HERD-1 Application note

HERD-1

HERD-1 is a high-performance lowpass filter with < 0.1dB insertion loss in the 0-12GHz band and over 50dB of attenuation in a wide stopband starting at 60 GHz and extending to 145 GHz (measured) and above. This unparalleled performance is achieved thanks to a patent-pending technology that directs high-frequency radiation away from the main propagating path of the filter and into an absorptive region. By contrast, low-frequency radiation never enters the absorptive region and propagates undisturbed across the filter.

Applications in superconducting quantum computing

Quantum processing units (QPUs) based on superconductors need to be cooled down to very low temperatures (<10 mK) and communicate to classical electronics via electromagnetic pulses in the 4-8 GHz band. At the same time, **QPUs are extremely sensitive to radiation at frequencies above a certain cutoff** $2\Delta/\hbar$, where Δ is the superconducting energy gap and $\hbar$ is the reduced Planck constant. **Radiation exceeding this frequency is referred to as Cooper-pair breaking radiation and can cause partial disruption of superconductivity, which is very detrimental for the performance of the QPU.**

For common materials and film thicknesses used in superconducting quantum computing, the cutoff is in the range of tens of GHz up to a few THz. For example, in Al, the most common material used to realize Josephson junctions – the core element of superconducting QPUs – the cutoff frequency is around 80 GHz. To protect QPUs, various filtering strategies have been implemented, including absorptive filters based on magnetically loaded dielectrics or copper powder (on input lines to the QPU), and ferrite circulators (on output lines from the QPU to a signal amplification stage). **Thanks to its ultralow loss in the passband, HERD-1 can be integrated in all signal lines connecting the QPU to higher temperature stages, thereby reducing thermal interference and delivering superior performance for the QPU.**

Integrating HERD-1 in a quantum computing setup

QPUs are stored and operated in a cryogenic environment, typically a dilution refrigerator. QPUs are connected to room-temperature electronics via measurement and control lines, serving as inputs to and outputs from the QPU.

Types of lines

Here are the four most common types of lines to be found in a superconducting quantum computer:

1. **Readout input lines** are used to drive readout resonators to query the state of the qubits. Any residual in-band thermal radiation results in degraded qubit performance via thermal-shot-noise-induced dephasing (even at the single-photon level, ~10^-24 W/Hz), so these lines are the most heavily filtered. They work in the 4-8 GHz bandwidth.
2. **Charge lines** are used to drive XY rotations on qubits. They are typically weakly coupled to the qubits to prevent the qubits from decaying into them, for this reason, they need to handle more power but can also tolerate a higher thermal background. They also work in the 4-8 GHz bandwidth.

3. **Flux lines** are used to drive Z rotations on qubits by changing the current flowing in on-chip superconducting loops. The currents to be carried are of the order of 1mA. They require a bandwidth from DC up to 1 GHz.
4. **Readout output lines** are used to collect signal from the readout resonators, with a power level in the order of -120dBm. Losses should be avoided, especially between the QPU output and the first amplifier in the chain.

Filtering strategy

In input lines of type 1-3, various attenuators and filters are deployed to reduce thermal background and protect the QPU from noise and interference. By contrast, output lines carry tiny electromagnetic signals encoding information regarding the state of the quantum bits. These signals are amplified by an amplification chain including one or more cryogenic amplifiers as the first stage, and nonreciprocal components (isolator, circulators) are used to decouple the QPU from the backaction of the noisy amplifiers. Broadband attenuation is a viable strategy for input lines (with constraints related to power handling and heat loads, see Ref.[1] for details), but not for output lines, because it would result in loss of useful signal and as a result worse performance in qubit readout (speed, fidelity). However, **the requirement of rejecting high-frequency radiation is common to all types of lines.**

Before and after HERD-1

Absorptive filters can be utilized in charge, flux, and readout input lines. Their attenuation profile (in dB) follows a constant decreasing slope as a function of frequency. However, they have the following limitations:

- **Unwanted in-band absorption**. This makes these filters less suitable or completely unsuitable for some applications. For example, they cannot be deployed in output lines. They can be deployed in charge lines but at the expense of a tradeoff related to increased attenuation in both the stopband and the passband. The latter also increases the active load on the coldest stage of the dilution cryostat, which in turn limits the number of qubits that can be controlled given a finite cooling power at that stage.
- **Dispersion**. Because the attenuation is frequency-dependent also in the band of interest, fast pulses are distorted.
- **Lack of reliability and reproducibility**, due to the manufacturing process which often involves filling a hollow enclosure with a mixture of absorptive particles and epoxy.
- **Sensitivity to high-magnetic fields**, in case magnetically loaded dielectrics are used.

