# Superconducting Digital Electronics for Cryogenic Detectors

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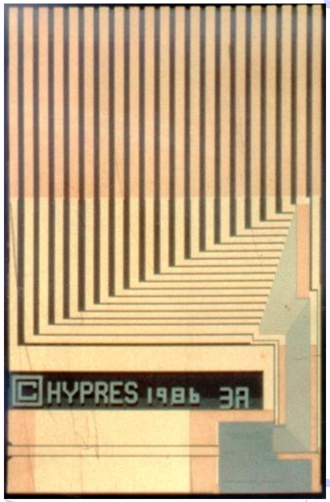
# Why Superconducting *Digital* Electronics?

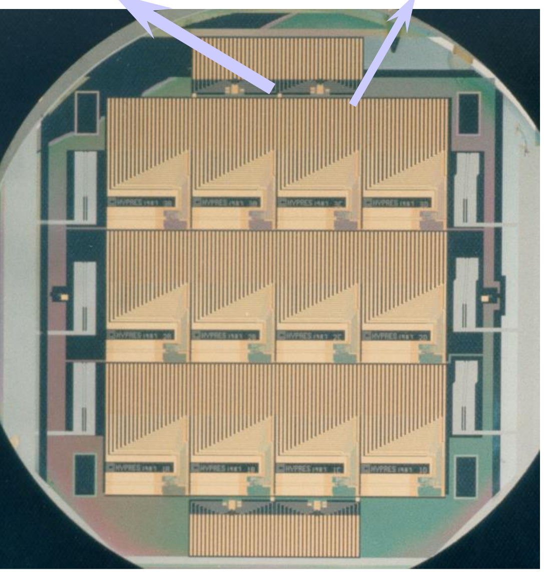
- Superconducting detectors are fast and sensitive, fabricated into arrays.
  - Typically operate at temperatures of 4 K or less
- Analog signals from detector arrays sent to semiconductor digitizers at 300 K.
  - Requires large linear amplification of weak signals
  - Possible noise and crosstalk
  - Data lines carry heat down to cryogenic environment
  - Semiconductor circuits may be sensitive to radiation damage if close to detectors.
- Alternative approach: superconducting digitizers in same cryogenic environment for analog-to-digital conversion and time-to-digital conversion.
  - Superconducting digital circuits are also fast and sensitive, based on Nb Josephson junctions.
  - Well matched to superconducting detectors -- little or no amplification required
  - Performance comparable or better than commercial semiconductor ADCs and TDCs
  - Placement close to detectors reduces noise and crosstalk
  - Pre-processing reduces number of data lines, permits scaling to larger arrays
  - Superconducting digital devices mostly insensitive to radiation damage
- Why isn't this done now?
  - Superconducting digital technology unfamiliar to most electrical engineers and physicists
  - Room-temperature semiconductor digitizers currently do the job (but may not scale)
  - Superconducting ADCs and TDCs are based on a less mature technology, but continue to advance

