WHITE PAPER

Cryogenic RF Switches

12-06-26 | FABRICE JANOT

DEFINITIONS

Z_C: System's characteristic impedance (Ω)

P: Power in watts

RAMSES : RAdiall Modular System for Electromechanical Switches

QuBits: Quantum bits

He : Helium

OFHC : Oxygen Free High Conductivity

RRR : Residual Resistivity Ratio

NbTi : Niobium Titanium

PCB : Printed Circuit Board

SEM : Scanning Electron Microscopy

BR : Brass material

PSD : Power Spectral Density

INTRODUCTION TO QUANTUM COMPUTING

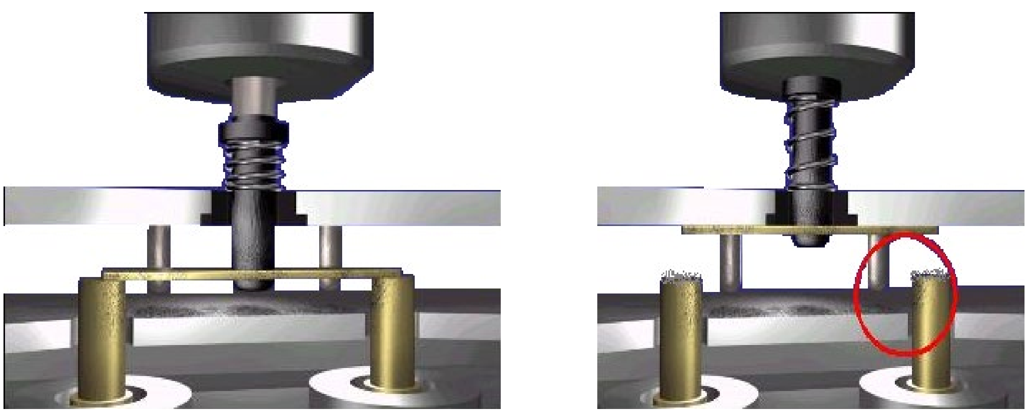
Radiall is working to customize and optimize RF switches for use in cryogenic cooling systems to support quantum computing. Quantum computing will revolutionize our understanding of the world by analyzing datasets that today's most powerful supercomputers can't handle. Instead of bits, quantum computers use qubits which can only be detected at extremely small energy levels and at temperatures close to absolute zero.

This requires cryogenic refrigeration systems with multiple stages of cooling and numerous RF cables of significant length. Radiall coaxial cryogenic switches, mounted at different temperature stages of the cryogenic chamber, help to switch several RF paths into cryogenic cooling systems.

SWITCH APPLICATION

The unique design of RAMSES is based on the suppression of friction, in order to improve reliability and avoid electric contact and RF characteristics degradation.

In general, traditional switches operate by moving a rectangular section contact reed inside a rectangular cavity. These contact reeds are linked to dielectric material “transmission pushers” and directed by guides made of insulated material. During the switching sequences, these dielectric parts rub against the reeds and in the transmission holes, and generate insulating particles in the RF cavity that pollute the contacts, ultimately causing running defects and an increase in insertion. Figure 1 illustrates the build-up of minute dielectric particles on a set of conventional switch contacts after one million cycles.



Closed position

Open position

Figure 1 : Conventional switch contacts after one million cycles.

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To eliminate this problem, all RAMSES devices incorporate the same modular patented system comprised of parallel spring blades suspended from a barrier located outside of the RF body. These blades create a rectilinear motion on the pusher. As a result, both friction and the production of particles inside and outside of the RF cavity are suppressed. Figure 2 shows a cutaway view of a patented RAMSES coaxial switch kinematics.

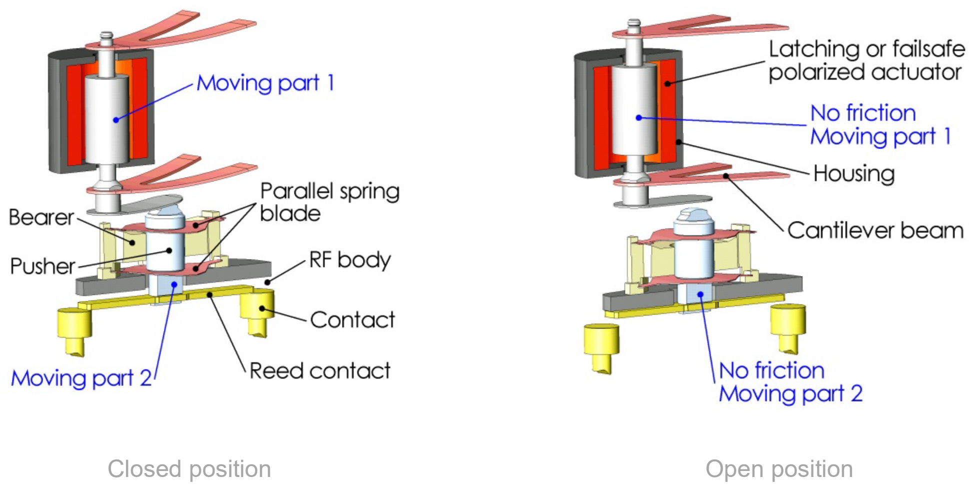
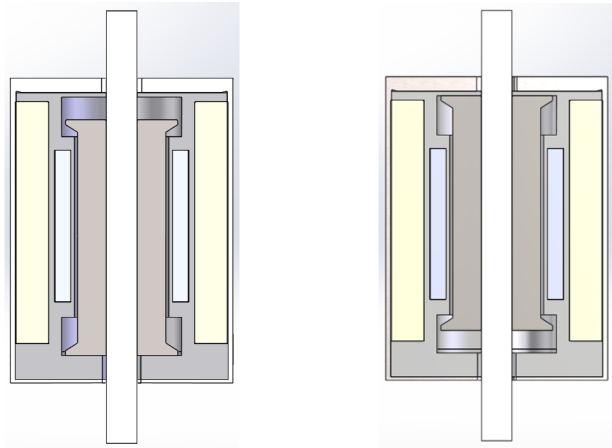


Figure 2 : RAMSES switch kinematics

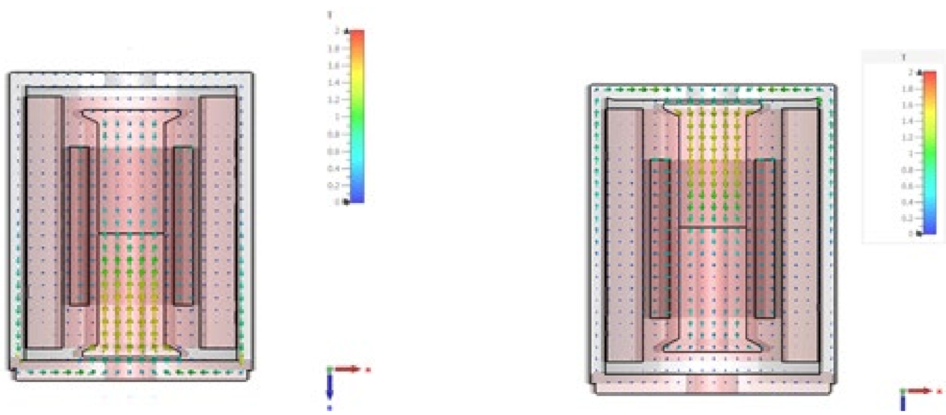
The patented RAMSES polarized linear actuator has been manufactured for several years by Radiall. The miniature design uses high-energy magnets, and can be incorporated in both failsafe and latching models. The actuator produces a locking force and above all, contact forces that far exceed those of traditional actuators, resulting in a power consumption of few Watts. Figure 3 shows a cutaway view of a patented RAMSES polarized linear actuator.