HERD-1 solves these problems by having:

- **Minimal in-band absorption** (< 0.15dB in passband)
- **Minimal dispersion** (< 0.1dB ripples in passband)
- **High reliability and reproducibility**, because variations in the filling of the absorptive volume have no impact on in-band properties.
- **Insensitivity to magnetic fields**

As a result, **HERD-1 can be used in all types of lines used to connect the QPU to higher-temperature measurement and control electronics**. A simplified wiring diagram of a QPU before and after the installation of HERD-1 is shown in Figure 1.

The main benefits are summarized here:

- Possibility to filter high-frequency radiation in readout lines. As a result, less circulators/isolators may be needed between the QPU and the first amplifier, which increases the efficiency of the amplification chain.
- In charge and flux lines, no tradeoff between desired isolation in the stopband and unwanted attenuation in the passband. As a result, reduced power load to the base plate.
- In charge and flux line, no unwanted in-band dispersion due to the absorption profile of the filter. As a result, possibility to drive faster (~ns) pulses with less predistortion.

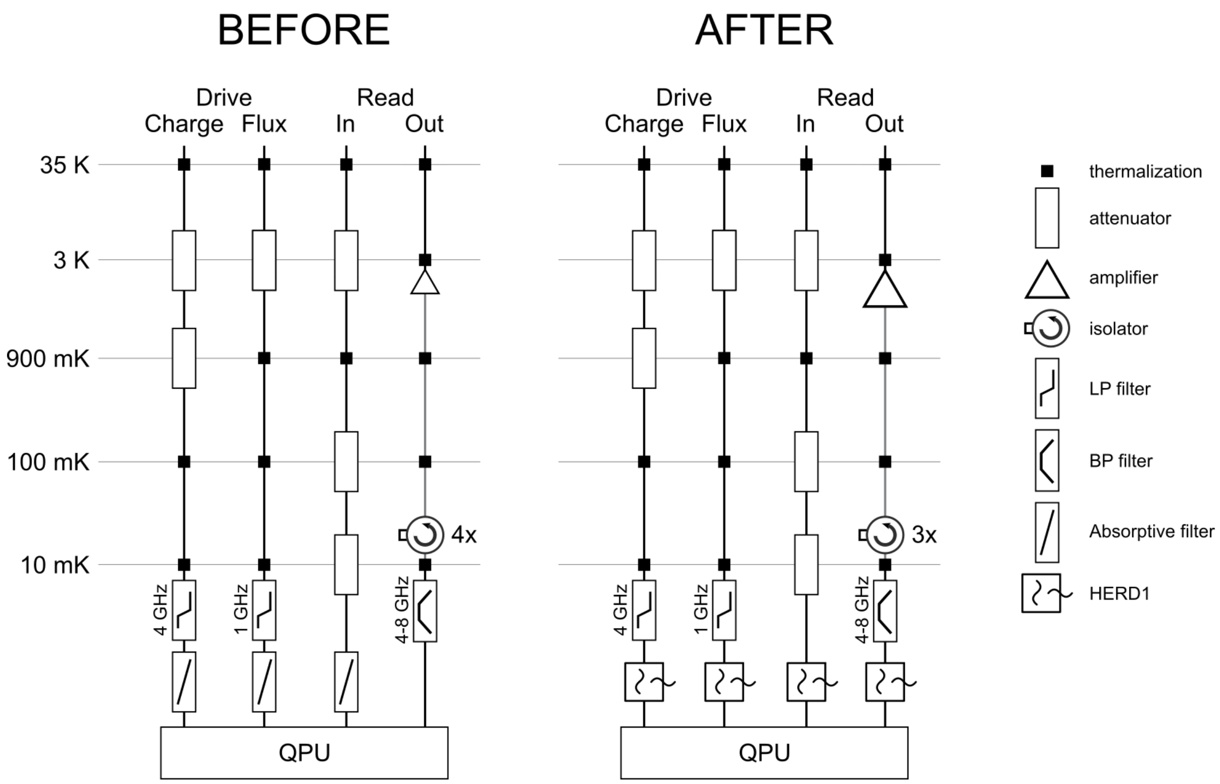


Figure 1

Recommendations how to install HERD-1

Integration. We recommend HERD-1 to be installed below the base plate of the cryostat and as close as possible to the QPU, to benefit the most from the high-frequency isolation provided by the filter. For best performance, we recommend installing HERD-1 on all lines connected to the QPU.

Magnetic properties. HERD-1 is completely nonmagnetic so it can be installed in close proximity to the QPU. It can also withstand very high magnetic fields, so it can be utilized in setups requiring such fields (for example, QPUs based on spin qubits).

Matching. HERD-1 is very well matched to 50 Ohm over a broad 20GHz bandwidth, so it does not introduce spurious standing waves in measurement and control lines. It can be conveniently combined with reactive filters to narrow the passband and define steep rolloffs.