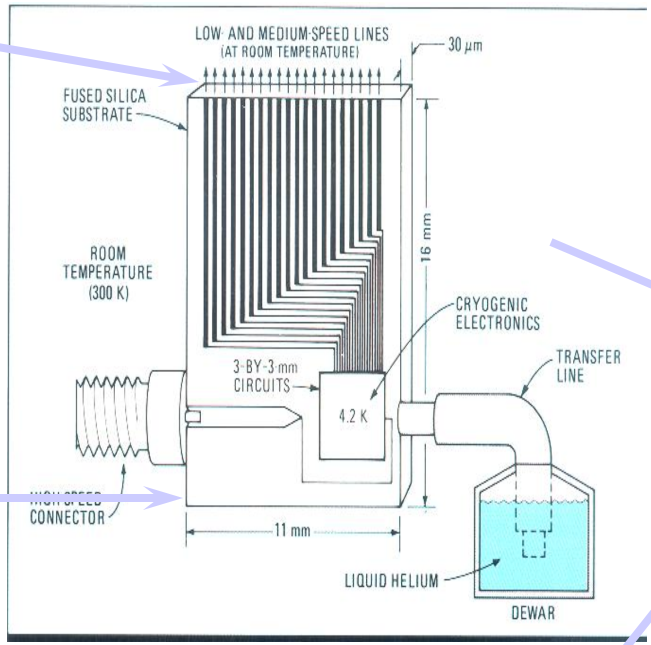
# History of HYPRES

- Small “start-up” with almost 40 years of history
  - Spun out from IBM Josephson Computer project in 1983, when that was terminated
  - Developed early 70 GHz sampling oscilloscope based on Nb chip
- Developed Josephson junction (JJ) technology for digital integrated circuits
- Primary Josephson voltage standard for 1-10 V, array of thousands of JJs
- SQUIDs and Detectors
- ADCs and TDCs, mostly for defense R&D
- Digital Logic Circuits for Computation and Control (including IARPA’s C3 program)
- Advanced Digital-RF Receiver (ADR)
- Integrated Cryogenic Electronic Testbed (ICE-T)
- Systems on compact cryocoolers without liquid helium
- Recent spinout from Hypres in 2019 to form SeeQC, (superconducting) Scalable Energy Efficient Quantum Computing company

