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

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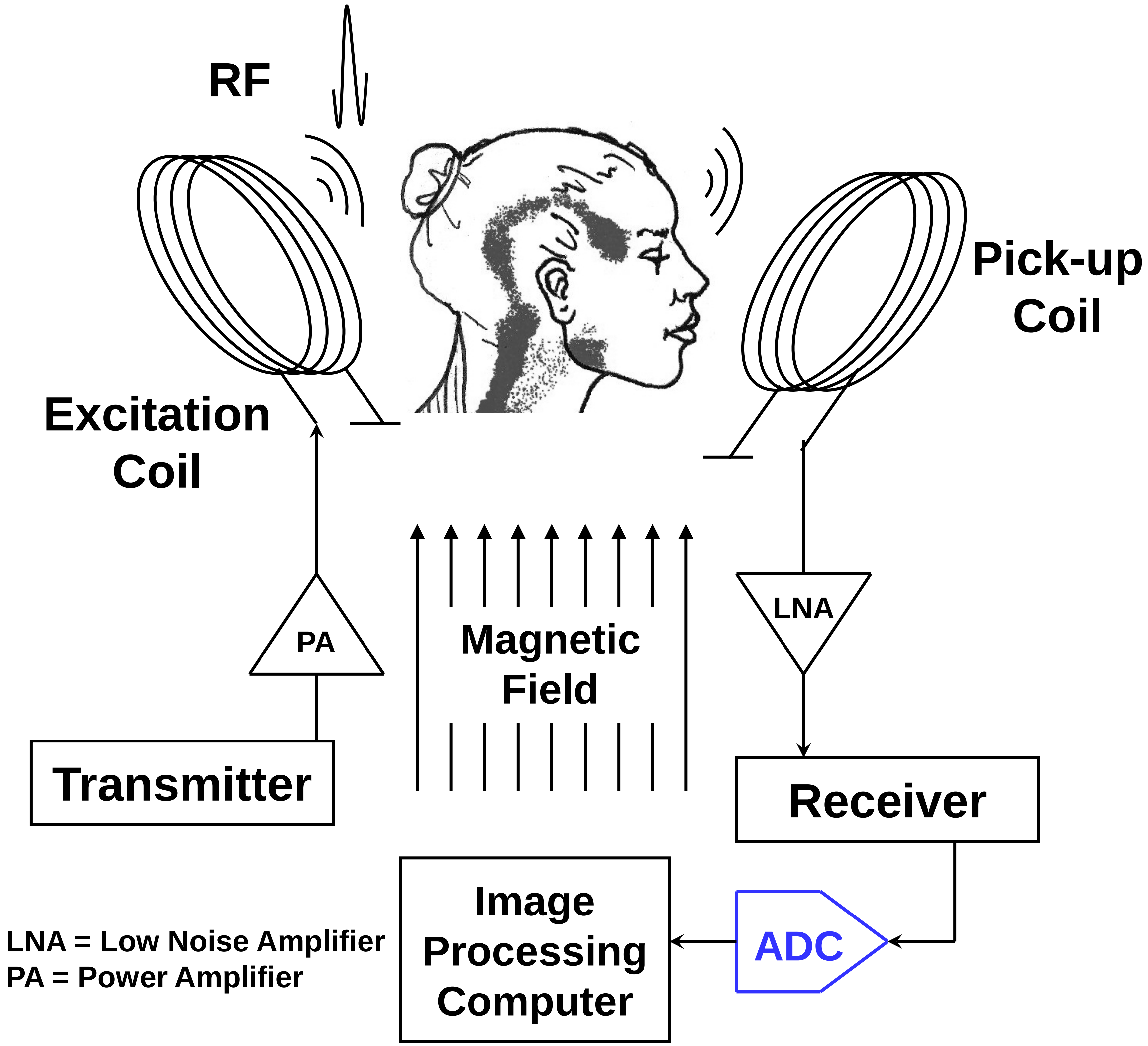
Summary

- **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**


RF
Excitation Coil
Pick-up Coil
PA
LNA
Magnetic Field
Transmitter
Receiver
Image Processing Computer
ADC
LNA = Low Noise Amplifier
PA = Power Amplifier

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 ~ 100 x 100 $\Rightarrow$ DR of ~10,000 ~ 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 → 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*

