FERMILAB-CONF-13-380-TD

DEVELOPMENT AND PERFORMANCE OF 325 MHZ SINGLE SPOKE RESONATORS FOR PROJECT X*

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Abstract

Two types of single-spoke resonators will be utilized for beam-acceleration in the low energy part of the Project X linac [1]. Single Spoke Resonator of Type-1 (SSR1) and Single Spoke Resonator of Type-2 (SSR2) will operate at 325 MHz with an optimal beta of 0.22 and 0.51 respectively.

After an initial phase of prototyping, a production run of ten SSR1 resonators was recently completed in US industry. During manufacturing, some issues were encountered and valuable experience was gained as a result. The processing and heat-treatment procedure has been optimized. The qualification of this group of resonators at the “bare” stage (without helium vessel) is proceeding successfully in the Fermilab Vertical Test Stand (VTS). Seven resonators have already been qualified with performance exceeding Project X requirements. A summary of the cold tests performed on the bare resonators is presented in detail in this paper.

Recent efforts have been focused on reducing the sensitivity of these resonators to helium-pressure variations. The first SSR1 has been outfitted with a helium vessel. Several tests were performed on this resonator at room-temperature to investigate its behavior and measure its sensitivity.

INTRODUCTION

Development of SSR1 resonators at Fermilab began several years ago [2]. Two prototypes for the SSR1 resonator were tested with successful results at the bare stage and with the helium vessel (jacketed stage) [3][4]. An order for ten SSR1 resonators was placed with C.F. Roark [5]. The purpose was to produce resonators for the first spoke cryomodule of Project X (containing eight SSR1 cavities), which will be initially tested as part of the Project X Injector Experiment (PXIE) [6].

All ten resonators have been manufactured, delivered to Fermilab, and inspected. Chemical processing and testing of this batch of bare resonators is nearly complete. The first qualified resonator was outfitted with a helium vessel at Meyer Tool [7] (see Figure 1) and is now undergoing extensive testing to evaluate several aspects of its performance.

The experience gained in the development of SSR1 resonators is being utilized now to feed the design of SSR2, which is nearly complete [8] and prototyping efforts are expected to begin soon.

*Operated by Fermi Research Alliance, LLC, under Contract DE-AC02-07CH11359 with the U.S. DOE

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Figure 1: The first jacketed SSR1 resonator for Project X.

DESIGN

The main parameters for these resonators are summarized in Table 1. With maximum magnetic and electric surface fields not to exceed respectively 70 mT and 40 MV/m, accurate geometrical optimizations produced very low peak field ratios allowing excellent nominal accelerating gradients of 10 MV/m and 11.2 MV/m respectively.

Table 1 Main Parameters of SSR1 and SSR2

Parameter	SSR1	SSR2
β	0.222	0.515
E_p/E_{acc}	3.84	3.53
B_p/E_{acc}	5.81 mT/(MV/m)	6.25 mT/(MV/m)
Aperture	30 mm	50 mm
Diameter	492 mm	560.8 mm
Effective Length	205 mm	475 mm
G	84 Ω	118 Ω
R/Q	242 Ω	275 Ω
Oper. Gradient	10 MV/m	11.2 MV/m
Q_0 at E_{acc}	> $0.5\ 10^{10}$	> $1.2\ 10^{10}$
Maximum B	58 mT	70 mT
Maximum E	38 MV/m	40 MV/m
Tuning constant	40 N/kHz	90 N/kHz
Sensitivity	< 25 Hz/torr	< 25 Hz/torr

Mechanical Design

The design of SSR1 was obtained by first optimizing the RF performance and later addressing the structural integrity of the resonator by adding an adequate system of stiffeners to the outside surfaces without any modification to the RF shape. The design of SSR2 was instead developed by considering RF, structural and manufacturing requirements simultaneously (see Figure 2).

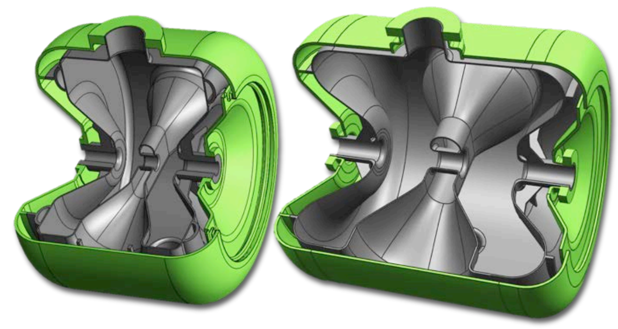

Figure 2: Sectioned views of SSR1 (left) and SSR2 (right). Niobium components are rendered in gray, steel components are rendered in green. The rounded end-walls in SSR2 require fewer stiffeners than SSR1.

