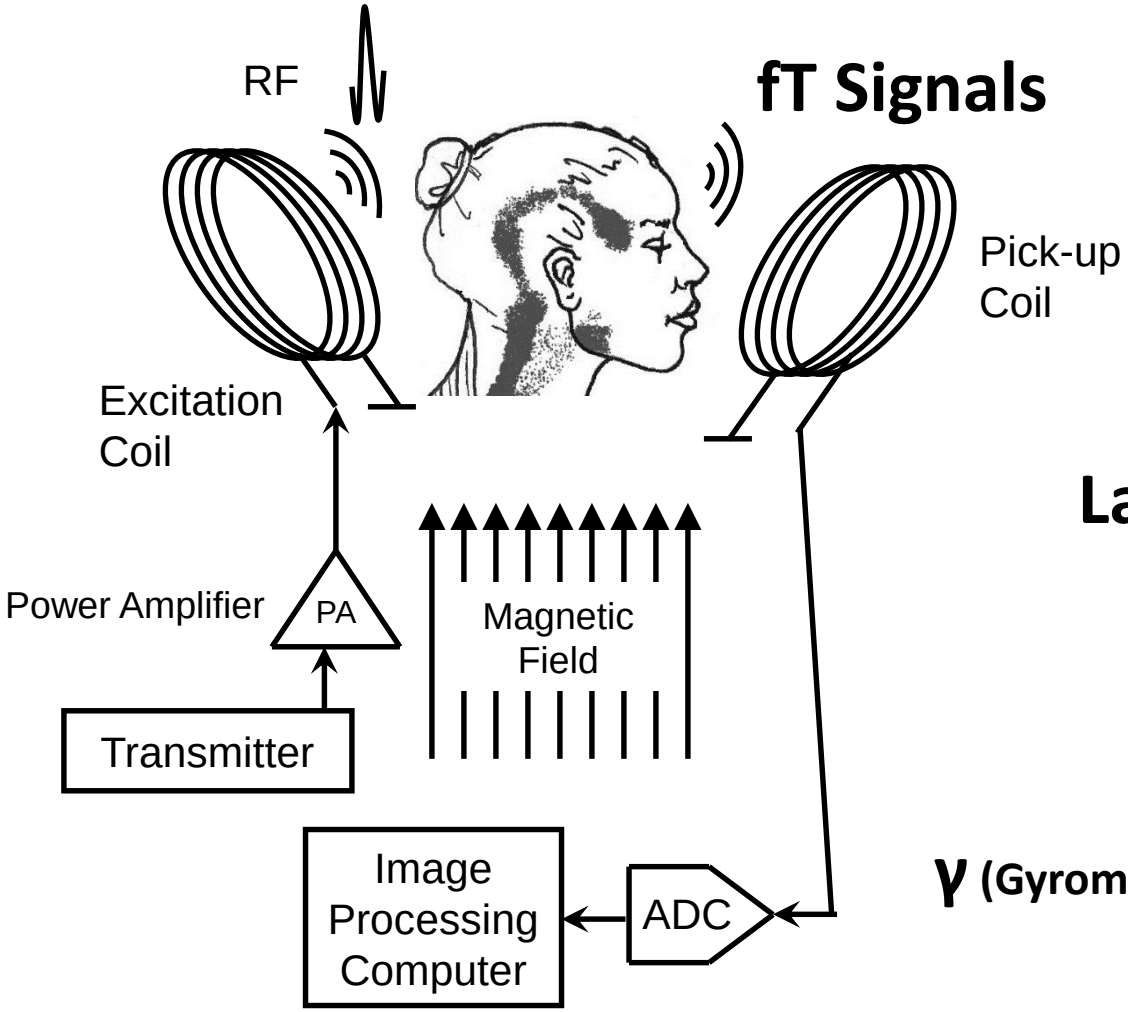
Commercialization Efforts

- Applications in Magnetometry:
  - MEG (Magnetoencephalography)
  - MRI (Magnetic Resonance Imaging)

Currently preparing a business plan for developing MRI receivers based on digital SQUIDs.