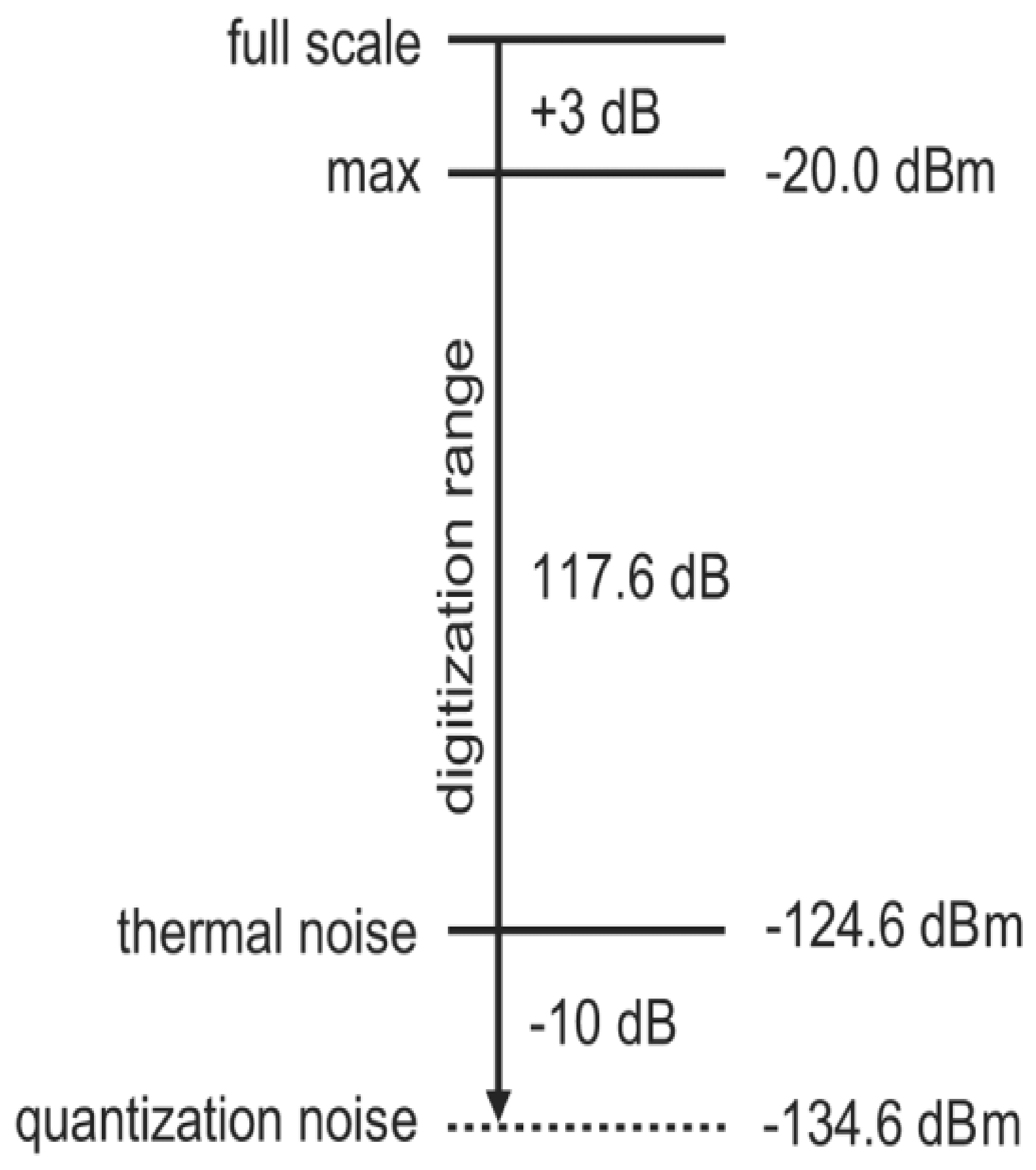
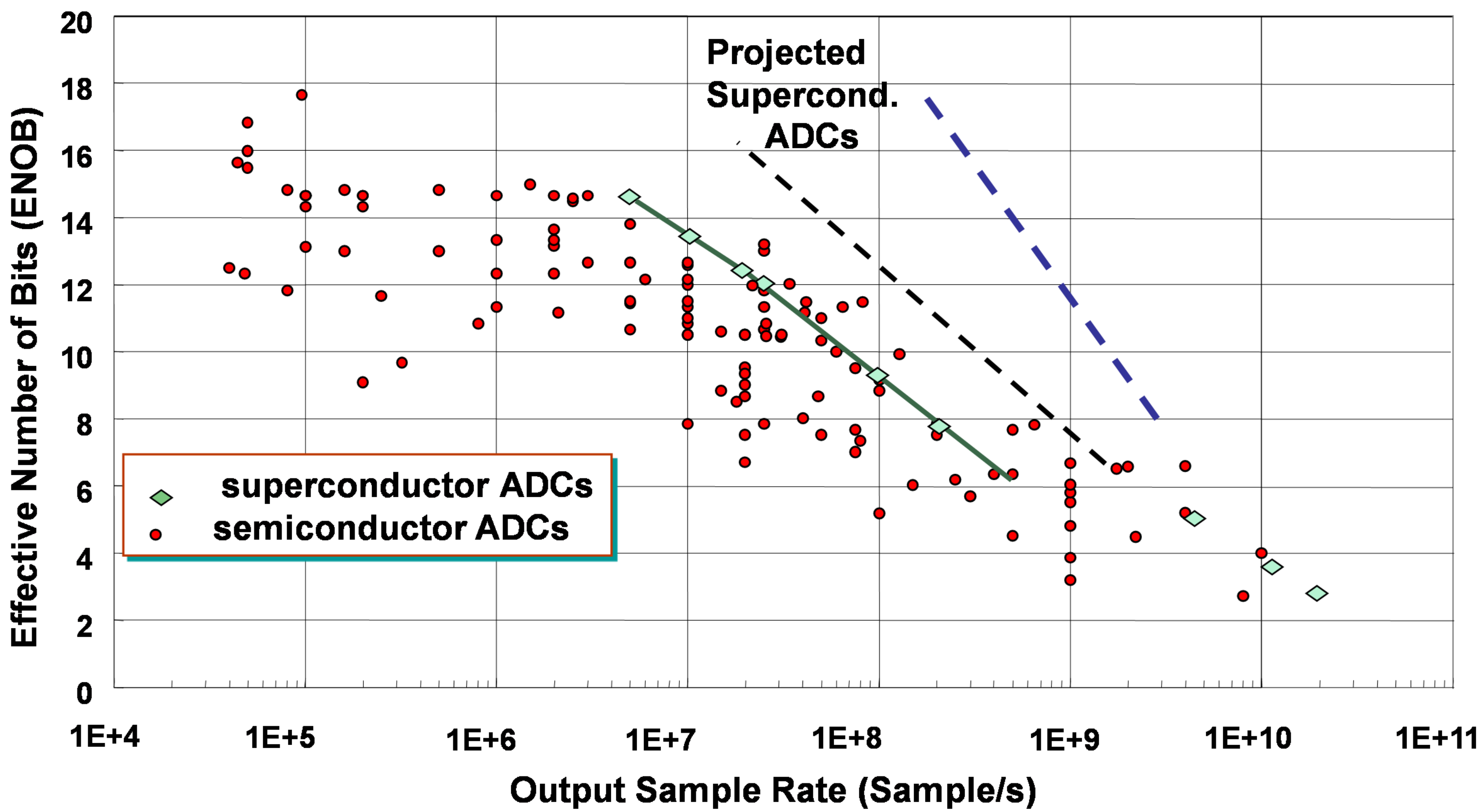


*Figure from Behin, et al., "Dynamic Range Requirements for MRI" Concepts in Magnetic Resonance (2005).