# Sampling Oscilloscope (1987)

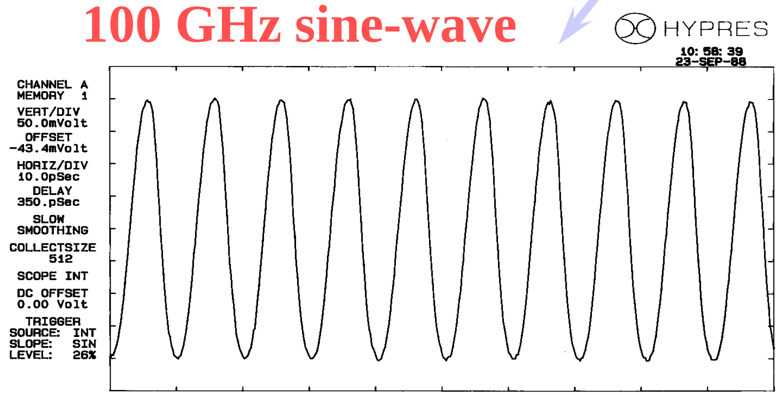






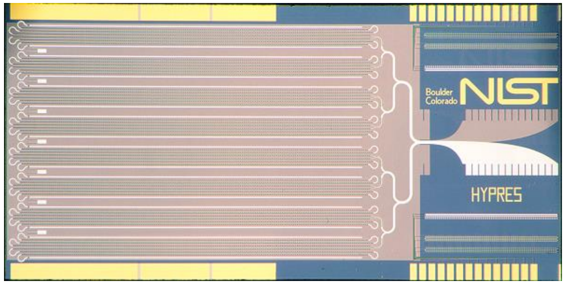
100 GHz sine-wave




70 GHz bandwidth

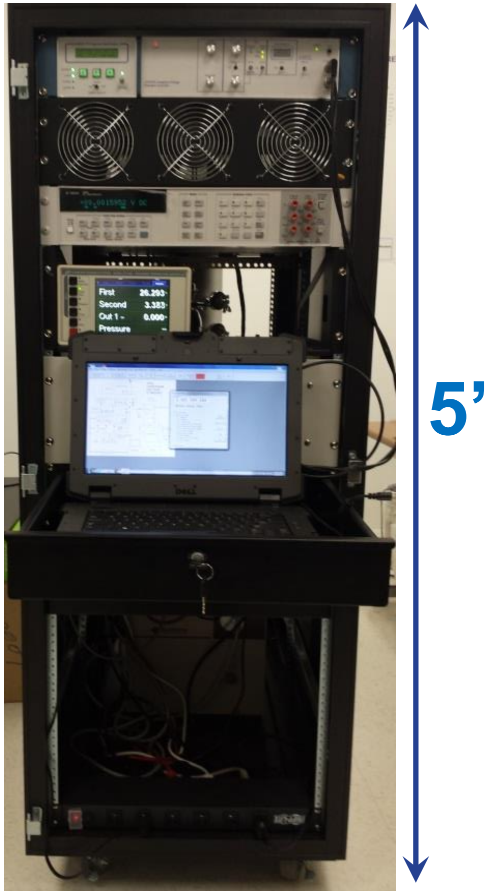
50 μV sensitivity

# Commercial Primary Voltage Standard




**1cm x 2 cm 10 Volt Chip with 5ppb accuracy (23,000 Josephson junctions)**


**(Gen 1)**



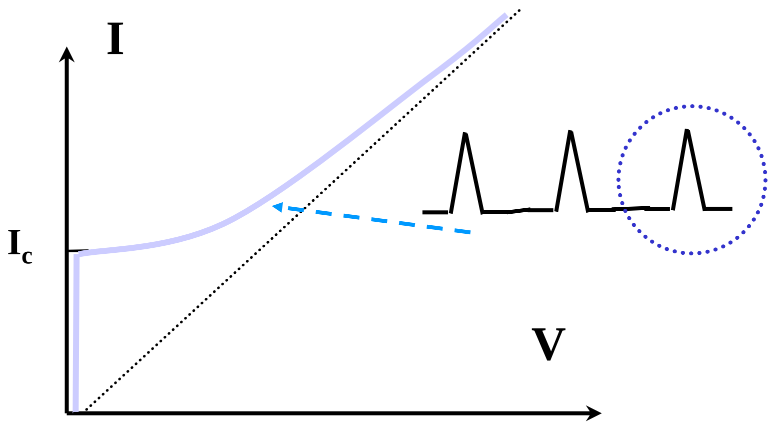

**(Gen 2)**

**(Gen 3)**
**Ruggedized – Transportable**

**Cryocooled Voltage Standard System**

# Magnetic Flux Quantization

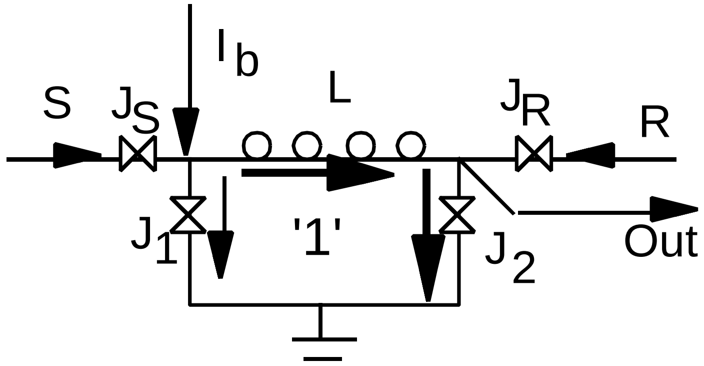
- Superconducting circuits naturally quantize magnetic flux $\Phi$ in units of $\Phi_0 = h/2e$
  - Physical basis for superconducting digital circuits
  - Since $\Phi = LI = \int V dt$, $\Phi_0 \sim 2$ mA-pH = 2 mV-ps
  - Sets scale of circuit parameters ~ 0.2 mA, 10 pH, 1mV, 2 ps, 5 Ω
- A (damped) JJ naturally generates periodic train of pulses at frequency $f = V/\Phi_0$.
  - Each pulse carries single flux quantum (SFQ)
  - Pulse height 1 mV, pulse width 2 ps.
  - Works only up to ~ 1 mV (500 GHz)