MRI System Block Diagram



Larmor frequency

$$\omega = \gamma \times B$$

γ (Gyromagnetic Ratio) = 42.58 MHz/Tesla

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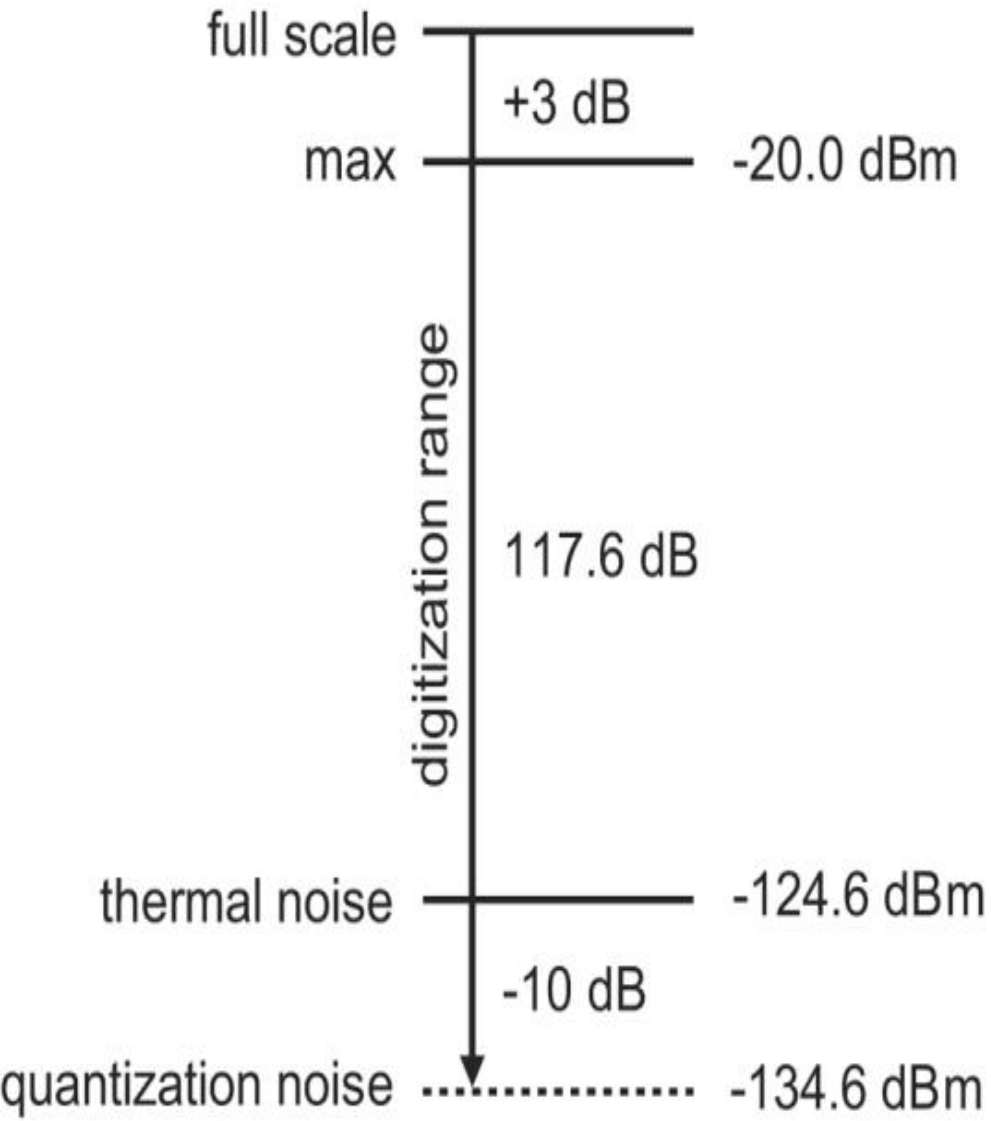
MRI Signal and Receiver Noise



ADC full scale should be about 3 dB above the maximum signal and its quantization noise level should be about 10 dB below the thermal noise, in order to provide an accurate measurement of the signal. Taken together, this corresponds to a required dynamic range of 118 dB, or about 20 bits; significantly larger than the 16-bit dynamic range of the ADC built into the MRI receiver.