Pressure-safety requirements are of great importance and determine the need to qualify each type of resonator to a certain maximum allowable working pressure (MAWP). For operational reasons and to avoid a catastrophic failure in the event of a severe malfunction (for example the loss of beam vacuum during operation), Project X spoke resonators are required to be rated at 2 atmospheres of external pressure with room-temperature material properties and 4 atmospheres with cryogenic properties. At Fermilab, this consists mainly in demonstrating compliance with the ASME Boiler and Pressure Vessel Code, which allows different approaches. For complex structures such as spoke resonators, it is advisable to follow a method based on finite-element analyses.

Several tensile tests were performed to fully characterize the raw material utilized to manufacture SSR1 resonators. The yield limit for this material is 75 MPa and the allowable limit was set to 47 MPa.

Figure 3: Von Mises stress distribution in a spoke resonator subject to 2 atmospheres of pressure in the helium space. Away from singularities and stress-concentration areas, the stress values are below the yield limit.

Sensitivity to Helium Pressure

For continuous-wave ion accelerators, for considerations based on RF power consumption, it is of great importance to have resonators that operate reliably within a small resonance bandwidth, typically in the order of 10 Hz. A feed-back tuning system should be present on the resonator having coarse and fine tuning capabilities but the stability of the resonator should rely only in part on this system. Resonators should be designed having low sensitivity to perturbations. Variations in the pressure of the liquid helium bath comprise the most predictable source of perturbations to the frequency of the resonator and may result in the largest perturbations seen by the resonator.

Spoke resonators for Project X are required to have a sensitivity of less than 25 Hz/torr. A systematic approach to evaluate this sensitivity and guide the design efforts was developed and is discussed in [9].

Among various methods of reducing the sensitivity, we describe here one. By modifying the system of stiffeners on the resonator one may influence the shape of the deformed profile (see Figure 4) when the resonator is subject to external pressure. In virtue of Slater's theorem [10], the resultant shift in frequency will depend on opposing contributes from regions having high magnetic fields and high electric fields. An accurate design may achieve self-compensating behavior that reduces such sensitivity.

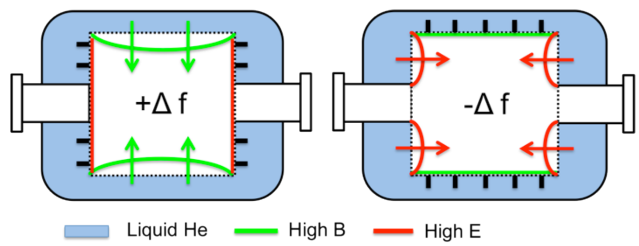

Figure 4: A schematic view of a resonator subject to an increase in liquid helium pressure. Different stiffening systems produce different behaviors. Inward deformations in high B areas (left) or high E areas (right), generate positive or negative frequency shifts respectively.

MANUFACTURING

Successful manufacturing of the bare cavity will rely for the most part on the quality of electron-beam welding of the niobium components. The outcome of welding will depend principally on the optimization of welding parameters and on the accuracy of fit between parts to be joined. Gaps between parts shall be kept below 100 µm. Mating surfaces shall have uniform thickness and offsets should be smaller than 0.5 mm. This is achieved by accurate development of forming-dies and by use of elaborate welding tooling allowing fine adjustments in the joint areas.

Deep-drawing is used to produce the two end-walls and the two spoke-halves. The outer conductor is rolled and seam-welded and ports are created by pulling a male die outwards, through an elliptical hole. All four flanges are made of stainless steel and brazed to niobium ports at a stock stage. After brazing, flange assemblies are finish-machined and joined to their cavity counterparts by electron-beam welding.

Frequency Targets

In order to achieve the desired resonant frequency in the operating conditions, intermediate goals are set for the frequency by estimating shifts due to major operations such as welding, chemical processing, cool-down and so on (Table 2). It is worth mentioning that in the specific case of SSR1, final electron-beam welding of the two endwalls to the outer conductor showed negligible shifts. Welding of the transition ring instead caused a shift of 500 kHz and was observed in both resonators which received the ring as of today.