Superconducting ADCs

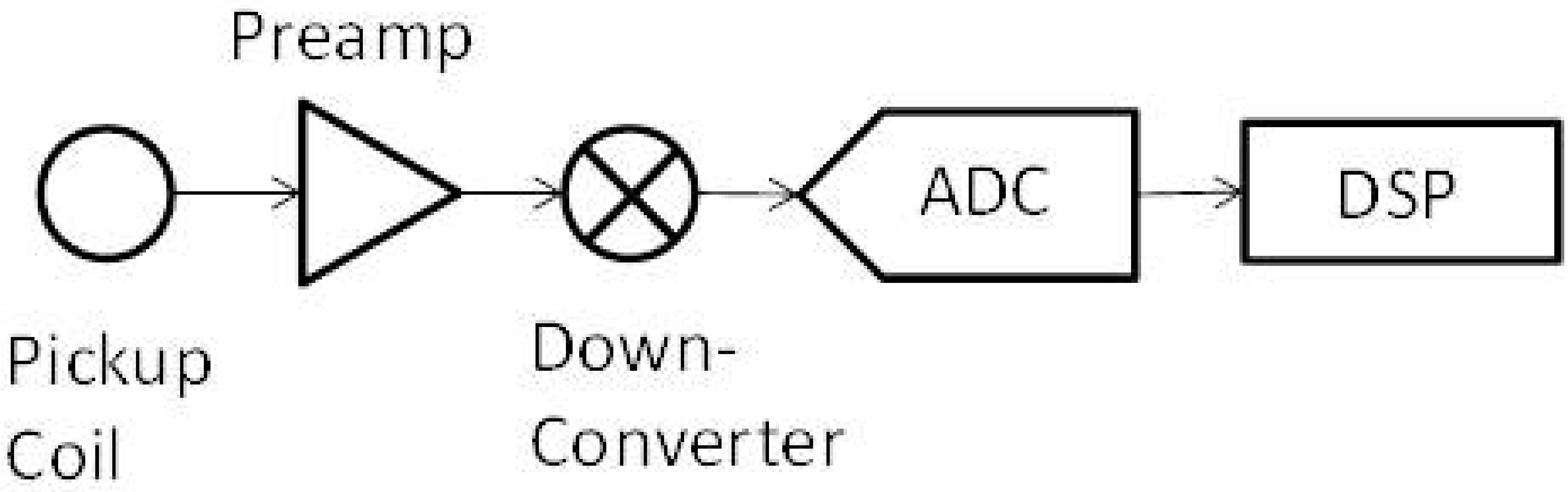
- Essentially Digital SQUIDs
  - Each flux quantum Φ_0=h/2e generates SFQ pulse
  - SFQ pulses counted in RSFQ digital counter
  - Low-noise and very linear
  - Nb integrated circuits operating near 4 K
  - Unlike analog SQUIDs, Not limited to low kHz frequencies
    Can work up to GHz
- Oversampling 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 ~ 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



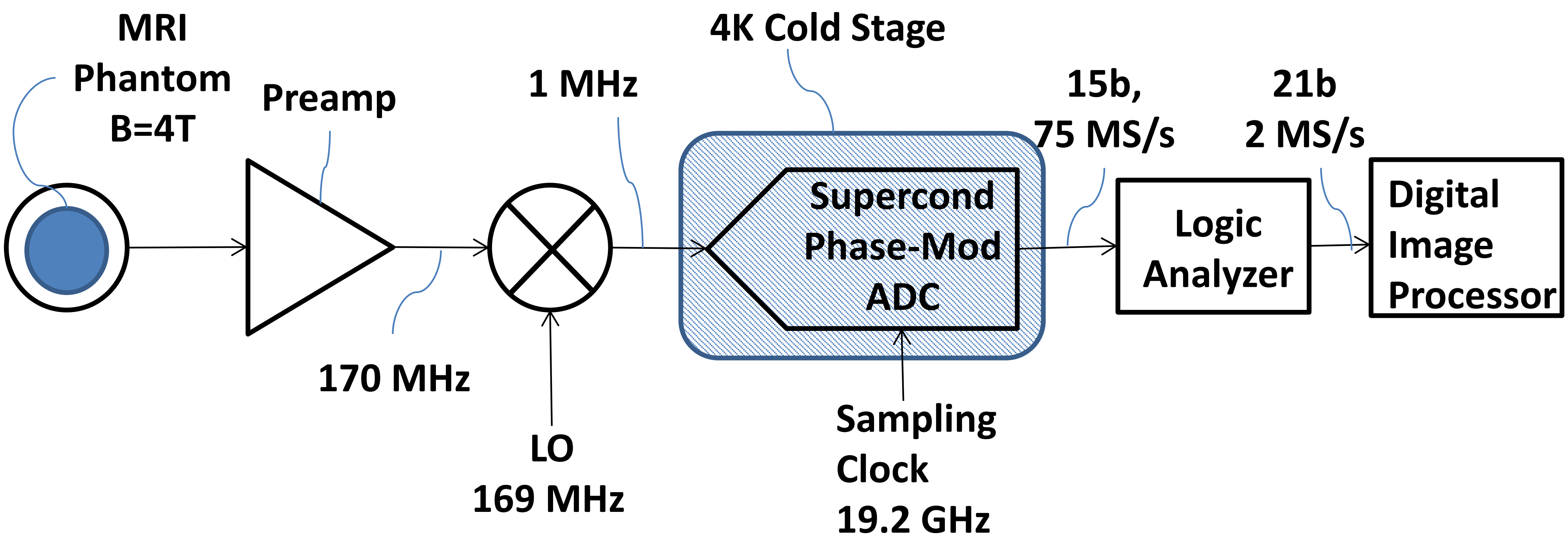
- DR (effective bits) vs. output sample rate for signals at the Nyquist freq. for high-performance semicond. and superconduct. ADCs
- Supercond. ADCs outperform more complex semiconductor ADCs (Mukhanov, "Superconductor ADC", Proc. IEEE, 2004)