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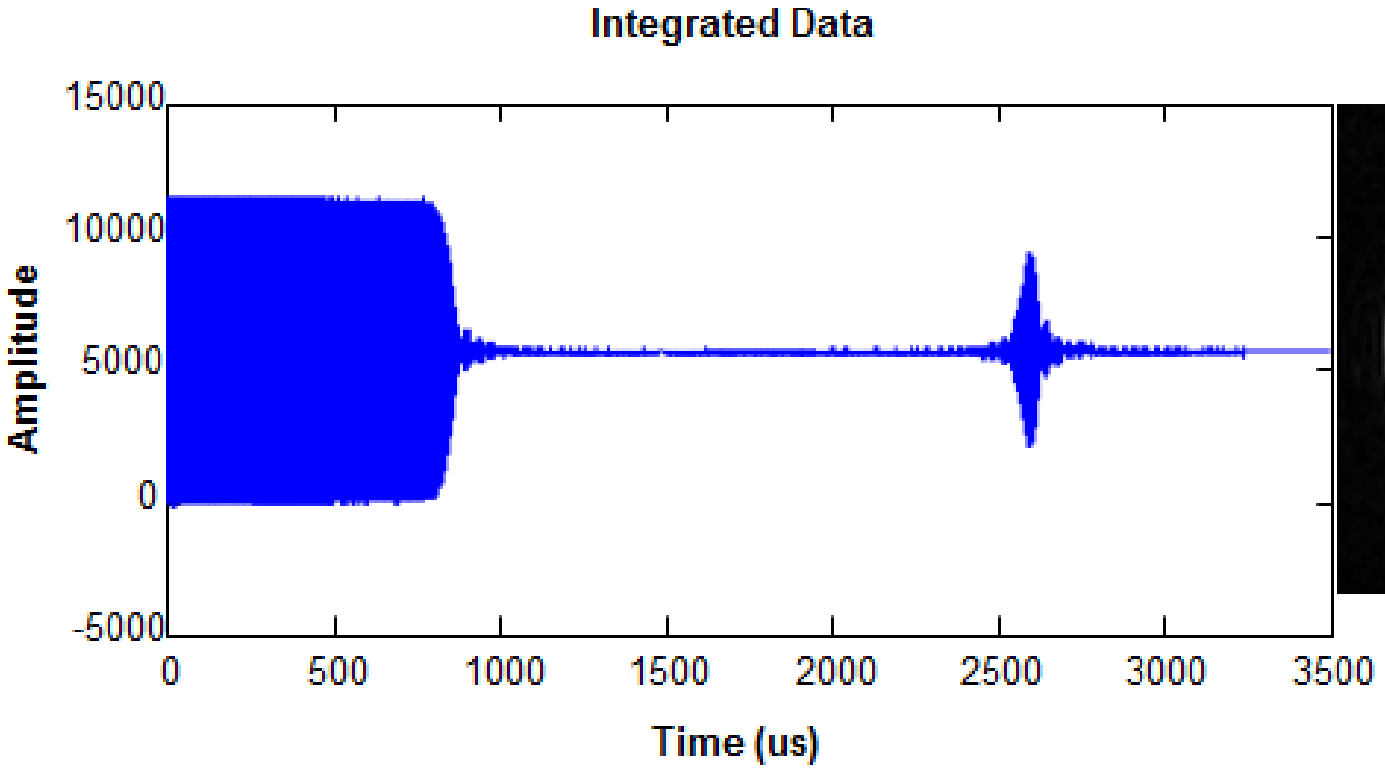
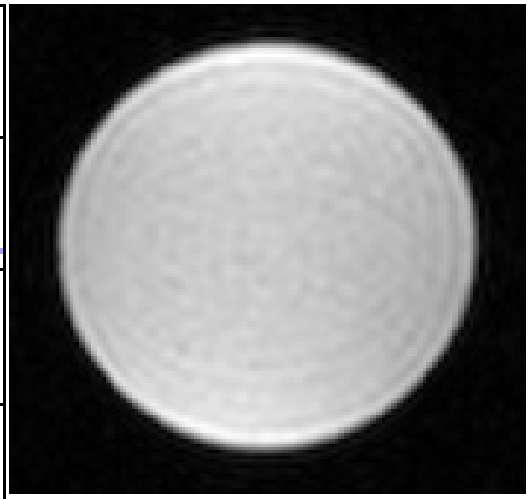
Experimental Results

A wideband high-performance All Digital Receiver (ADR) system developed for military and cellular applications was utilized as a receiver of a pre-clinical MRI system. The system is based around a superconducting Analog-to-Digital Converter (ADC), with high sensitivity and high linear dynamic range.

Image Acquisition





Sample MRI signal and resulting image of phantom. The superconducting ADC enabled slightly higher SNR and resolution than the standard 16-bit ADC, limited by the pick-up coil.