Closed position Open position

Figure 3 : Patented RAMSES polarized linear actuator

Figure 4 illustrates a cutaway view of the magnetic field for both positions. The system is used in the production of both failsafe and latching actuators, depending on how it is applied in the switch. These patented actuators have locking forces when the coil is energized of 800g.



Closed position Open position

Figure 4 : Patented RAMSES polarized linear actuator magnetic field

Figure 5 shows the relationship between locking forces and position of polarized actuator with and without current.

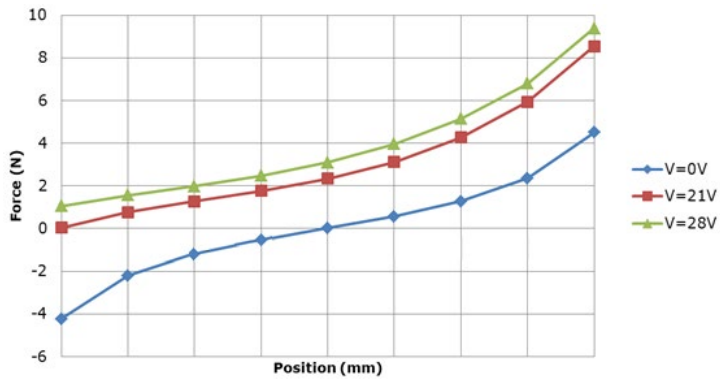


Figure 5 : Relation between locking forces and position of polarized actuator with and without courant.

The actuator has the advantage of very low magnetic leakage, allowing actuators to be used in close proximity to one’s magnetic source without any degradation of performance. Figure 6 shows the integration of Radiall cryogenic switches inside dilution refrigerator. Close to RF switches bobbin with magnetic strength more than 1 Tesla is used.

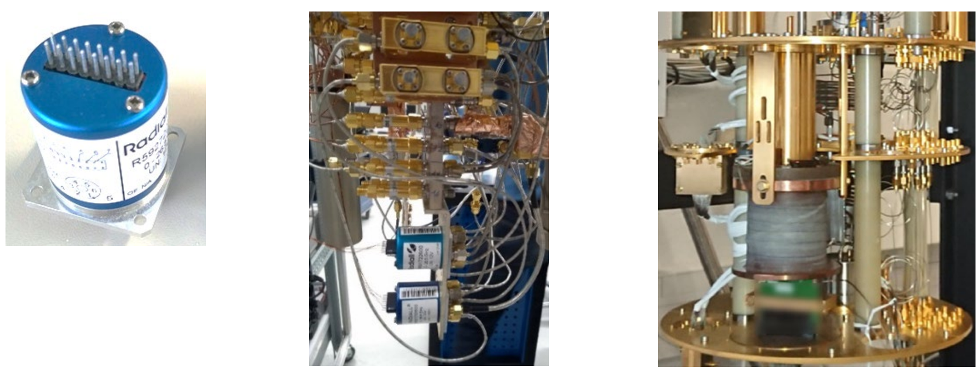


Figure 6 : Cryogenic switches inside dilution refrigerator.

Magnetic field leakage test campaign was performed on bipolar cryogenic SP6T coaxial switches using the following test samples:

R5927B2141 cryogenic SP6T made with aluminum alloy

Cryogenic SP6T with cap made with brass material

Cryogenic SP6T with RF body made with brass material

Figure 7 : Cryogenic switches for magnetic tests campaign.

Leakage field amplitudes were performed and recorded with continuous power supply and without power supply on the test samples.

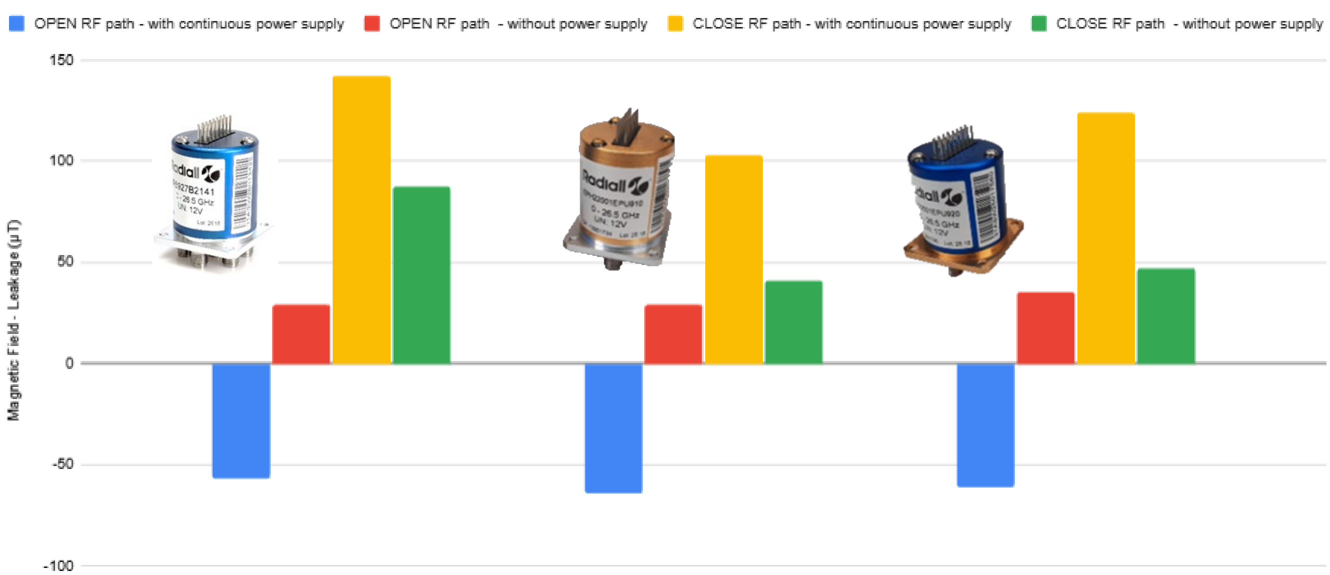


Figure 8 : Impact of power supply on magnetic field leakage

There is no clear variation depending on the nature of the cap – or RF body – between brass and standards versions. In addition, there is no clear variation among the different switches based on the nature of the shielding.

Then, the leakage field amplitude was measured and recorded with and without a cap on the following test sample.

Figure 9 : Impact of cap on magnetic field leakage

For this product, leakage field measurements were made with and without cap. The cap has an effect on shielding, but it remains limited. The internal shielding in the product is such that the cap has a limited role.

Throughout the campaign, a maximum magnetic field of 150µT was measured at the surface of the anodized aluminum (R5927B2141 type) or brass cylindrical cap (R5927B2141BR type). The leakage fields are very low.

SPECIFIC FEATURES FOR CRYOGENIC USE

To ensure reliable connections at cryogenic temperatures, all solenoid pins are soldered directly to the printed circuit board. The pushpin receptacles which could be fail at temperatures close to absolute zero are removed. In addition, for reliability at cryogenic temperature, there is no PCB to PCB internal connection. Figure 10 illustrates the main parts of the cryogenic RAMSES SP6T switch.