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

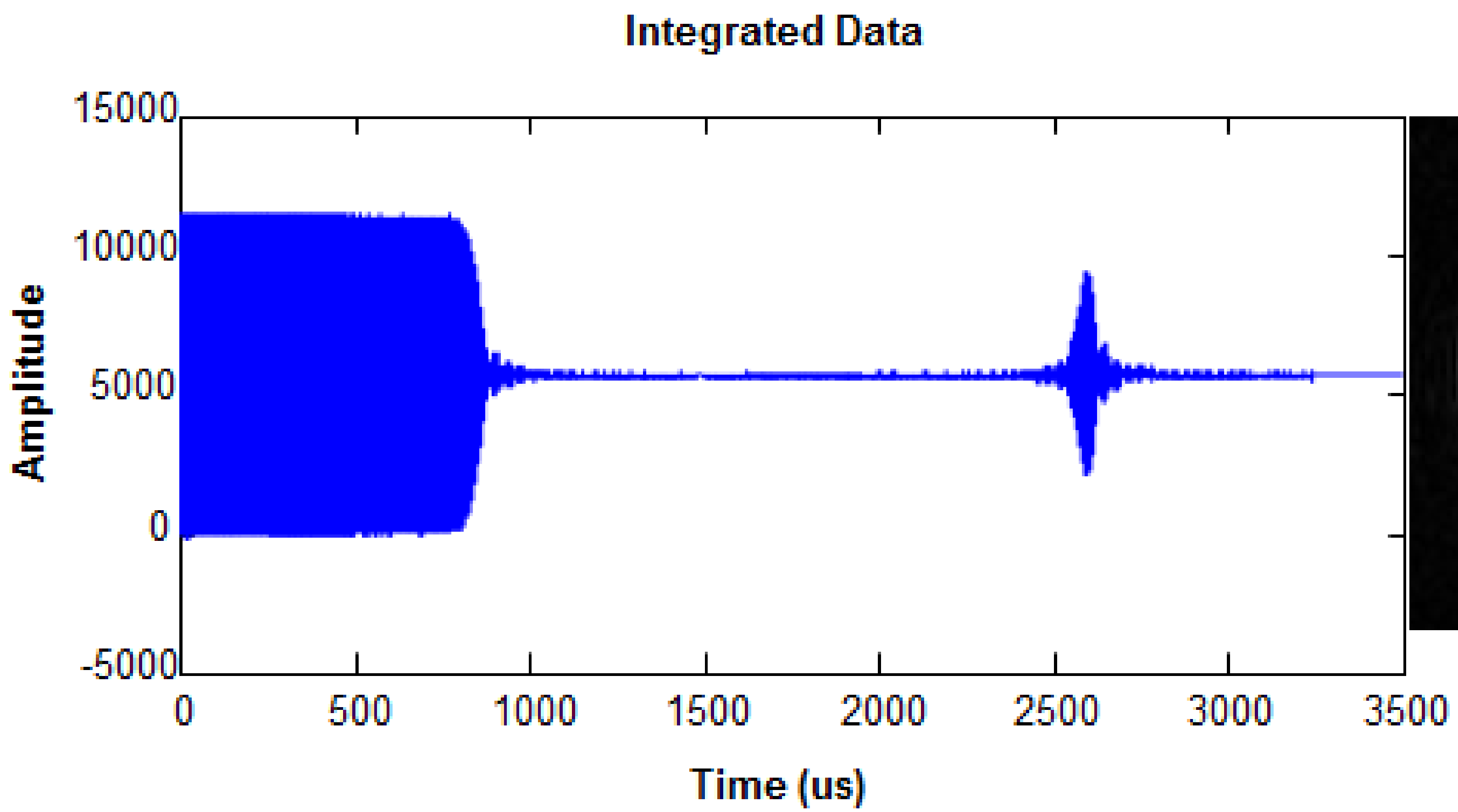


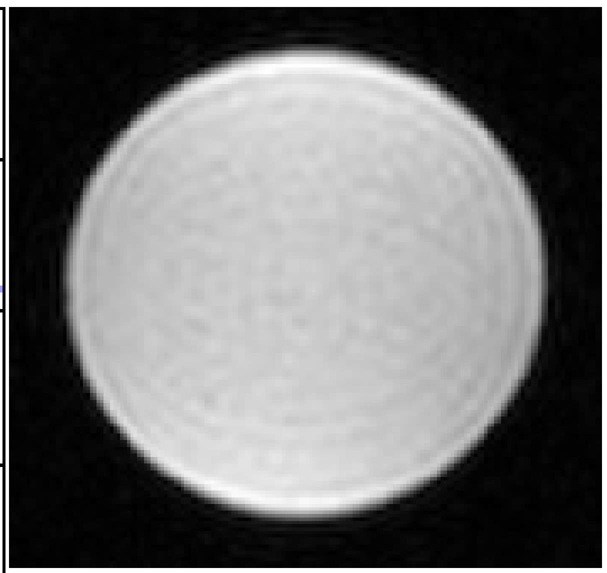
ADC substituted for the 16-bit ADC of a Bruker Avance 4T small-animal MRI system at Yale Magnetic Resonance Research Center.