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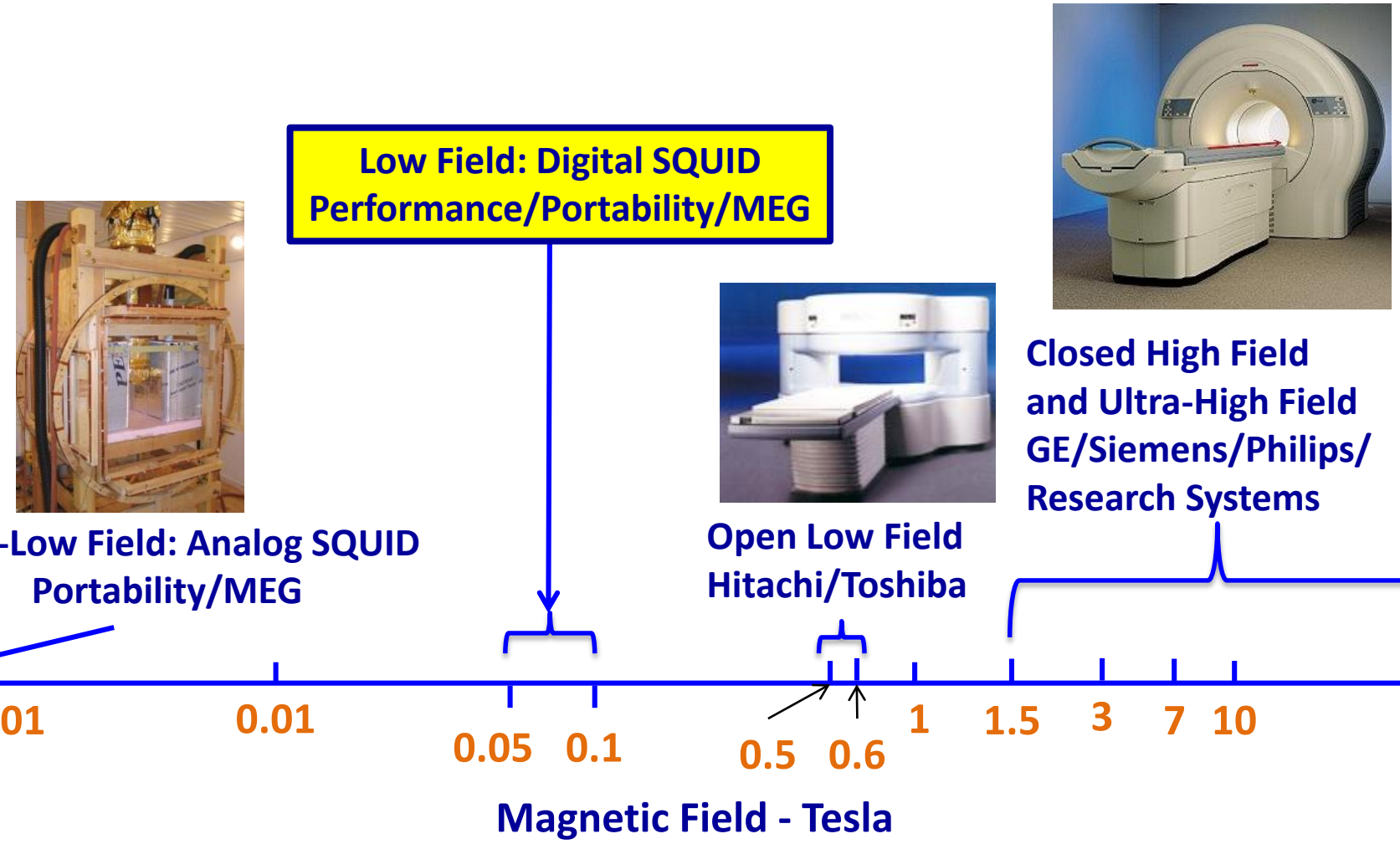
Digital SQUIDs enable unique regime