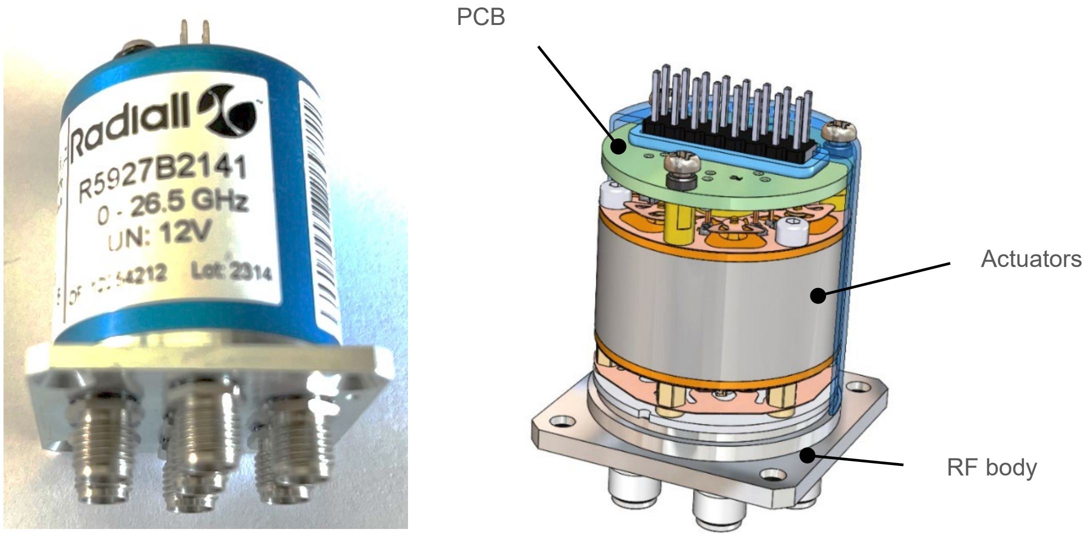


Figure 10 : Main parts of cryogenic RAMSES switches.

Electromechanical latching switches without any options contain a mechanism that will maintain a chosen RF contact path whether the voltage is maintained or not after switching is accomplished. A simple pulse duration equal to the maximum switching time is enough to change the switch position.

For example, on latching SP6T fitted with SMA type connectors the nominal coil resistance is 60 Ω at ambient temperature. The nominal operating current is 200mA at 23°C. Figure 11 shows the electrical characteristics of a non-cryogenic RF switch.

Operating mode	**Latching**
Nominal operating voltage (Vdc) (across operating temperature range)	**12** (10.2 / 13)
Coil resistance (+/-10%) (Ohms)	60
Nominal operating current at 23°C (mA)	200

Figure 11 : Electrical characteristics of none cryogenic RF switch.

To close the desired RF path, ground must be applied to pin "–C" and power supply must be applied to corresponding "drive" pin. To open the paths, complete the operation by applying power supply to "reset" pin. Figure 12 illustrates the electrical schematic of non-cryogenic RF switch.

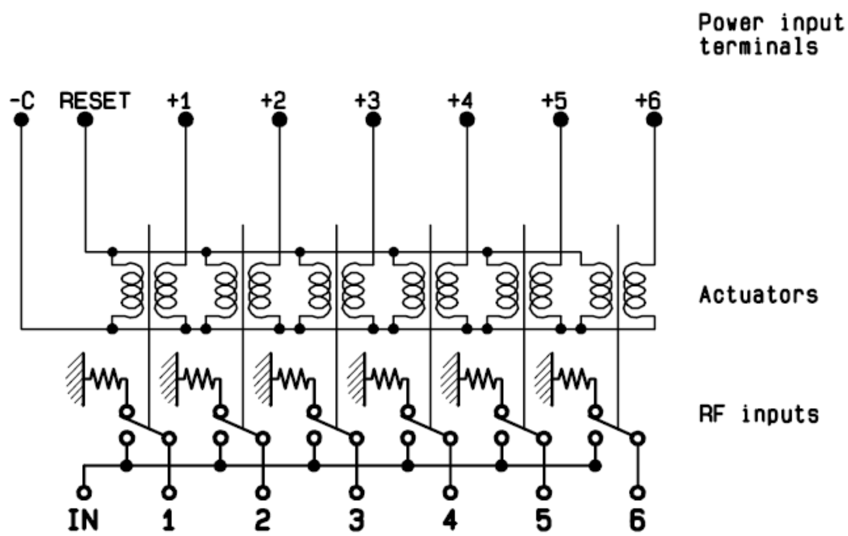


Figure 12 : Electrical schematic of none cryogenic RF switch.

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To minimize the impact on system temperature, the set and reset coils of each actuator are connected in series in Radiall's cryogenic switches. The same magnetic field can be applied with half current. Reset can be accomplished be reversing the direction of the current in the circuit. It limits the heating of the coils which is linked to a higher current value at low temperature. Figure 13 illustrates the electrical schematic of a Radiall cryogenic RF switch.

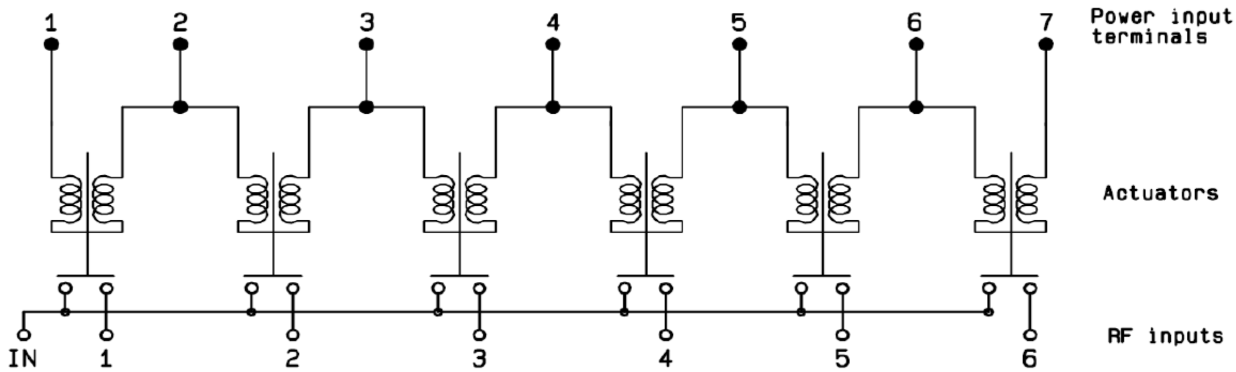


Figure 13 : Electrical schematic of Radiall cryogenic RF switch.

Using both set and reset solenoids in series the power dissipation is divided by 2. Figure 14 shows the power consumption between standard and cryogenic Ramses switches.

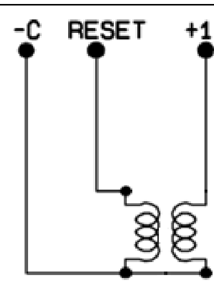
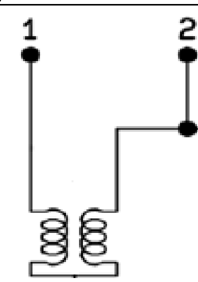
	Standard Ramses switch	Cryogenic Ramses switch
60 Ω per solenoids		
P = U²/R	12²/60 = **2.4W**	12²/120 = **1.2W**

Figure 14 : Shows the power consumption between standard and cryogenic Ramses switch.

In addition, lesser voltage can be used to drive the same current through the circuit and the dissipation at low temperatures is much less.

DC RESISTANCE OF STANDARD AND SPECIAL COILS USED IN RF SWITCHES

Three type of resistance were evaluated for coils at cryogenic temperature. The aim was to extract resistance variation versus temperature. Three coils made of said “normal copper”, “oxygen free copper”, and of superconducting NbTi in copper were measured and evaluated.

First, the superconducting wire used into coil actuators is composed by only one metallic strand of NbTi coated with a layer of copper. Figure 15 illustrate the SEM measurements of NbTi wire.

