Superconductor Analog-to-Digital Converter for High-Resolution Magnetic Resonance Imaging

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Summary

• Superconducting ADC increases SNR of high-field MRI

• ADC not yet optimized – RSFQ ADC originally designed for broadband digital radio receiver

• Mounted on 4K cryocooler - Operated in instrument room

• Most applicable for small-coil MRI systems, such as those for small animals, and for arrays of small coils

• Future plans: Couple an optimized ADC to a cryogenically cooled coil and preamplifier to further enhance SNR

• Projected significant improvement in image resolution
Large Dynamic Range of MRI Signal

- Dynamic range (DR) of MRI RF signal is much larger than DR of resulting image
- \( B_{rf\text{-max}} \) = coherent signal from entire slice
- \( B_{rf\text{-min}} \) = weak signal in single voxel
- Min. image resolution \( \sim 100 \times 100 \Rightarrow \) DR of \( \sim 10,000 \sim 13 \) bits in addition to bits for image contrast.
- Standard ADC in MRI systems has 16 bits of DR
- DR may be limited by:
  - Body noise
  - Receiver noise
  - Quantization noise
ADC Limits not Widely Recognized

- Classic human-scale MRI uses single large receive coil:
  - Couples body noise from entire body
  - Resolution limited by body noise
  - 16-bit ADC may be sufficient

- Recent trends to larger static B \(\rightarrow\) increased SNR
  - Up to 3T for humans, up to 9.4T for small animals.
  - May require ADC with more bits

- Small coils couple less body noise with increased SNR and finer resolution.
  - Small-bore MRI systems for small animals
  - Multi-coil arrays, with receiver for each coil
  - Cooled small coils can increase SNR even further
  - May require ADC with more bits
Example of MRI Dynamic Range*

*Figure from Behin, et al., “Dynamic Range Requirements for MRI” Concepts in Magnetic Resonance (2005).
Superconducting ADCs

- **Essentially Digital SQUIDs**
  - Each flux quantum $\Phi_0=h/2e$ generates SFQ pulse
  - SFQ pulses counted in RSFQ digital counter
  - Low-noise and very linear
  - Nb integrated circuits operating near 4 K
  - Unlike analog SQUIDs, Not limited to low kHz frequencies
    Can work up to GHz

- **Oversampling** superconducting ADCs
  - Very high sampling rate ~ 20 GHz, much higher than Nyquist rate for signal bandwidth
  - Oversampling by factor R increases DR by ~ $R^{1.5}$
  - If $R \sim 10^5$, DR ~ 25 bits, so 100 kHz signal can be measured to 25 bits precision
  - Extremely high speed of RSFQ circuits enables simple supercond. ADCs to outperform complex semicond. ADCs

- Phase-modulation ADC works well for low frequencies, existing PM-ADC designed for digital-RF receiver was used in present experiment.
Superconducting ADC Performance

- DR (effective bits) vs. output sample rate for signals at the Nyquist freq. for high-performance semiconduct. and superconduct. ADCs
Conventional Receiver Technology

- Pick-up coil couples a weak RF magnetic field at a frequency of order 100 MHz (1 T ~ 42.6 MHz) to a low-noise preamplifier
- The signal is mixed down to an intermediate frequency and digitized by an ADC
MRI Superconducting Receiver

ADC substituted for the 16-bit ADC of a Bruker Avance 4T small-animal MRI system at Yale Magnetic Resonance Research Center.
Cryocooled ADC

- Single-rack high-performance All Digital Receiver (ADR) system developed for military and cellular application
- Used here as a receiver of a pre-clinical MRI system
- System based on a superconducting ADC with high sensitivity and high linear dynamic range
- Circuit operated in the instrument room adjacent to the 4T MRI system, with a standard mu-metal shield to screen out stray magnetic fields
- ADC chip mounted on the 4K stage of a Sumitomo two-stage cryocooler
Image Acquisition

MRI signal and resulting image of phantom. Superconducting ADC enabled higher SNR and resolution limited by the noise of pick-up coil.
Alternative Direct Digitization

- Digitize 170 MHz RF signal
- Bypass analog mixer
- Tested in the same system
- Generated image
- DR in this configuration is reduced due to much lower oversampling ratio
- Bandpass ADC optimized for direct digitization would perform much better
Future: Add Cryogenic Receiver

- Cold coil and preamplifier primarily used in small-animal MRI systems and NMR chemical analysis
- Bruker commercial systems use large cryocooler with circulating cold He gas to cool both coil and LNA in/near the magnet
Advantages of Cooling Small MRI Coils

- Darrasse (2003) compared coil noise \( \propto (R_c T_c)^{1/2} \) to sample noise (i.e., body noise \( \propto (R_s T_s)^{1/2} \)) over a range of frequencies and coil sizes (see Plot).

- The lines represent the boundary between the body-noise-dominated regime (upper right) and that dominated by coil noise (lower left), for warm and cooled copper, and for superconducting coils.

- For small-coil high-field MRI, cooling the coil becomes essential to increase SNR.

- This also permits increased resolution requiring an ADC with high DR.
Coil Noise vs. Body Noise*

*from Darrasse and Ginefri, “Perspectives with Cryogenic RF Probes in Biomedical MRI”, Biochemie (2003).
A future MRI system is proposed that combines a coil/LNA cooled to ~ 60 K (using a compact single-stage cooler) with an optimized high-DR superconducting ADC, cooled to 4 K.

Such a modular system with separate, non-interfering coolers may be simpler and more reliable than a fully integrated system.
Preliminary Design of Cryocooled Coil

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

Transmit coils and shield are not represented.
Future Design: Portable Low-Field Brain MRI

- Array of cryogenic coils (~70K) in static field of 100 mT, coupled to 4K digital-SQUIDs (ADCs) operating at 4 MHz
- Provides sufficient SNR for brain image in reasonable time
Conclusions

• In small-coil, high-field regime, standard ADC is insufficient for full dynamic range of MRI signal, limiting resolution

• Superconducting ADC has larger DR than standard ADC, improving resolution in 7T small-animal MRI

• Even larger DR possible using cryocooled coils
  ➢ Combining these with supercond. ADC enables better resolution for magnetic resonance microscopy

• A similar approach using array of small cooled coils and digital superconducting electronics enable a portable MRI system in a field ~ 0.1 T with good resolution and scanning time
References