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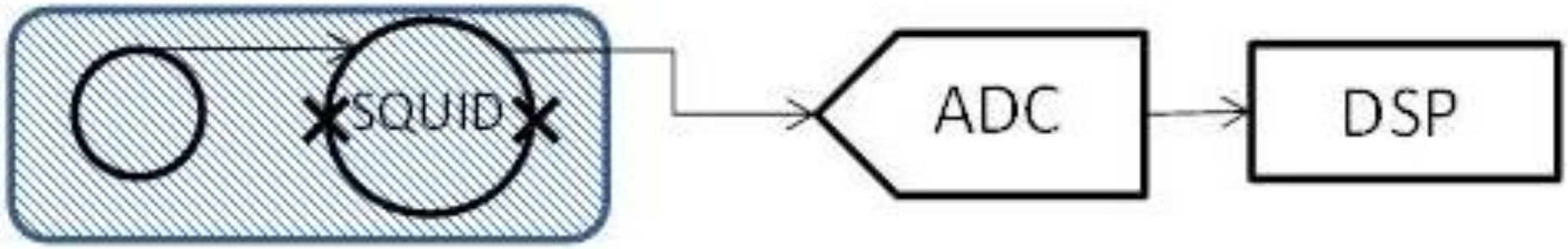
Receiver Low Field Systems



Cooled conventional pick-up coil and SQUID, operating at low magnetic field (milli-T) and frequency (a few MHz). Under development.

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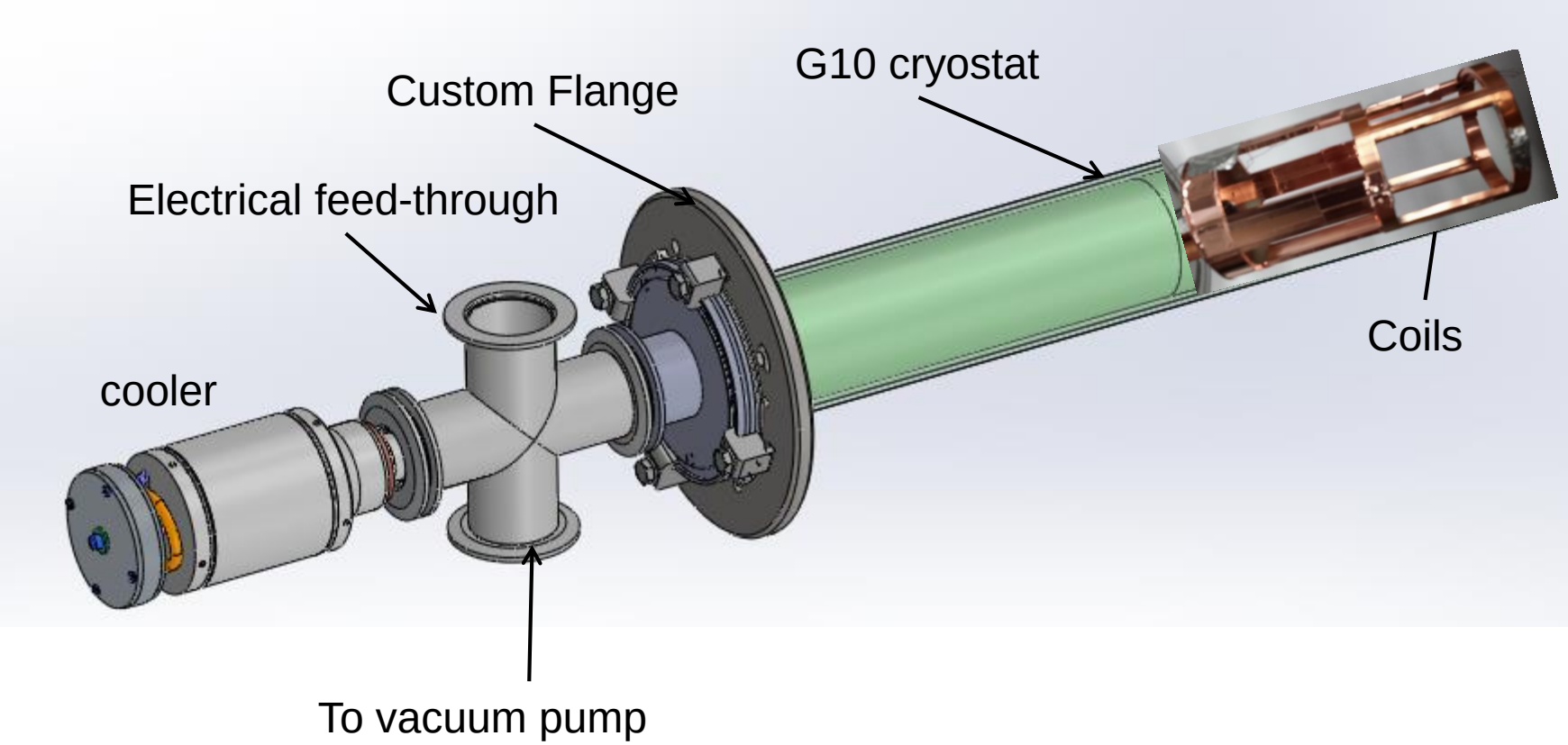
Probe Design