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

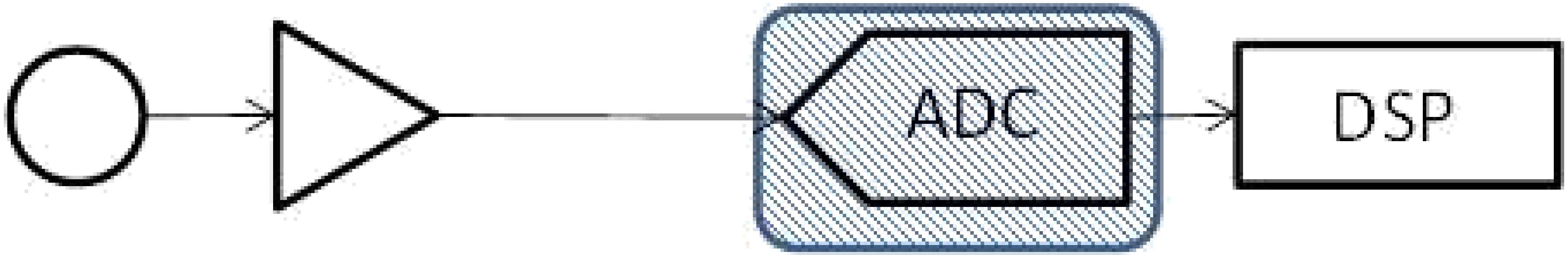
Image Acquisition





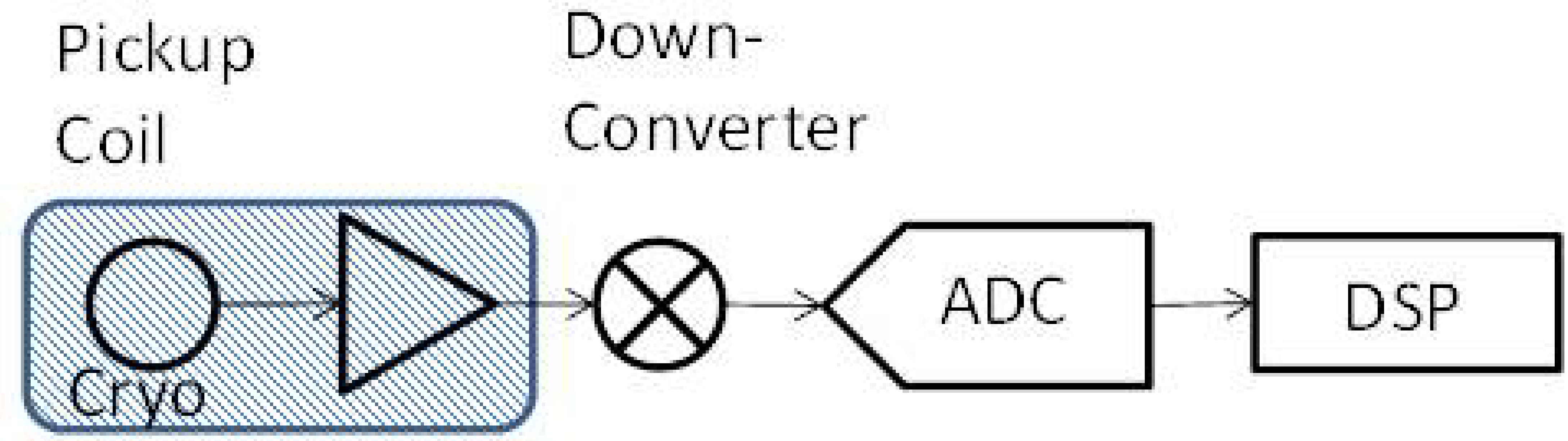
MRI signal and resulting image of phantom. Superconducting ADC enabled higher SNR and resolution limited by the noise of pick-up coil.