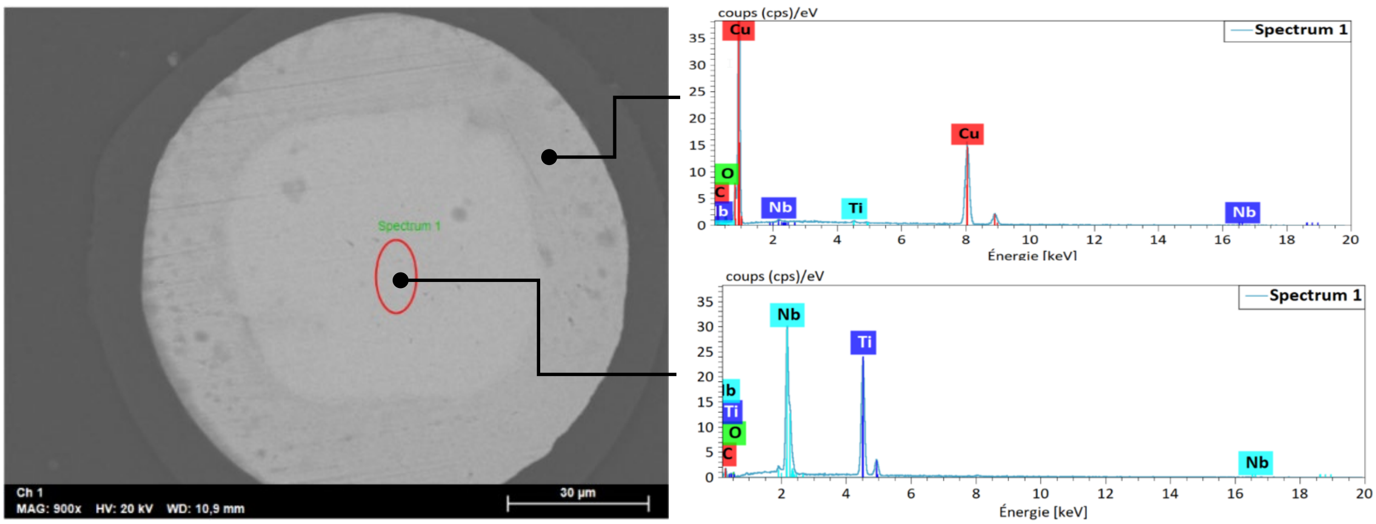


Figure 15 : SEM measurements of NbTi wire.

The setup used to measure the temperature dependence of the coils’ DC resistance uses a calibrated 0-300K thermometer and a 4-wire measurement technique. Each coil is protected from water condensation by scotch tape. The head is plunged in liquid helium and then raised slowly until the helium vapors above the liquid. The resistance as well as the temperature are recorded during the temperature rise. Figure 16 shows pictures of the test method.

Figure 16 : Head protected with scotch tape plunged in a liquid Helium.

Then, the two copper coils (said “normal copper” and “OFHC”) showed a very similar resistance, decreasing from 63Ω at room temperature down to 0.55Ω below 10K. The residual resistivity ratio (RRR) of 102 is observed. This is typical of technical copper. The NbTi-Cu coil have an 83Ω resistance at room temperature, it decreases down to 0.52Ω just before its superconducting transition at 8K, and then dropping to zero (less than 0.4 mΩ measured). Figure 17 shows the resistance variation versus temperature for each coil.

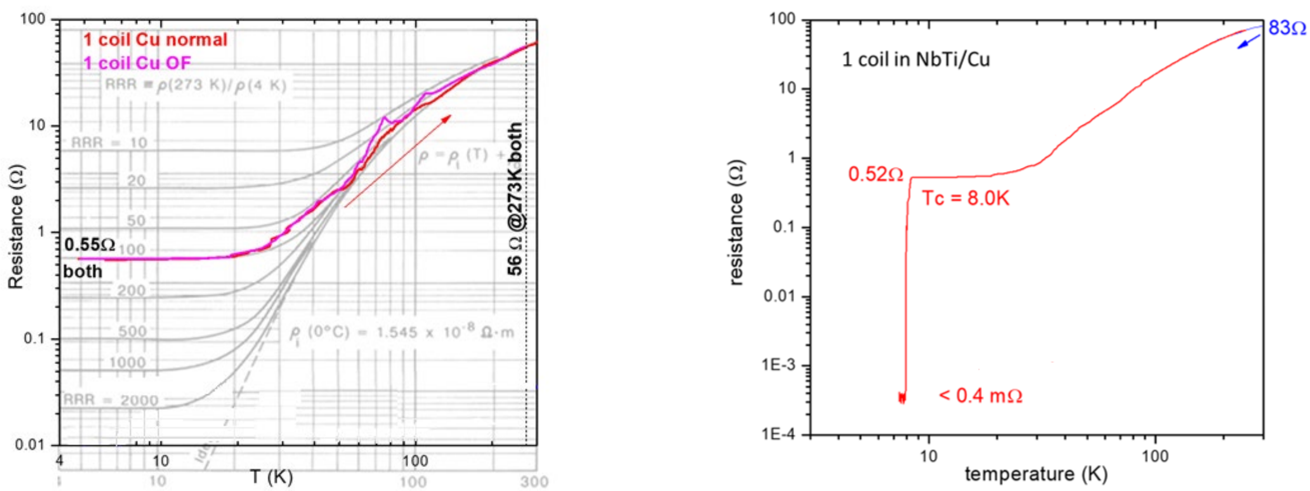


Figure 17 : Resistance variation vs temperature for each coil.

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SWITCHING PULSE AMPLITUDE AND DURATION AT ROOM TEMPERATURE

We have approximately determined the appropriate nominal pulse current, duration and dissipated Joule energy to switch reliably with several SP6T switches placed either at room temperature.

The success probability is then plotted as a function of the pulse duration and current. The plot is complemented by iso-nominal pulse Joule energy lines (not taking into account the mechanical energy of the actuator in the switch).

Figure 18 shows the results for a SP6T with normal copper coils tested at room temperature. Region of 100% success (yellow) follow approximately iso- Joule energy lines (although it is slightly unfavorable to use short intense pulse rather than long-less intense ones).

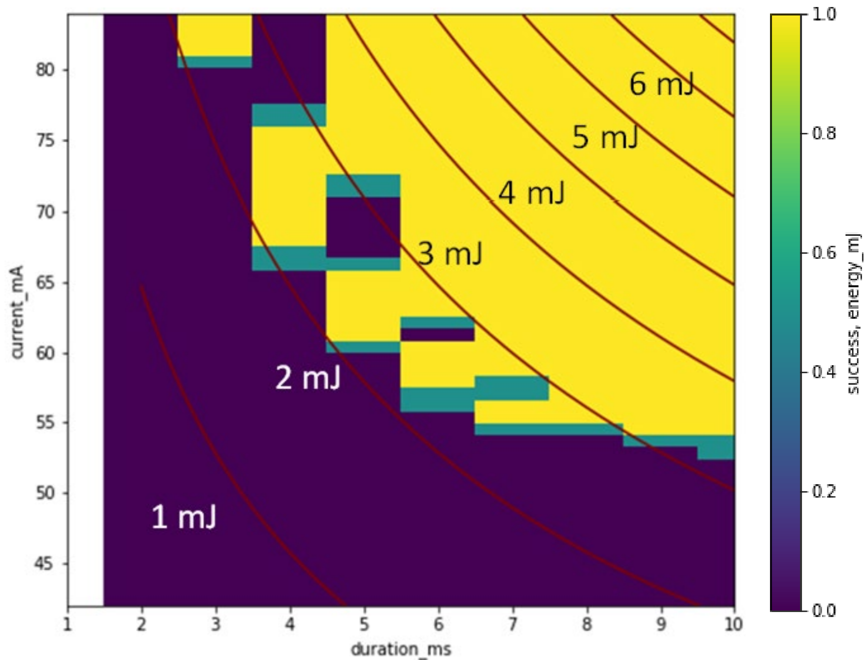


Figure 18 : Success probability at room temperature. Normal copper coils.