Table 2 Intermediate goals for frequency

Operation	Shift (kHz)	Freq. (MHz)
End-wall Welding	Negligible	323.975
BCP (120-150 μm)	+ 160	324.135
BCP (20-30 μm)	+ 40	324.175
Ring + Jacketing	+ 500	324.675
BCP (20-30 μm)	+ 40	324.715
Cool-down	+ 385	325.100
Tuner Engaged	- 100	325.000

Manufacturing Issues

Certain issues became apparent only after having manufactured most resonators of the production batch. In four resonators, while performing full-penetration electron-beam welds, a hole (or blow-through) appeared in the weld seam (see Figure 5) without any apparent reason.

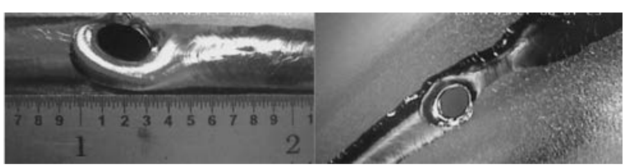

Figure 5: A typical blow-through viewed from the outside (left) and from the inside of the cavity (right).

Parameters for the process were producing a cosmetically excellent weld seam for all electron-beam joints, but the long-term stability of the process was not acceptable, producing roughly a defect every two resonators, equivalent to about one defect every 45 minutes of welding. Initially, the welding equipment and power supply were investigated and determined not to have impact on the issue. It is thought that the weld seam produced with the original parameters, although cosmetically excellent, was too wide (~ 8 mm) and therefore very sensitive to any type of geometrical variation in the joint (thickness, gap and offset) and susceptible to disruption at locations where mismatch was largest. An extensive set of tests was performed to develop a new set of parameters allowing the weld bead to be thinner and no holes were observed in the last four resonators completed. Defects were repaired by machining the holes to a known regular shape and thickness and inserting a niobium plug, which is later completely consumed.

Another issue encountered was an unacceptably low success rate for vacuum seals on the cavity flanges. Such sealing surfaces appeared leak-tight during initial inspections and their failure rate increased to about 25% for each of the four flanges in clean-room conditions. All four vacuum flanges on SSR1 are ConFlat (CF) type. Each face of the two mating CF flanges has a knife-edge which cuts into the softer metal gasket, providing an extremely leak-tight, metal-to-metal seal. The issue was attributed to the low quality of machining of the sealing surfaces aggravated in some cases by mechanical damages caused by handling. Initial leak-checks are performed by sealing the flanges using silver-plated screws having a lower friction coefficient with steel, than silicon-bronze screws, used thereafter. Silver-plated screws are capable of transmitting a larger axial thrust to the sealing surface and is thought to be the most plausible explanation for the increased failure rate.

Additionally, it was discovered that the roughly machined knife-edges have a tendency to detach particulates from the copper gasket when disassembled. This phenomenon alone was considered unacceptable for cryomodule assembly due to the serious implications in cavity performance. It was concluded to change the design of all vacuum flanges from CF to DESY/TeSLA aluminum seal, which employs flat surfaces on the mating flanges and an aluminum circular gasket having a diamond section. The completed cavities will be reworked to accommodate the new type of vacuum seal.

CHEMISTRY AND HEAT TREATMENTS

After initial inspection to verify compliance with mechanical and RF requirements, resonators undergo a series of operations involving cleaning, acid-etching and baking (see Table 3). The baseline recipe is aimed at obtaining the best performance in the VTS.