Thermalization. The center conductor of HERD-1 is well thermalized by the connectors. The outer body is thermalized by the absorptive material which is in contact with the connectors. If HERD-1 is connected to the base plate via metallic coaxial cables or adapters, no additional thermalization is required for the filter. A dedicated thermalization braid or bracket could be added to improve thermalization if superconducting cables are used to connect HERD-1 to the base plate.

Absorptive coating

As described above, the HERD-1 filter guides high-frequency radiation away from the main propagating part of the signal and leads it into an absorptive coating. The absorptive coating is accomplished by a carbon infused PETG material wit high resistivity up to 10^9 ohm-cm. The absorber does not change the filter performance. However, the radiation will leak out from the filter and may enter into other leakage paths in the cryogenic set up. It is therefore recommended to use the absorber if this is suspected to be a problem. The effects on qubit performance with and without absorber is still to be investigated.

Validation

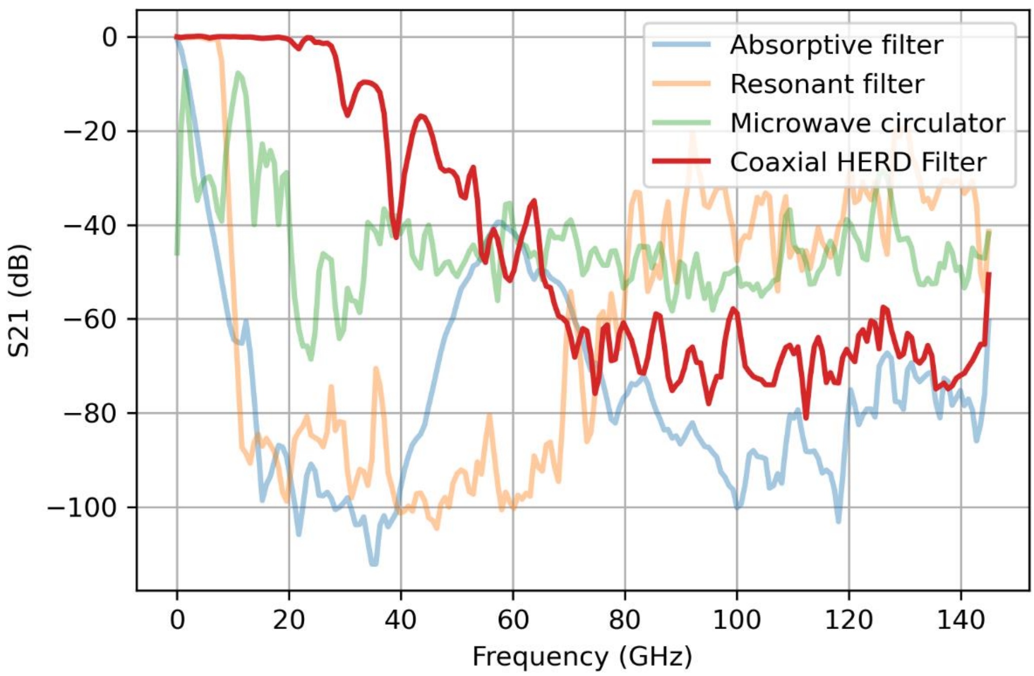
To verify that HERD-1 improves the performance of your quantum computing setup, we suggest the following experiments:

- Measure coherence times of a superconducting qubit with and without HERD-1 installed. If coherence times are limited by quasiparticles, you should see an improvement after installing HERD-1.
- Measure quasiparticle tunneling rates across a Josephson junction, for example, by using a charge-sensitive transmon qubit. If the tunneling rates are limited by quasiparticle generation or photon-assisted tunneling due to high-frequency radiation in the control line, you should see an improvement after installing HERD-1.

Using HERD-1, the group of S. Gasparinetti has measured coherence times in excess of 60us (T1) and 80us (T2), a residual thermal occupation of 0.001-0.0009 at 5 GHz (effective temperature 33.94 mK), and a quasiparticle tunneling rate of 2-4 Hz in a single-islanded, charge-sensitive transmon. We regularly update these figures based on feedback from collaborators and end users.

Comparison between HERD-1 and other microwave components

The plot below shows the scattering parameters of various microwave components, measured at room temperature from DC up to 145 GHz: (blue) an in-house-made absorptive filter, (orange) a microwave circulator, (green) a commercial low-pass filter based on cascaded LC sections, and (red) an early prototype of the HERD-1 filter. The absorptive filter has significant in-band loss. The circulator has an intermediate performance. The low-pass filter performs very well in the passband and has a steep rolloff, but it leaks at high frequencies. Finally, HERD-1 combines optimal in-band performance with around 60dB isolation in the high-frequency range.



References

1. Krinner, S. *et al.* Engineering cryogenic setups for 100-qubit scale superconducting circuit systems. *EPJ Quantum Technology* **6**, 2 (2019).