10 switching attempts were performed to compute a success probability. At room temperature, to close or open RF paths the switch needs 4mJ between 5 and 10ms.

SWITCHING PULSE AMPLITUDE AND DURATION AT 4.5K

We then compared the switching parameters at cryogenic temperature with those at room temperature in a new measurement round in a dilution refrigerator. The switching current and durations remains the same regardless of the operating temperature. In contrast, the pulse Joule energy is 110 times lower (50µJ vs 5.5 mJ) at low temperature.

The success probability is plotted as a function of the pulse duration and current. The plot is complemented by iso-nominal pulse Joule energy lines (not taking into account the mechanical energy of the switch actuator). Figure 16 shows the results for a SP6T with normal copper coils tested at room temperature and at 4.5K. Region of 100% success, which roughly follow iso-Joule energy lines, are drawn in cyan, although using short, intense pulses is slightly less favorable than using longer, less intense ones.

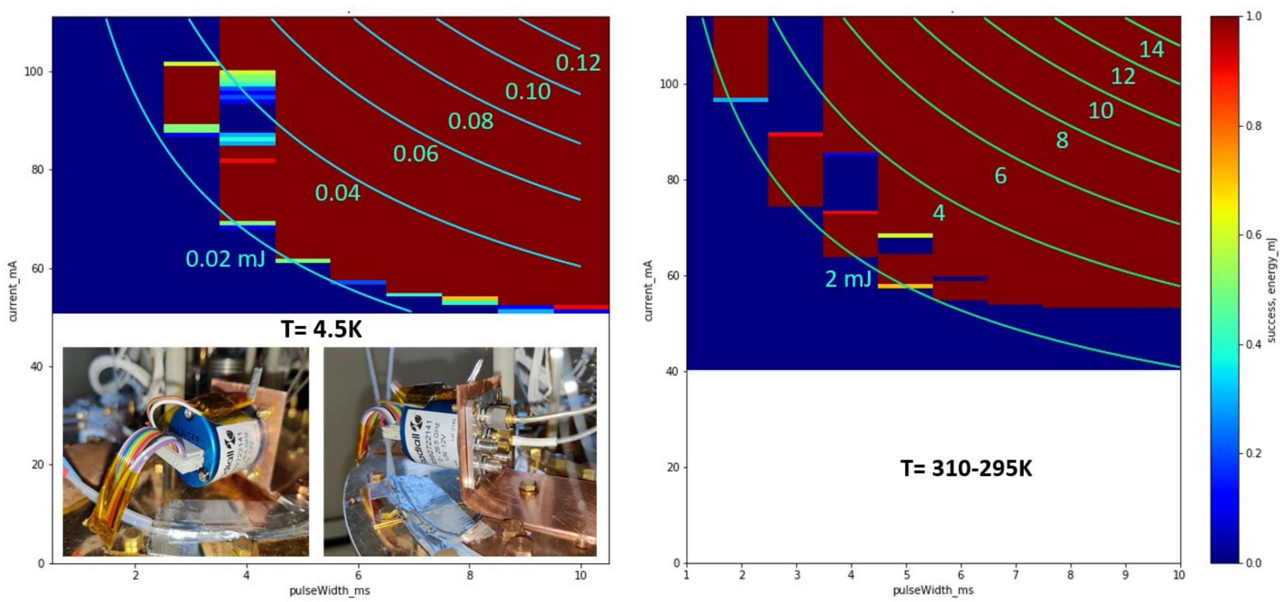


Figure 19 : Success probability at room temperature and 4.5K. Normal copper coils.

Energy dissipated at this working point is 40µJ for normal copper coils at dilution temperature. Switching thermal impact will be visible in most dilution refrigerators but recoverable in minutes. NbTi coils should completely solve the thermal impact of a switching event.

SWITCHING PULSE AMPLITUDE AND DURATION AT 50MK

The heating of a dilution refrigerator induced by the switching of different SP6T was measured. The aim was to measure the impact of actuations close to absolute zero. The refrigerator is then cooled down at cryogenic temperature near 50mK. Figure 17 shows the results of the heating due to 7 close-open cycles (14 actuations) performed on SP6T fitted with normal copper coils every 2 seconds. The temperature of the base plate rises from T_{eq} 50mK up to 72 mK in less than 26s and then decays in a few hours back to T_{eq}.

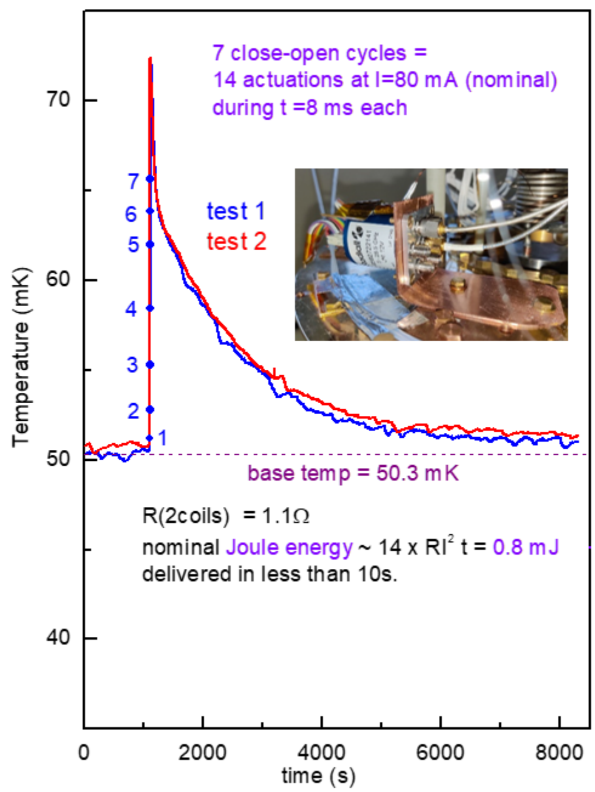


Figure 20 : Heating due to 7 close open cycles at 50mK. Normal copper coils.

The 0.8mJ Joule energy of the 14 pulses represents less than 7% of the about 12 mJ dissipated in total. This indicates that Joule dissipation in the coil resistance is far from being the main source of dissipation.

The interpretation of this result is that the inductive energy of the coil being transferred to the mechanical energy of the actuator (solid friction and kinetic energy) at a level of about 0.8mJ per actuation (12mJ/14 actuations).

We have also performed this type of measurement with an RF switch fitted with NbTi-Cu coils undergoing the same 7 close-open cycles as before, and with this same switch fed with 14 open pulses starting from the open state. Figure 21 shows the results compiled.

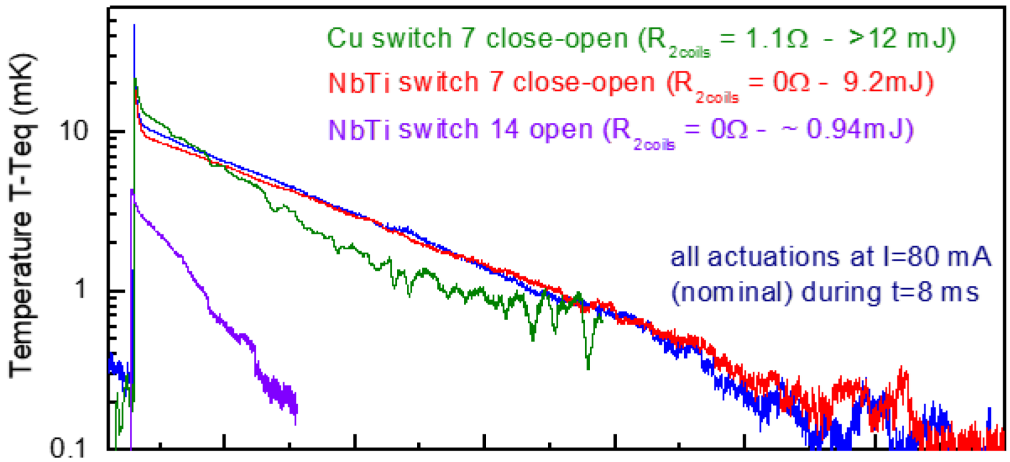


Figure 21 : Refrigerator heating due to several experiments.