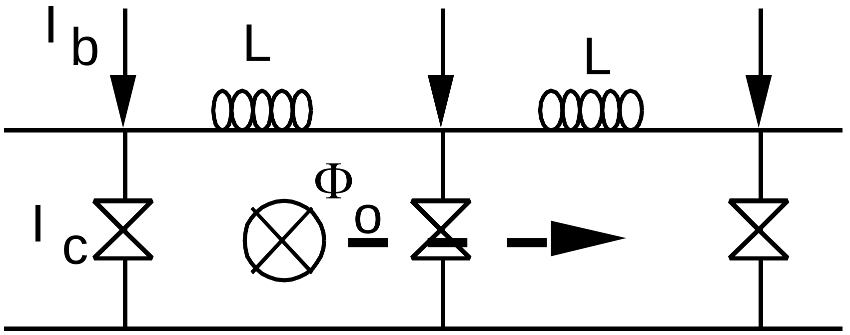

- Applying a frequency generates a voltage.
  - Thousands of JJs in series generate voltage ~ 1-10 V for primary voltage standard.
- Applying a fixed voltage generates a clock
  - SFQ pulses can propagate without loss on superconducting transmission lines to other parts of circuit
- Applying a time-varying voltage generates a sequence of pulses
  - If you count the pulses in a binary counter with a clock reference, you have an ADC

# Transmission and Storage of SFQ Pulses

- A SQUID (Superconducting Quantum Interference Device) = 2 JJs in a loop
- SQUIDs are well known as sensitive detectors of magnetic field on scale of $\Phi_0$
- But a SQUID is also a fast Digital Gate
  - RS-flip-flop, also memory cell
  - Loop can store magnetic flux $\Phi_0$
  - Can release flux to create SFQ pulse
  - Basis for binary counter and logic gates




- Parallel array of JJs acts as transmission line (JTL) to distribute SFQ pulses around circuit



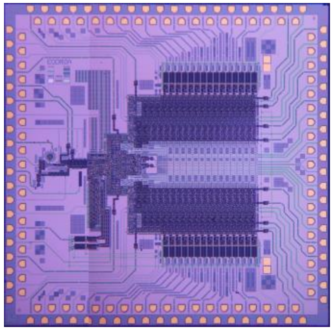

- SFQ pulses may also be distributed on-chip and between chips on superconducting passive transmission line (PTL)

# SFQ Digital Logic Families

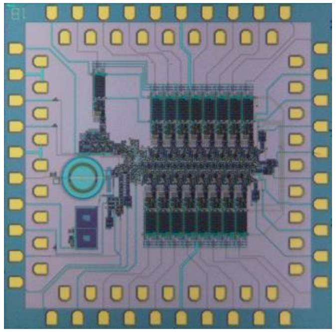
- RSFQ (Rapid SFQ) – Likharev & Semenov (Mukhanov) – first and dominant family
- RQL (Reciprocal Quantum Logic) – Herr & Herr – AC clock
- ERSFQ (Energy-efficient RSFQ) – Kirichenko/Kirichenko/Mukhanov – low power
- AQFP (Adiabatic Quantum Flux Parametron) -- Takeuchi et al. – even lower power
- Note all have “quantum” in name, but are NOT for quantum computing
- Hypres now focuses on RSFQ (also ERSFQ)
  - Synchronous circuits clocked up to 50 GHz.
  - Up to ~ 10K JJs on a chip
  - Data Converters (ADC, TDC)
  - Digital radio receivers (ADR)
  - Classical computer processors (arithmetic logic units and memory circuits)
  - Detector readouts
- (SeeQC is developing RSFQ and ERSFQ interfaces for quantum computers.)