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

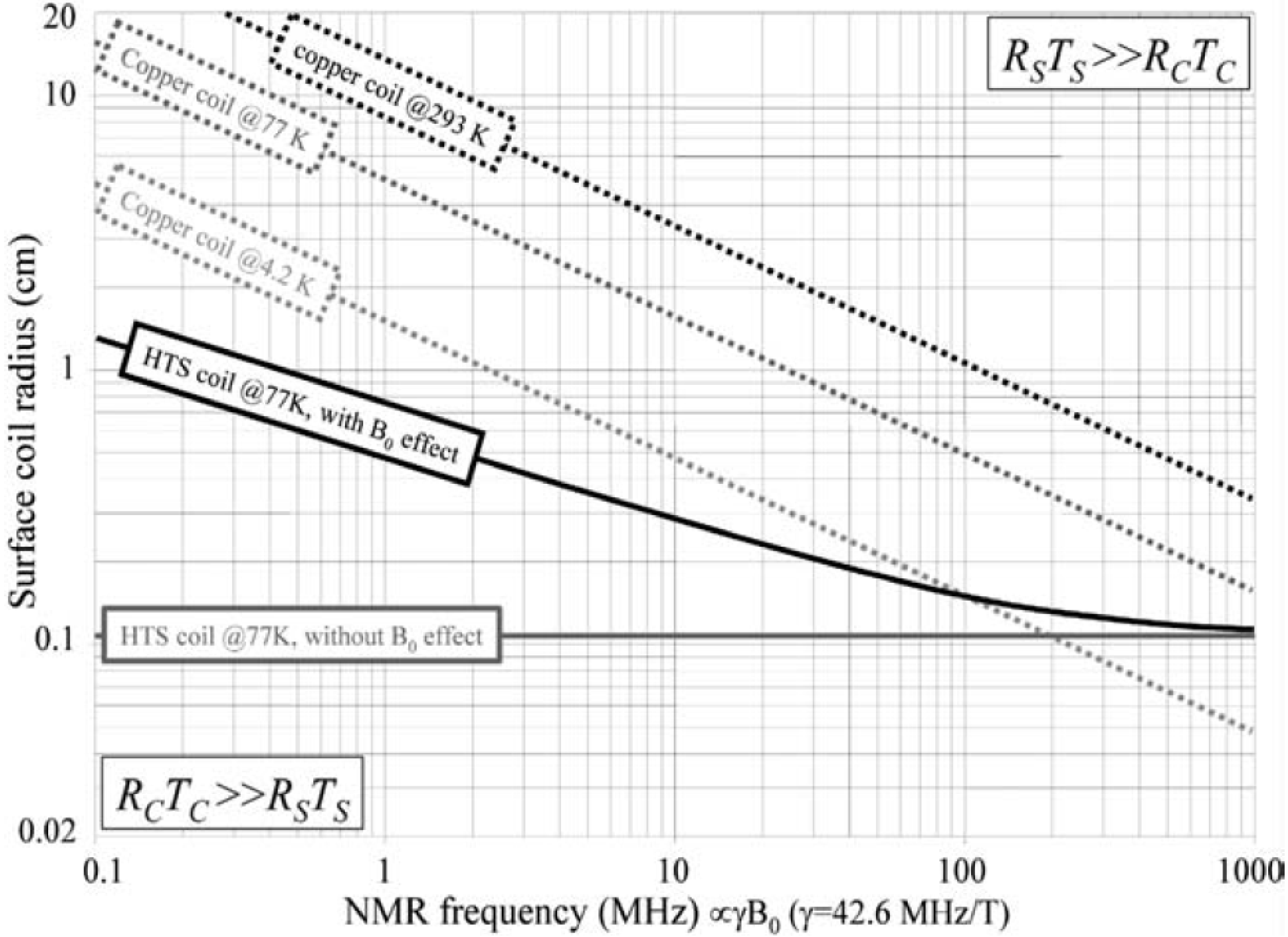


- Cold coil and preamplifier primarily used in small-animal MRI systems and NMR chemical analysis
- Bruker commercial systems use large cryocooler with circulating cold He gas to cool both coil and LNA in/near the magnet

Advantages of Cooling Small MRI Coils

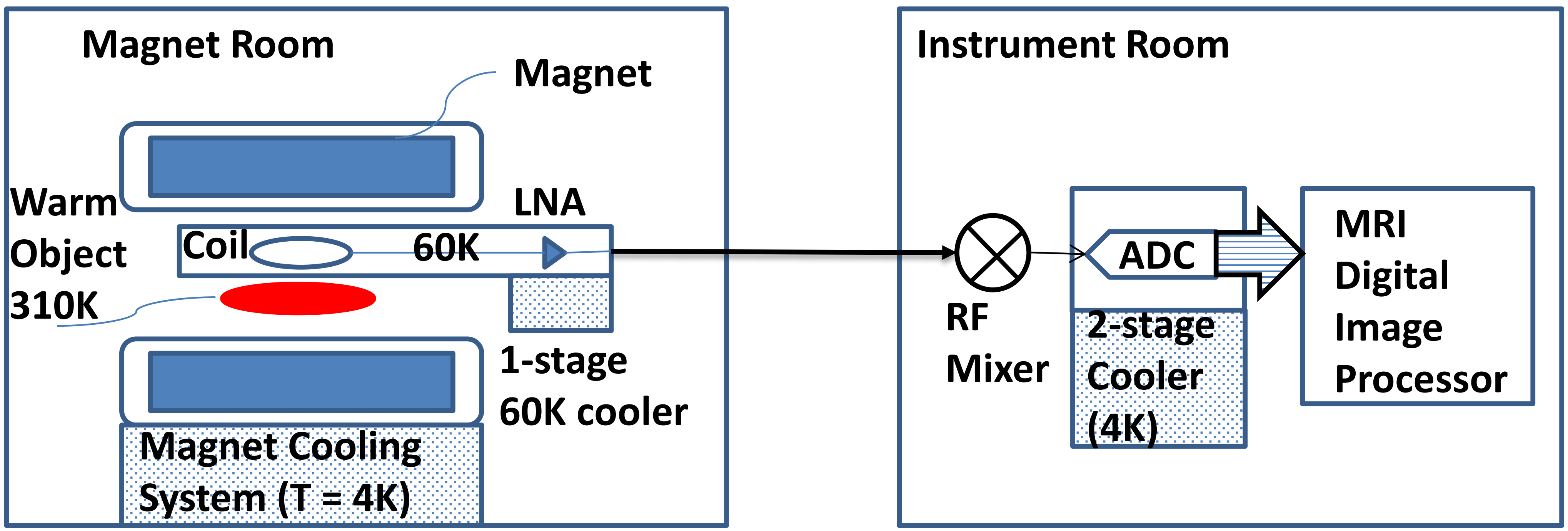
- Darrasse (2003) compared coil noise [$\propto(R_c T_c)^{½}$] to sample noise (i.e., body noise $\propto(R_s T_s)^{½}$] over a range of frequencies and coil sizes (see Plot)
- The lines represent the boundary between the body-noise-dominated regime (upper right) and that dominated by coil noise (lower 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).