The first observation when we compare green and red curves is that the measured dissipated energy when switching with non-superconducting coils is 10%-15% higher than with superconducting coils, thus confirming that Joule effect in the coil is a minor cause of heating. We found that 85% of the energy is not burnt in coil resistance.

Then, the second observation, when applying the same electrical pulses in a direction that does not switch the actuator, the dissipated power is 10 times smaller than when the actuator switches when we compare red and violet curves. This shows that the main source of dissipation comes from the mechanical actuator and kinetic energy.

The conclusion is than NbTi-Cu coils do not bring any advantage to the cryogenic RF switches.

RF PARAMETERS AT CRYOGENIC TEMPERATURE

Insertion loss on RF coaxial switches fitted with SMA type connectors can be modeled using “conductor loss” β_1 and “dielectric losses” β_2.

A = $\beta_1 + \beta_2$

β_1 (dB/cm) = Conductor Loss = $\frac{0,274}{Zc}\left(\frac{\sqrt{\mu_1}}{a\sqrt{\sigma_1}}+\frac{\sqrt{\mu_2}}{b\sqrt{\sigma_2}}\right)\sqrt{F}$

β_2 (dB/cm) = Dielectric Losses = $0,91.\sqrt{\varepsilon}.\tan\delta.K.F.10^{-3}$

Where:

Zc: Characteristic impedance (Ohms)

a: Outer conductor inside diameter (cm)

b: Inner conductor diameter (cm)

F: Frequency (MHz)

σ_1: Conductivity of inner conductor $(\Omega.cm)^{-1}$

σ_2: Conductivity of outer conductor $(\Omega.cm)^{-1}$

μ_1: Magnetic permeability of inner conductor

μ_2: Magnetic permeability of outer conductor

ε : Dielectric constant

$\tan\delta$: Loss tangent

K = Ratio between the two conductor’s b/a

The composite insertion loss of a transmission line is determined by the losses associated with the inner and outer conductors, the dielectric medium and characteristic impedance mismatches.

At cryogenic temperatures, the conductor loss is neglected due to superconductivity. Figure 22 shows the RF characteristic of an RF Ramses switch installed on 10K stage of cryostat.

Temperature monitors were attached directly to RF body of Ramses SP6T switch. RF performances were tested in-situ.

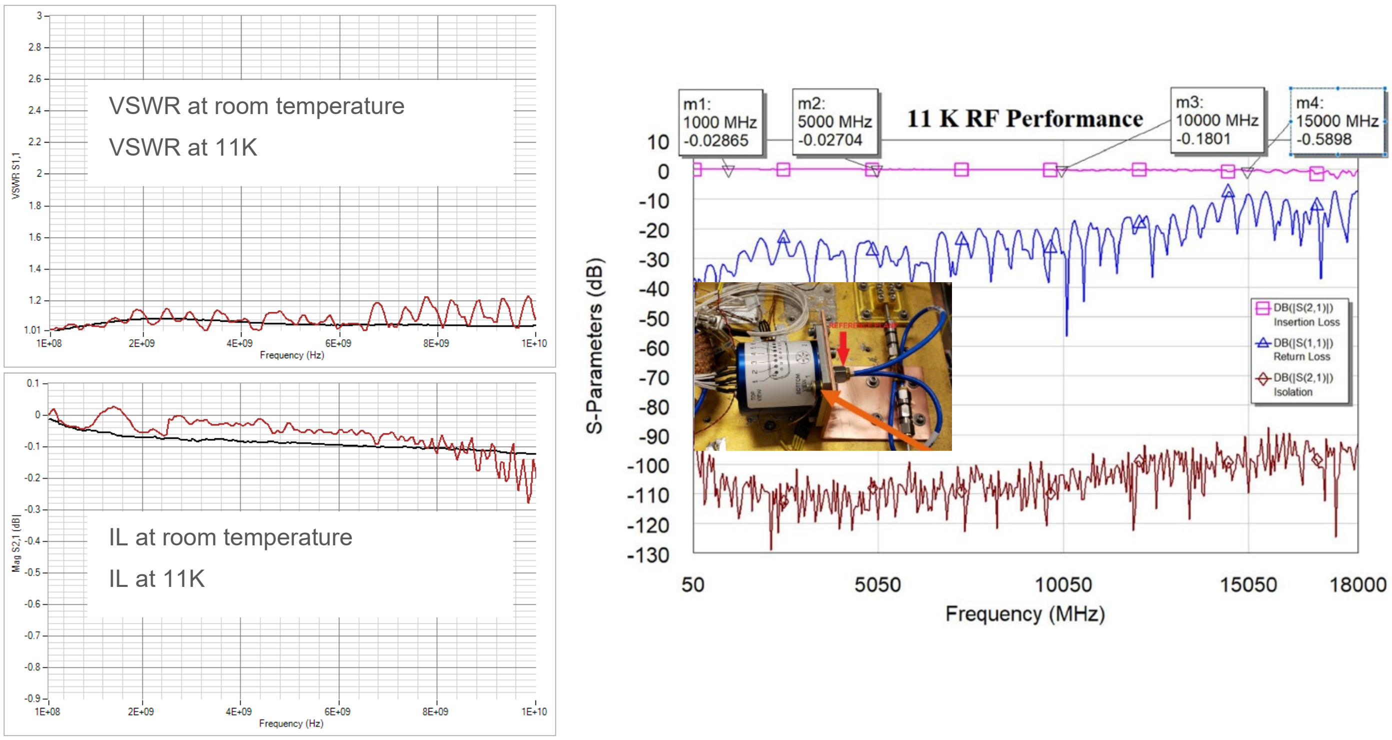
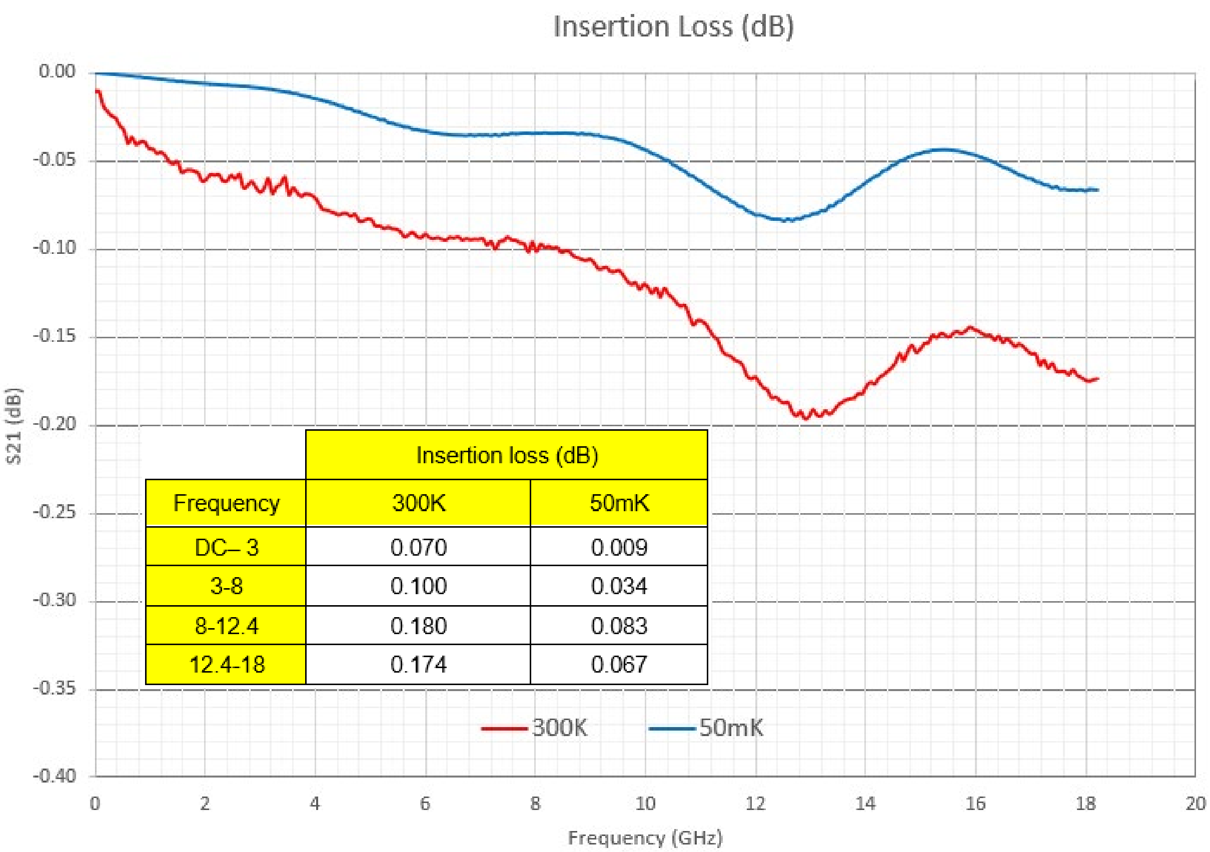