Transmit coils and shield are not represented

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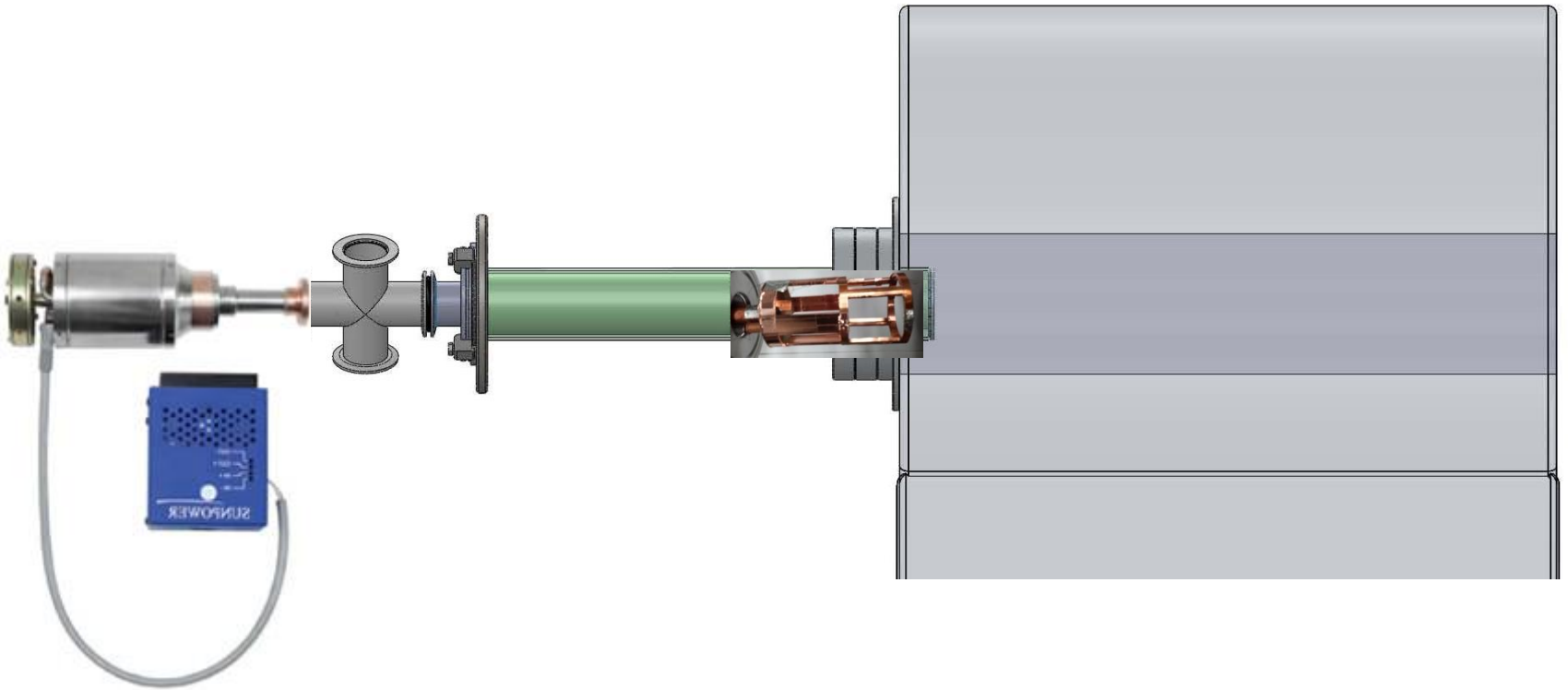
Cryocooled Coil

- 4 Pickup coils, integrated with their LNAs, are cooled using a Sunpower cryocooler (70K @11W) in a 10cm bore of an MRI system.



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Accomplishments

- Completed the design, simulation, fabrication of two iterations of the 4-channel digital SQUID amplifier chips.
- Full functionality was demonstrated.
- In addition to as readout of cryogenic detectors, a business plan is being prepared to utilize digital SQUIDs in MRI receivers.