# Superconductor ADCs and TDCs

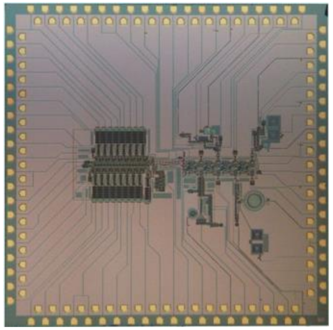
- Hypres has developed families of both ADCs and TDCs based on RSFQ logic
- Example:
  Dual ADC/TDC chip with time resolution to 6 ps and current resolution to 4 nA*
- Broadband digitizers with instantaneous bandwidth up to 25 GHz, enabled by very fast clocks of superconducting digital circuits. (Future plans for up to 40-50 GHz)
- Associated very fast circuits for digital filters, data correction, and digital output amplifiers to transmit data to room temperature for further data processing



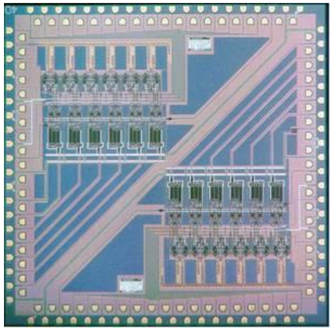
**(a) Lowpass PMD Δ**



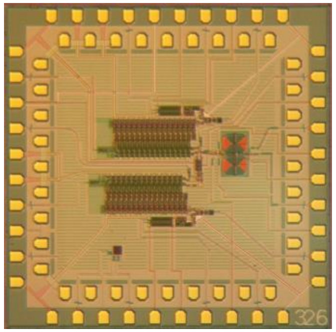
**(b) Bandpass ΔΣ**



**(c) 4-band (PMD + 3 ΔΣ)**



**(d) Dual 6-bit Flash**

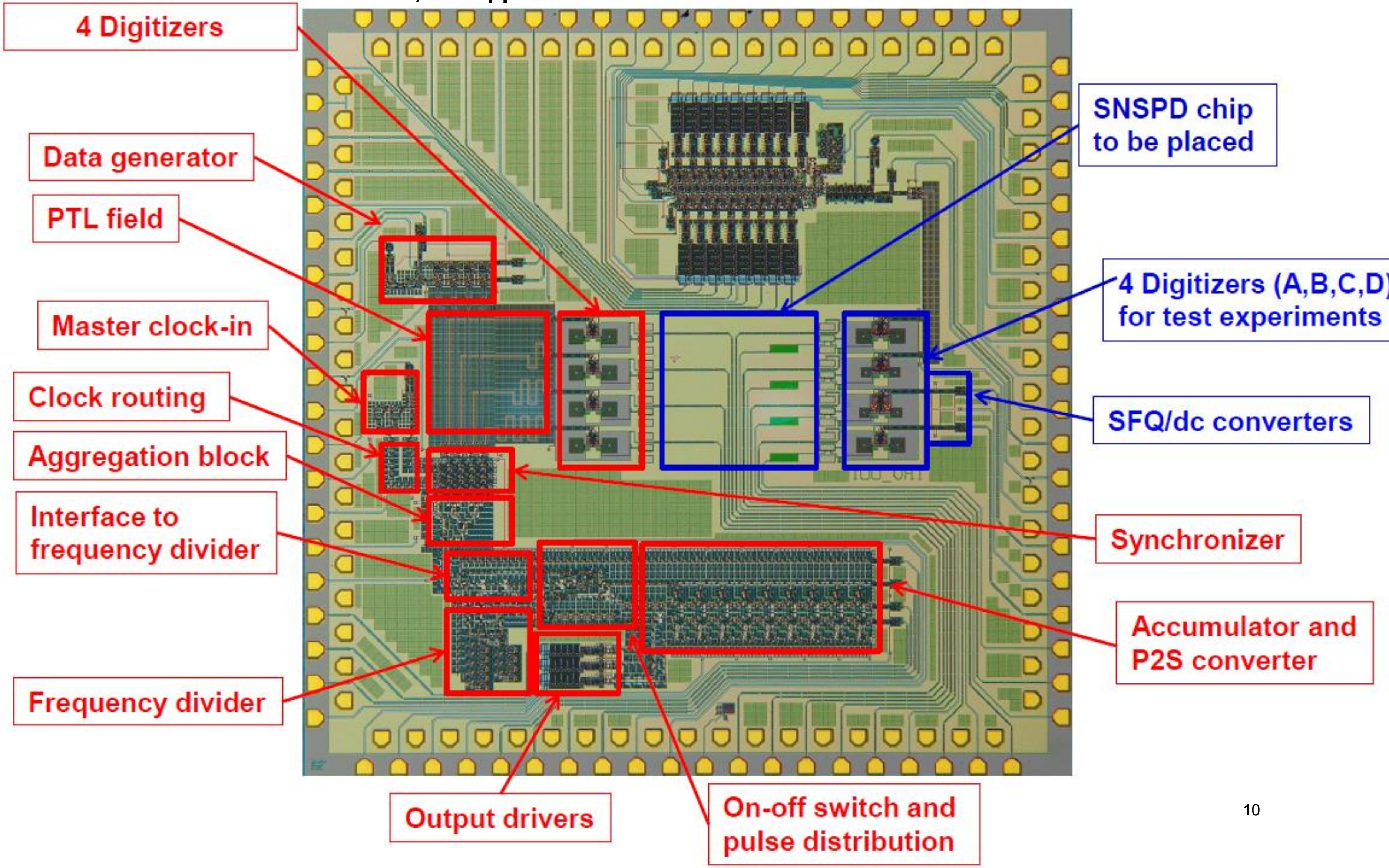


**(e) Dual ADC +TDC**

*** Sarwana, et al., "High-sensitivity, high-resolution, dual-function signal and time digitizer", Appl. Phys. Lett., vol. 80, p. 2023, 2002.**