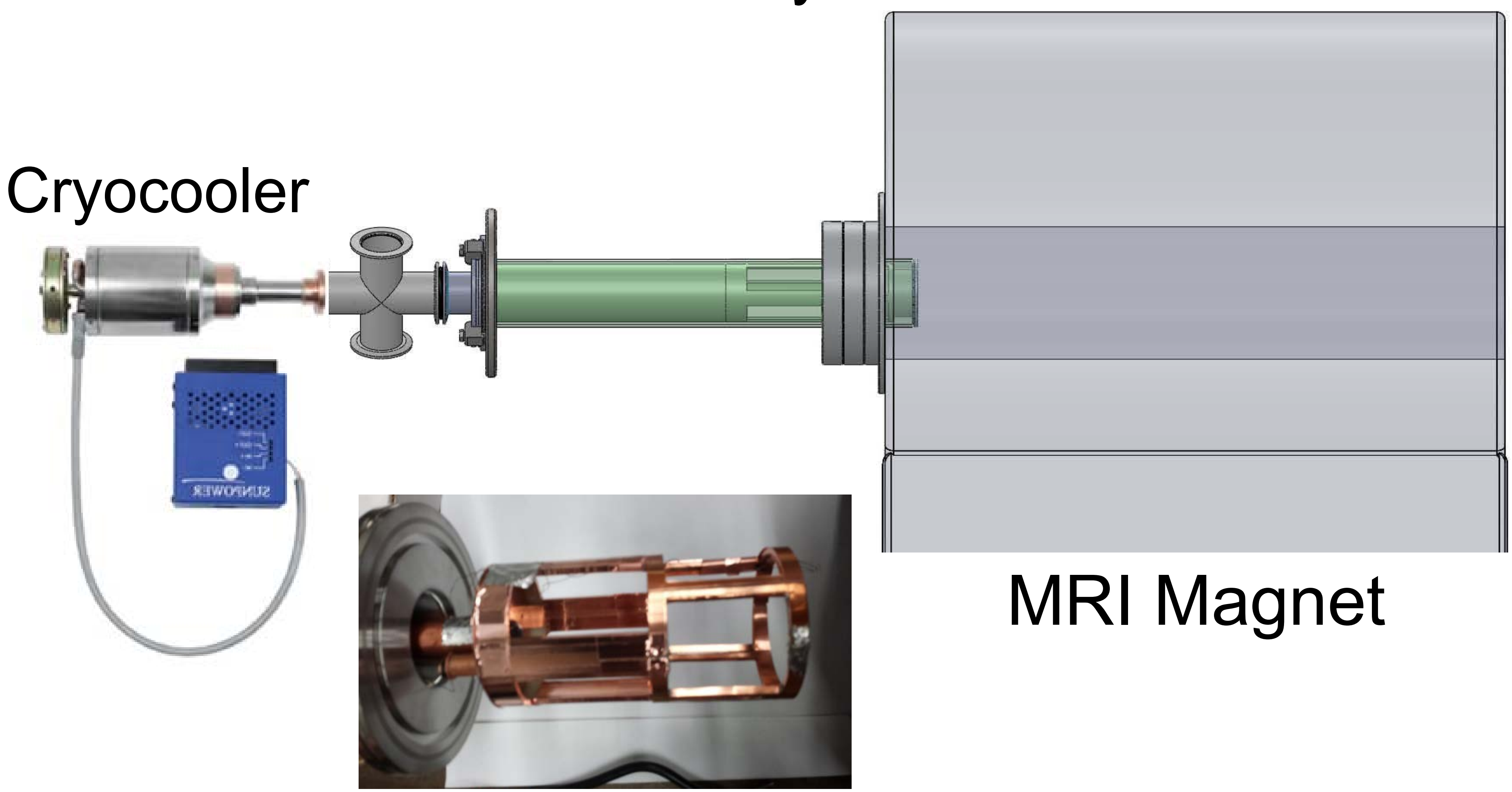
Proposed Split Cooler MRI System



- 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

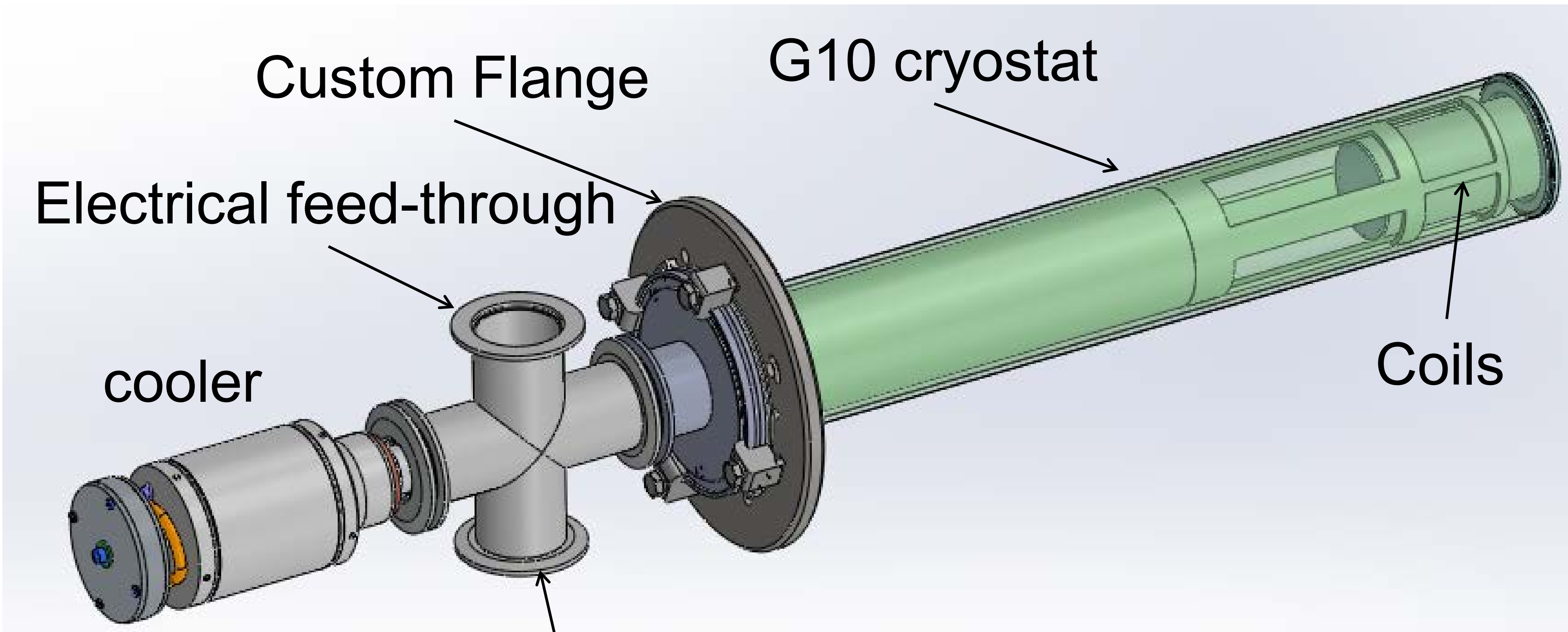
Preliminary Design of Cryocooled Coil

