DESIGN, FABRICATION AND TESTING OF SINGLE SPOKE RESONATORS AT FERMILAB*

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Abstract

The Fermilab High Intensity Neutrino Source (HINS) linac R&D program is building a pulsed 30 MeV superconducting H- linac. The linac incorporates superconducting solenoids, high power RF vector modulators and superconducting spoke-type accelerating cavities starting at 10 MeV. This will be the first application and demonstration of any of these technologies in a low-energy, high-intensity proton/H- linac. The HINS effort is relevant to a high intensity, superconducting H- linac that might serve the next generation of neutrino physics and muon storage ring/collider experiments.

In this paper we present the RF design, the mechanical design, the fabrication, the chemistry and testing of the first two SSR1 (Single Spoke Resonator type-1) prototype cavities that were built. These cavities operate at 325 MHz with β=0.21. The design and testing of the input coupler and the tuning mechanism are also discussed.

INTRODUCTION

Multi-spoke superconducting cavities have been developed and demonstrated excellent performance at 345-352 MHz [1][2]. The advantages of single-frequency medium energy proton linacs based on multi-spoke cavities have been discussed elsewhere [3]. Some important geometric and RF properties of the SSR1 are given in Table 1.

Table 1 : Geometric and RF properties of the SSR1.

Operating temperature in HINS	4.4 K
HINS accelerating gradient, E_{acc} [1]	10 MV/m
Q_0 at accelerating gradient	> 0.5×10^9
Beam pipe, Shell ID	30 mm, 492 mm
Lorenz force detuning coefficient [2]	3.8 Hz/(MV/m)^2
E_{peak}/E_{acc} [1]	2.56
B_{peak}/E_{acc} [1]	3.87 mT/(MV/m)
G	84 Ω
R/Q_0	242 Ω
Geometrical Beta, β_g	0.21

[1] See section *High gradient measurements* for the definition of E_{acc}.
[2] With helium vessel.

RF DESIGN AND OPTIMIZATION

The RF design and optimization of the SSR1 has been done using Microwave Studio® (MWS) software [4]. In Figure 1 the main geometrical parameters used for optimization are shown.

Beam dynamics considerations led us to the choice of β=0.21 and a 30 mm aperture diameter. Also an iris-to-iris distance L_{iris} = 2/3 βλ was chosen.

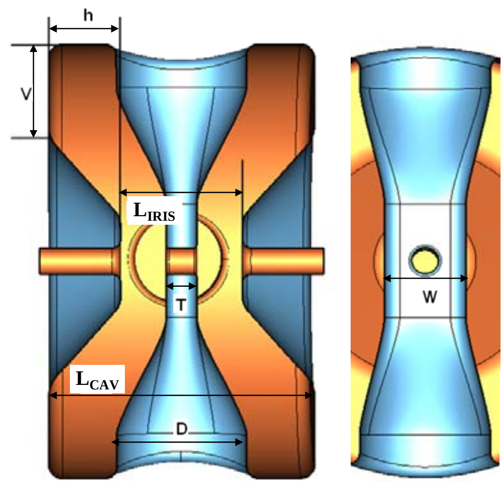

Figure 1 : Cross section of the SSR1 with the main parameters used in the optimization process: L_{cav} – cavity length, L_{iris} – iris to iris length, D – spoke diameter, W – spoke width, T – spoke thickness, h and v – endwall dimensions.

The spoke width W and gap ratio T/L_{iris} were optimized to achieve a low peak electric field. The results of the simulations are shown in Figure 2.

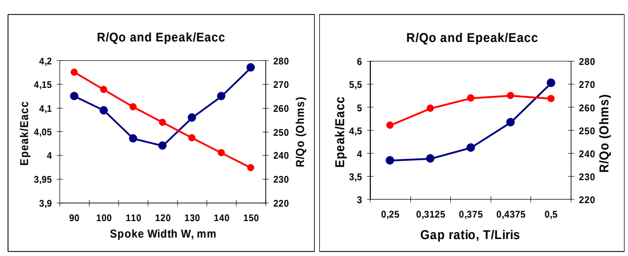

Figure 2 : R/Q0 (red) and Epeak/Eacc (blue) vs. W and T/Liris

The ratio D/L_{cav} and the end cup profile dimensions were optimized to achieve a low peak magnetic field. The results of the simulations are shown in Figure 3.