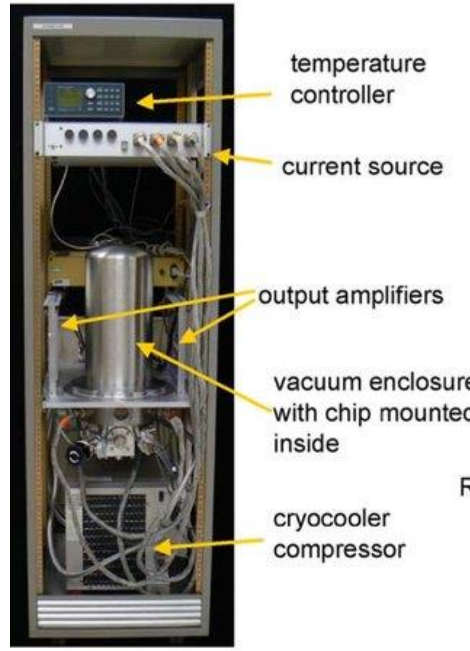
# Digital Readout Chip for 4 SNSPDs

E. Celik, T. Filippov et al.

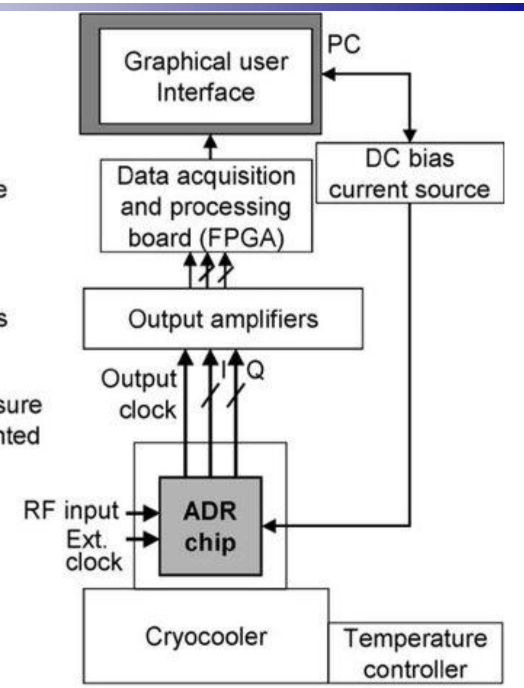


# Superconductor Advanced Digital-RF Receiver (ADR)

- Hypres has developed a complete turnkey digital communications receiver for military communications, based around ultrafast superconducting ADC
  - https://www.hypres.com/products/advanced-digital-rf-receiver/
- Built around compact cryocooler at 4-5 K, with no liquid helium coolant required