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



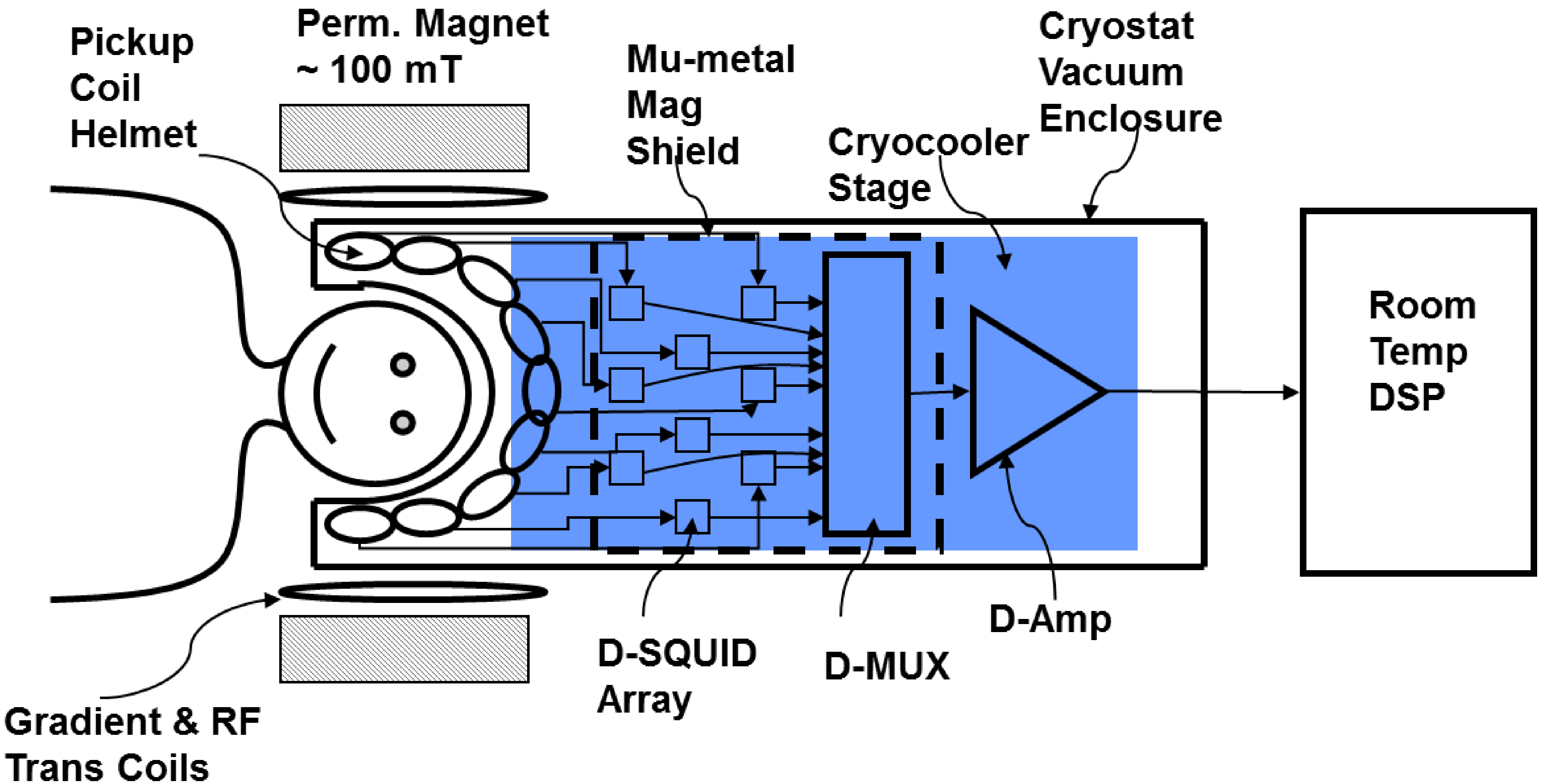
Enlarged view of coils

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

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