Figure 22 : Cryogenic RF performance at 11K.

Figure 23 shows the maximum insertion loss at 300K and 50mK at several frequencies on a Ramses cryogenic SP6T switch.



	Insertion loss (dB)	
Frequency	300K	50mK
DC– 3	0.070	0.009
3-8	0.100	0.034
8-12.4	0.180	0.083
12.4-18	0.174	0.067

Figure 23 : Cryogenic RF performance at 300K and 50mK.

RF REPEATABILITY AND DISPERSION

Radiall has improved the life expectancy and reduced size of the switches. On the subminiature SP6T series, the attachment of the only moving part of the actuator on two parallel cantilever beams suppresses the friction surfaces between the housing and the moving parts of the actuator. This improvement associated with the mounting of the second moving part suspended between the two spring blades eliminates all friction inside of the Ramses switches.

The main difference between the Ramses design and a classic design is its electrical life expectancy. The Ramses design allows users to perform life tests successfully beyond several million switching cycles without RF contact resistance failure or switching time variation over the entire operating temperature range. The particular suspension system ensures strong steady contact force, perfect geometric positioning of the RF blade into the RF line, and exceptional contact cleanliness switching cycle after switching cycle. Repeatability test campaigns performed on subminiature SP6T series have demonstrated standard deviation repeatability results up to 10.000.000 switching cycles. See table below.

	Insertion loss		V.S.W.R.
Frequency	Magnitude (dB)	Phase (°)	
DC– 26.5	0.035 dB	0.98°	0.037

Figure 24 shows curves in 3D illustrate the RF characteristics over the entire life span guaranteed into the technical data sheet at ambient temperature.

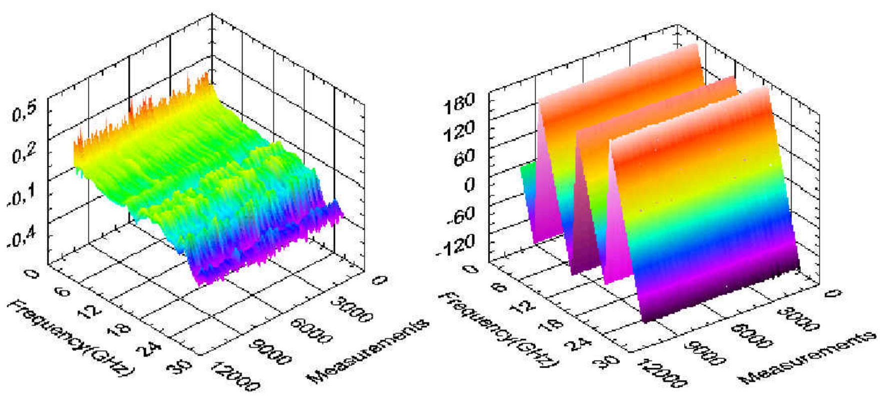


Figure 24: Insertion loss in magnitude and phase over 10 million switching cycles

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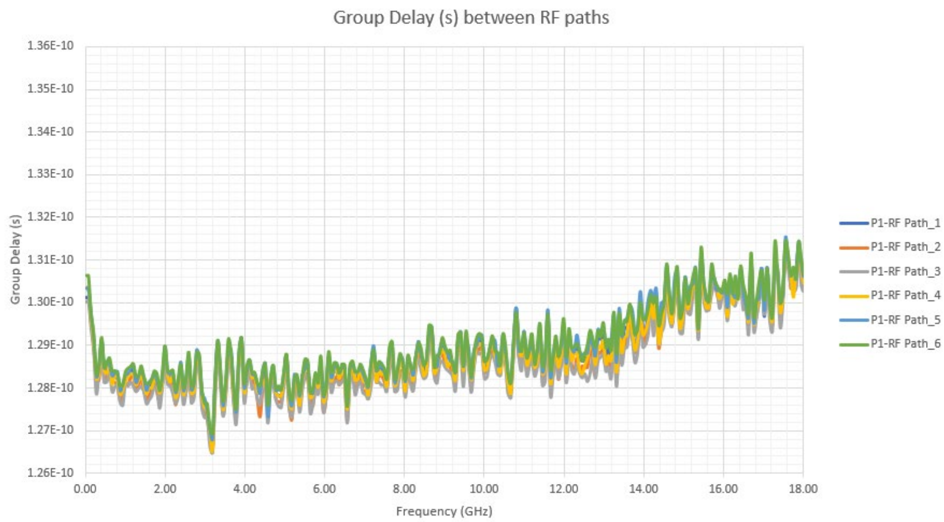
For applications which need to use a VNA to calibrate at cryogenic temperature, Radiall RF switches have good repeatability and consistency among the channels. Figure 25 shows that the electrical length variation is lower than 1ps from DC up to 18GHz.



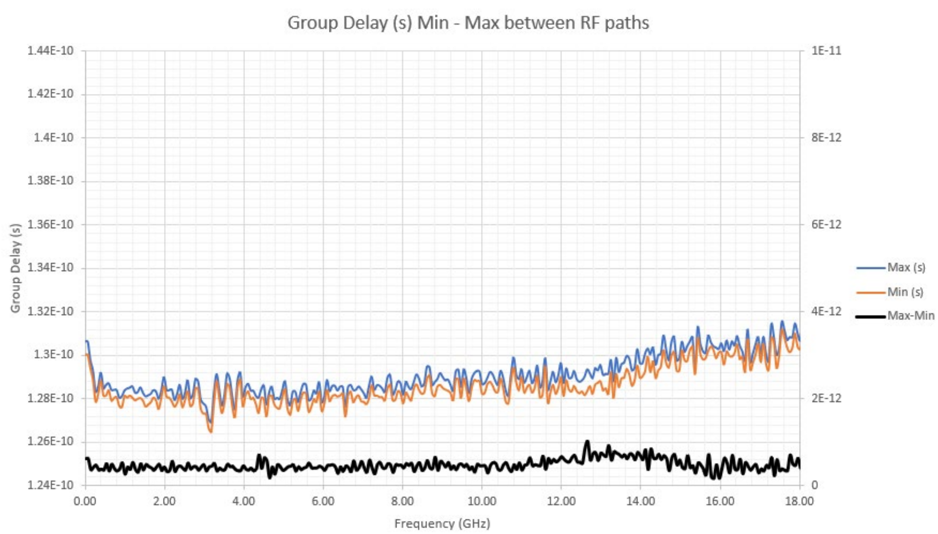


Figure 25: Electrical length variation (Group Delay) on 6 RF paths from DC up to 18GHz

CRYOGENIC SWITCHES THERMALIZATION

Inside the cryostat, we have two cryogenic switches. The current switch used is cryogenic SP6T made with aluminum alloy (R5927B2141 type). The second switch is made with brass material (R5927B2141BR type).