- Can directly digitize a wideband signal up to 20 GHz wide, and send it for further processing at room-temperature
  - Channelization into multiple narrow-band signals can be done in room-temperature silicon, in parallel
  - Very similar processing can be applied to frequency-multiplexed microwave signals from detector arrays



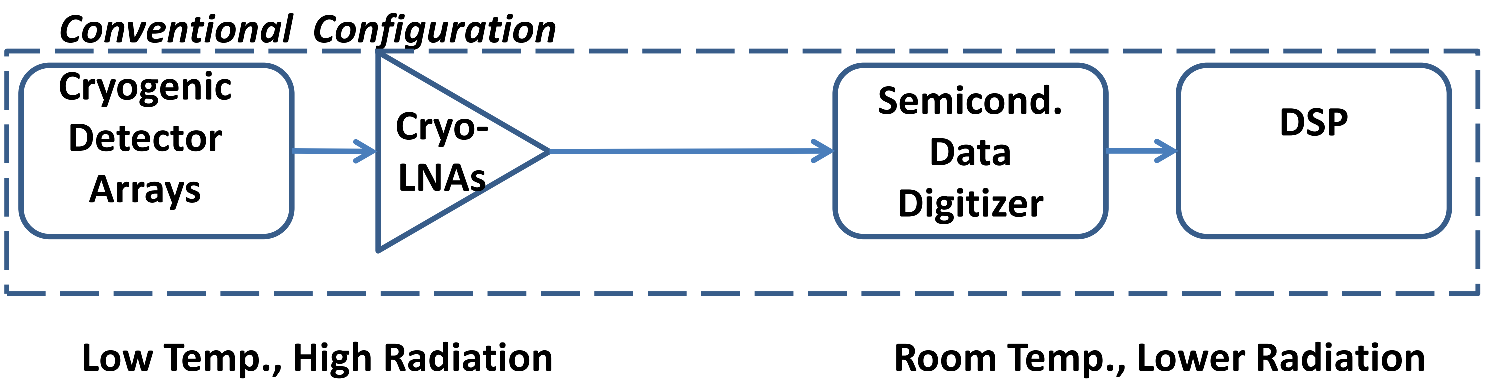
(a)

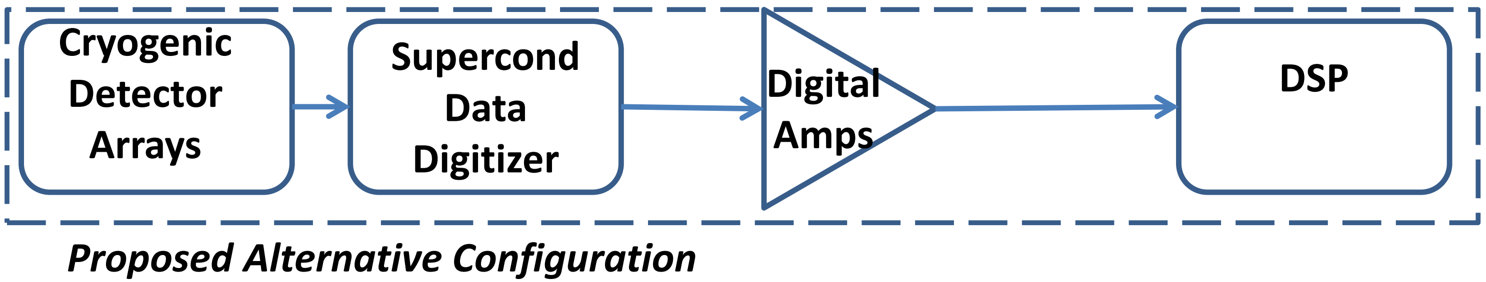


(b)