Initially, resonators need to be cleaned to remove any residue left by the manufacturing process. This is done by degreasing all surfaces in an ultrasonic tank followed by a thorough rinsing with ultra-pure water. Next, a layer of about 120-150 μm is removed with a buffered-chemical-processing solution (bulk BCP). This is achieved through two sub-cycles interposed with a rotation of 180 degrees to improve uniformity. After another cycle of degreasing and rinsing, resonators are subject to a high-pressure rinse with a tool having a vertical water wand. Subsequently, resonators are baked at 600 °C with a 10-hour plateau and a climb rate of less than 5 °C/min, this is referred to as hydrogen-degassing and serves the purpose of reducing the onset of Q-disease. After an intermediate step of RF measurement and tuning, resonators are again degreased and rinsed and routed for a second cycle of chemistry, only removing 20-30 μm this time (light BCP). After another cycle of degreasing and rinsing, the resonator is subject to a thorough high-pressure-rinse (HPR) performed on two distinctive tools, one having the pressure wand in the vertical position, the other in the horizontal position. Utilizing both tools on the same resonator has been shown to improve the performance in the cold tests in terms of field emission (FE). Finally, the resonators are evacuated, leak-checked to 10^{-10} mbar-l/s or better and baked under vacuum at 120 °C for a minimum of 24 hours. This helps substantially in reducing the time necessary for processing through multipacting barriers which SSR1 resonators are known to suffer from. After the transition ring and the helium vessel are welded onto the qualified resonators, an additional cycle of light BCP and HPR will be performed.

Table 3 Preparation Steps for Cold Tests

Operation	Details
Bulk BCP	2 x 60-75 μm
HPR	Vertical
Heat Treatment	600 °C, 10h
Light BCP	20-30 μm
HPR	Vertical + Horizontal
Assembly + Leak Check	< 10^{-10} mbar-l/s
Low-T bake	120 °C, 48h

COLD TESTS

The first cryomodule of SSR1 will be tested within the scope of PXIE and for experimental purposes, the requirement on the gradient of SSR1 is set to 12 MV/m, slightly above the Project X requirement (10 MV/m).

A detailed description of all tests performed on SSR1 resonators is reported in [11]. Seven resonators were qualified for use in the PXIE cryomodule (Figure 6).

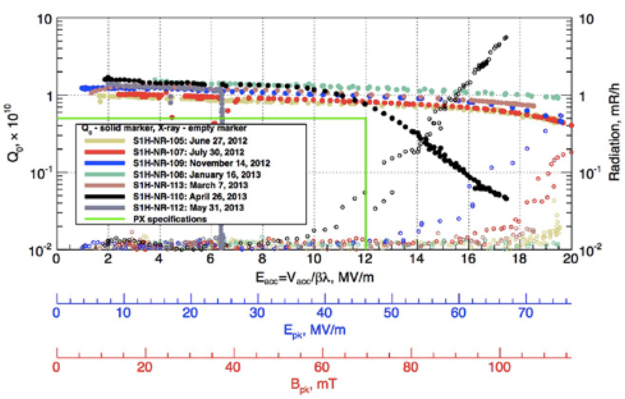

Figure 6: Summary of the qualification process for SSR1 resonators. All plots refer to testing at 2 K.

Among these seven resonators, three were qualified after the first test (or pass), including resonator 113, which has a repaired hole. Other three were qualified after the second test after additional HPR or additional BCP and HPR. Finally, resonator 112 was qualified conditionally based on the gradient achieved at 4.4 K and Q achieved at 2 K at the multipacting barrier around 6.5 MV/m which was not overcome. All resonators appear to perform similarly, exceeding the PXIE requirement of E_{acc} > 12 MV/m and Q_0 > 0.5 10^{10}. Resonator 110 shows a slightly lower performance and is expected to improve after additional processing and rinsing (see Table 4).

Table 4 Summary of qualification process

Cavity	**E_{MAX} – Q_0 at 12 MV/m**	**Status**
105	19.5 MV/m – 0.8 10^{10}	Qualified at 2nd pass
107	21.7 MV/m – 0.8 10^{10}	Qualified at 1st pass
109	19.6 MV/m – 0.98 10^{10}	Qualified at 1st pass
108	21.3 MV/m – 1.2 10^{10}	Qualified at 2nd pass
113	18.5 MV/m – 1.0 10^{10}	Qualified at 1st pass
110	17.3 MV/m – 0.77 10^{10}	Qualified at 2nd pass
112	17* MV/m – 1.2 10^{10}	Qualified conditionally

*at 4.4K, limited by multipacting

JACKETING AND MEASUREMENTS

A transition ring was developed at ANL [12] and electron-beam welded onto the resonator to allow structural coupling between cavity and helium vessel (see Figure 7). The ring is perforated to facilitate rinsing and processing operations and to allow cooling of the central area during operation. A shift of + 500 kHz was caused by the welding of this ring alone.

Figure 7: S107 with the perforated transition ring. The outermost portion of the ring appearing shinier is made of stainless steel.