To evaluate the thermalization differences between the brass and aluminum alloy cryogenic switches, in the first experiment, temperature variations were measured following the transition from the open to the closed position.

In the figure 26, t=0 corresponds to the switch actuation.

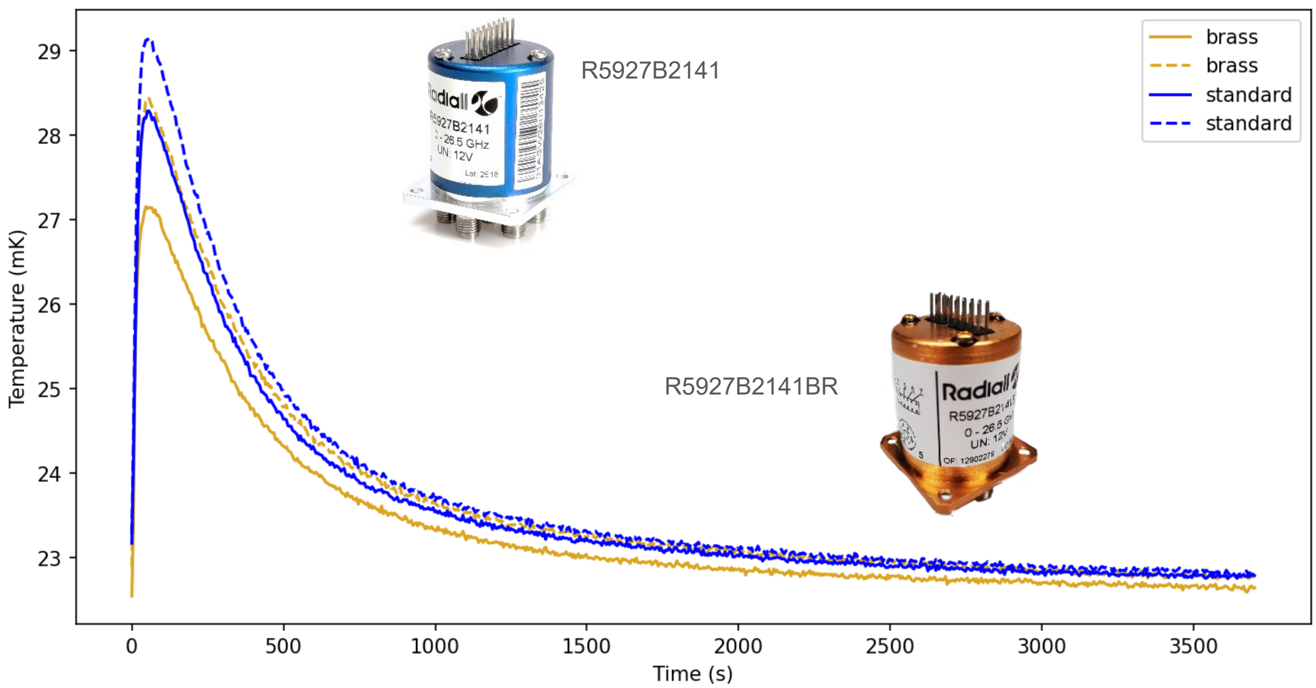


Figure 26: Refrigerator heating due to experiments.

There is no significant variation depending on the nature of the switch between the standard version and the version with the brass materials.

Another test campaign was conducted to extract the Power Spectral Density (PSD) for both the standard and brass cryogenic switches. This density represents the noise level emitted by the switches; with values normalized relative to the first measurement point, are shown in Figure 27.

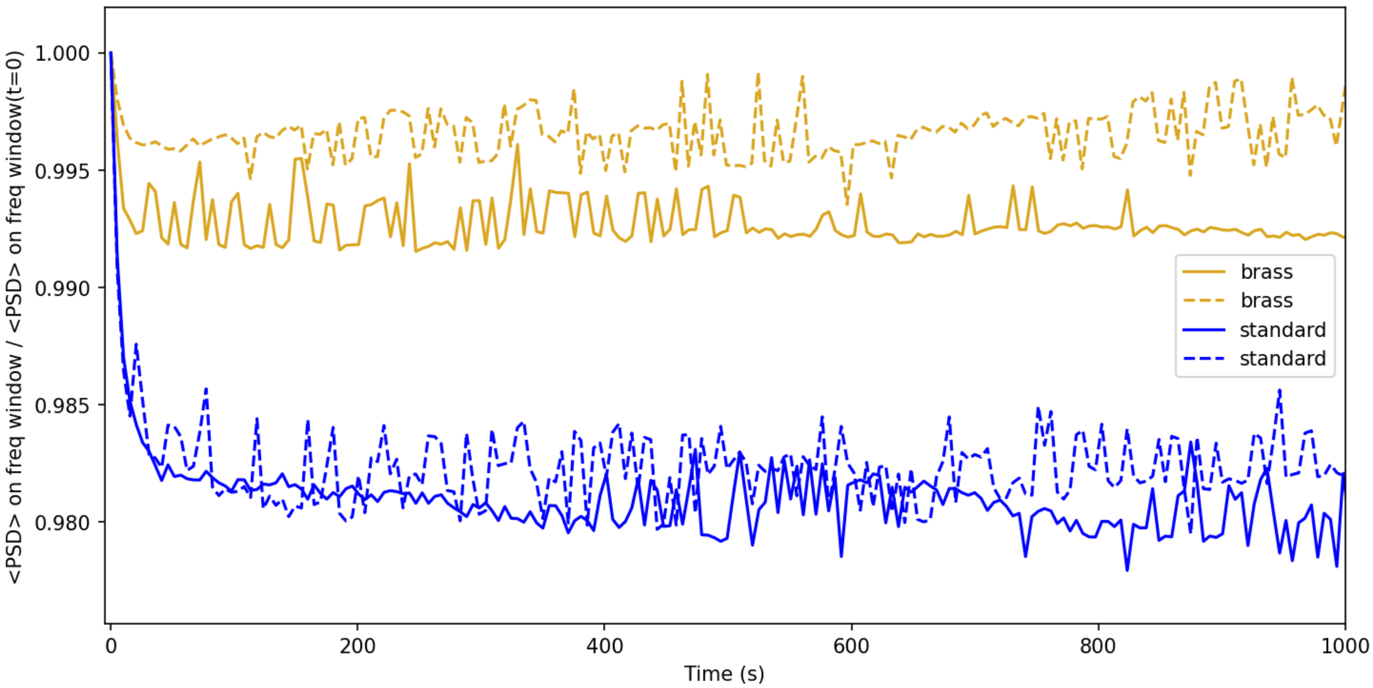


Figure 27: Power Spectral Density on R5927B2141 and R5927B2141BR cryogenic switches

As shown in the figure, the brass version reaches a plateau significantly faster than the standard version, stabilizing in less than 200 seconds compared to more than 600 seconds for the standard cryogenic version.

Then, we can estimate that thermalization time is close to 10-15 minutes for switches made with aluminum alloy (R5927B2141) and 3-4 minutes for switches made with brass material (R5927B2141BR).