# Applications to Detector Readout

- Broadband ADCs for frequency-multiplexed signals from large arrays of superconducting detectors such as TES and KID
- Ultrafast TDCs for event timing from superconducting detectors such as SNSPD
- Placing superconducting digital electronics close to detectors for high-energy physics should enable scaling to larger arrays for high-energy physics
- Superconducting digital circuits compatible with high radiation levels



# Radiation Tolerance of Supercond. Circuits

- Nb JJs are tunnel junctions with ~ 1 nm $Al_2O_3$ barrier layer – all polycrystalline
  - Insensitive to radiation damage
- Si transistors are single crystals, very sensitive to radiation damage
- Many years ago, Hypres superconducting digital circuit exposed to high radiation level, without damage.*
  - Nb IC, RSFQ shift register – digital memory circuit
  - Performed the same before and after large cumulative dose
  - Exposure in accelerator to 1016 protons/cm2 (6.5 MeV), equivalent to 5000 Mrads
  - Much larger dose than ~ 100 Mrads for superconducting detectors, which would damage transistor circuits
- Not tested with recent complex Nb ADC and TDC chips, but similar tolerance expected
- Superconducting ADCs and TDCs will be ideal for packaging close to large cryogenic sensor arrays in high radiation
- (Of course, magnetic shielding is required for superconducting circuit operation but techniques exist to effectively provide such shielding)

***Pagano, et al., "Radiation hardness of Josephson junctions and digital superconductive devices", Proc. International Superconductive Electronics Conference, Berlin, Germany, June 1997.**
**http://www.hypres.com/wp-content/uploads/2010/12/Radiation-Hardness-of-Josephson-Junctions.pdf**

# Some Recent Hypres Papers

- Sahu, et al., “Low-power digital readout circuit for SNSPDs”, 2019.
- Celik, et al., “25 GHz operation of ERSFQ Time-to-Digital Converter,” 2021.
- Inamdar, et al., “Design of 64-bit ALU using improved timing characterization methodology for RSFQ cell library,” 2021.
- Filippov, et al., “Parallel counters for low-pass phase-modulation ADC,” 2018.
- Shukla, et al., “Serial biasing technique for electronic design automation in RSFQ circuits,” 2022.
- Kirichenko, et al., “ERSFQ 8-bit parallel ALU”, 2019.
- Sahu, et al., “Digital time-division multiplexing readout circuit for sensor arrays,” 2016.
- Ghadri, et al., “Modeling and design of resistor ladder network for superconducting flash ADC,” 2021.
- Dotsenko, et al., “Superconducting IC testing with integrated cryogenic electronics testbed (ICE-T),” 2017.
- Truitt, et al., “Commercially fabricated low-loss superconducting resonators integrated with detectors for frequency-domain multiplexing readout of future cosmic microwave background experiments,” 2019.
- Gupta, et al., “Digital output data links from superconductor ICs,” 2019.

# Conclusions

- Superconducting digital electronics is fast and sensitive, for same reasons as superconducting analog detectors
- Digital data conversion (ADC & TDC) based on flux quantization and SFQ pulses is fundamentally linear, and well matched to superconducting detectors
- Broadband superconducting ADCs ideal for large array of frequency-multiplexed detectors
- Superconducting TDCs ideal for ps timing of detectors such as SNSPDs
- Nb JJ circuits are tolerant of high-level radiation, enabling placement close to superconducting detectors
- Superconducting digital circuits show promise for interfacing future larger arrays of cryogenic detectors
- Hypres looking for partners to further develop, integrate, and apply this improved technology