Components of the helium vessel were made by spin-forming, rolling and machining sheets made of 316L stainless steel having a thickness of 6 mm. Oxygen concentration, temperature and frequency were constantly monitored throughout the process. Due to the requirement of not exceeding 80 °C on niobium surfaces at any time, welding was conducted in small sections of about 20 mm causing the whole process to take three weeks. This is fairly normal for resonators of such complexity.

In order to minimize the deformations induced on the resonator by the welding process, it is very important to estimate the amount of shrinkage for each weld joint. Extra material should be present where necessary. Also, if at all possible, the resonator should be left free to move within the assembly while performing the heavier welds.

Figure 8: An intermediate moment during welding operations on SSR1. The transition ring at the top of the picture is not yet welded.

Despite having planned in this way, certain joints contracted more than expected and, as can be seen in Figure 9, the resonant frequency drifted non-negligibly in some occasions during the process requiring corrective actions. For example, during the welding of the two large ports, the process was interrupted and the joint area was trimmed to relieve the tension. This allowed recuperating almost 200 kHz. The total shift due to jacketing operations was about +250 kHz. For the next resonators, the process will be improved based on the experience gained and the frequency shifts will be reduced.

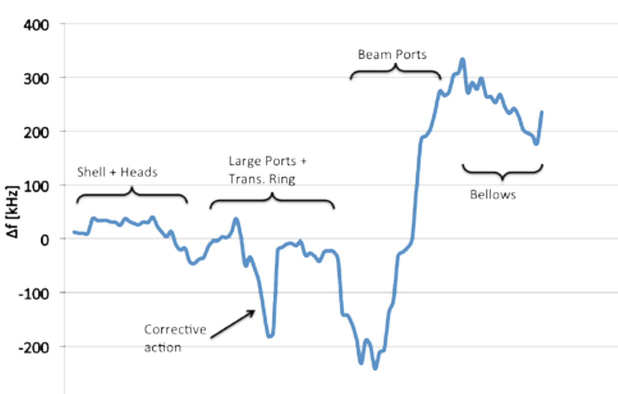

Figure 9: Plot showing the history of resonant frequency during welding operations. The overall shift was about 250 kHz.

Room-Temperature Measurements of Sensitivity

The jacketed cavity was subjected to several tests. A leak check and a pressure test was performed at Meyer Tool where the helium vessel was welded. The helium space was pressurized to 115% of the MAWP. The pressure test at room temperature was repeated at Fermilab to investigate the sensitivity of the cavity to pressure variations. The pressure was cycled several times between vacuum and 1.4 atmospheres recording the frequencies and mechanical displacements at various steps. The setup for these tests can be seen in Figure 10. Tests were performed with the cavity free to move at the tuning interface and also with a dummy-tuning device having a rigidity of 30 kN/mm. The sensitivity measured in both conditions was 8-10 Hz/torr and 13-15 Hz/torr respectively.

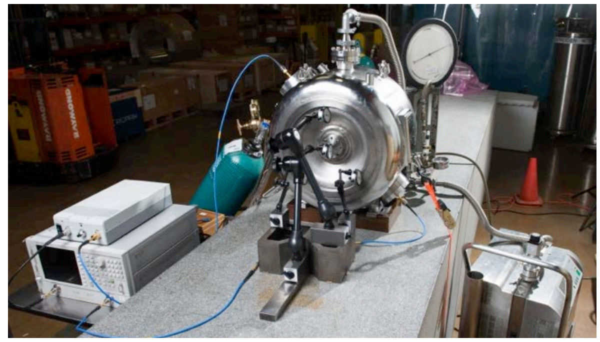

Figure 10 : Setup utilized for measuring the sensitivity of the resonator to helium pressure variations. The pressure in the helium circuit was cycled repeatedly using a nitrogen bottle (left) and a vacuum pump (right) while recording the resonant frequency and mechanical displacements.

SUMMARY

Ten SSR1 resonators have been manufactured in US industry. Some issues were encountered during fabrication and lead to the development of a new electron-beam welding process. Additionally, due to repeated vacuum leaks at the cavity flanges, the design was changed from ConFlat to the DESY-TeSLA aluminum seal. Cold tests for the ten resonators are proceeding well. Seven resonators have been qualified exceeding PXIE and Project X requirements. One resonator was outfitted with a helium vessel and its sensitivity to helium pressure was measured to be within the requirements.

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