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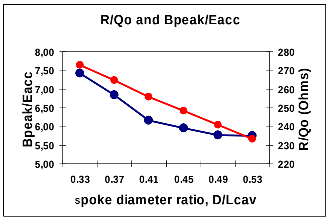

Bpeak/Eacc				
V \ h	50	60	70	80
30	8,63	7,70	7,13	6,54
55	8,39	7,61	6,98	6,40
80	8,13	7,36	6,75	6,21
105	7,95	7,19	6,55	5,96

Figure 3 : Dependence of R/Q0 (red) and B_{peak}/E_{acc} (blue) on the spoke and the endwall profile dimensions (in mm).

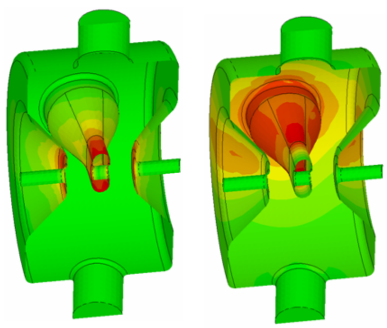

Figure 4 : Surface electric (left) and magnetic (right) fields in SSR1. The field strength increases as the color changes from green to yellow to red.

MECHANICAL DESIGN AND FABRICATION

The SSR1 mechanical structure needs to withstand the pressure exerted by the liquid helium. One also desires to minimize shifts in the resonant frequency (i.e. cavity tune) due to variations in liquid helium pressure (and other microphonics) and to Lorentz forces (HINS is a pulsed linac). Stiffening the cavity endwalls and shell reduces the Lorentz force detuning (LFD).

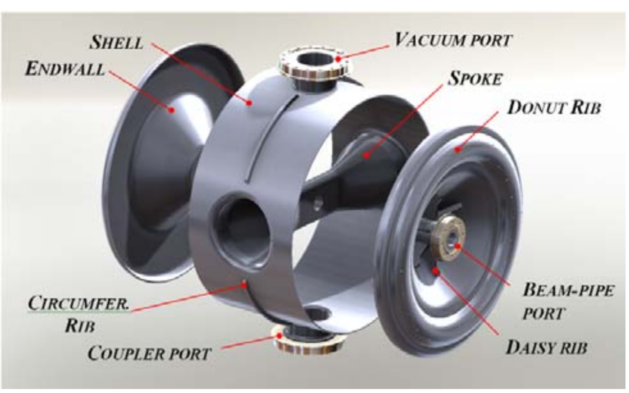

Figure 5 : Exploded view of the SSR1 resonator showing the three major sub-assemblies.

With reference to Figure 5, each endwall of the spoke resonator is reinforced by two systems of ribs: a donut rib with elliptical section in the end wall outer region and six daisy ribs in the inner region. These two systems are not connected to facilitate a controlled displacement of the nose area for cavity tuning. A third and final system of 4 circumferential ribs is present on the cylindrical portion of the cavity. All stiffeners have a stock thickness of 6.35 mm and are made of reactor-grade niobium.

The static LFD coefficient was calculated with a coupled MWS-ANSYS [5] algorithm as described in [6]. In the simulations, we found that the addition of the four shell ribs reduced the detuning coefficient from 4.2 $Hz/(MV/m)^2$ up to 3.8 $Hz/(MV/m)^2$.

The resonator components are fabricated from high RRR niobium sheets with a nominal thickness of 3.15 mm that is reduced by forming and BCP to an average of 2.8 mm. The components are joined using electron beam welding. The two beam flanges, the vacuum flange and the power coupler flange of the resonator are made of 316L stainless steel and are joined to the niobium cavity by brazing. This cryogenic leak-tight copper-brazed transition was developed at Argonne National Laboratory (ANL) and described in [7].

The helium vessel was designed and fabricated according to the ASME Boiler and Pressure vessel code. It is rated up to 24.7 psi. It is constructed in 316L stainless steel and all welds are TIG welds. After completion of all welding operations, the resonant frequency of the cavity shifted of less than 50 kHz. The helium vessel is welded directly to the cavity at the coupler and vacuum ports. A bellows connects the helium vessel end-plate to the cavity beam pipe flange through a transition ring.

Figure 6 shows a cut out view of the SSR1 resonator with the helium vessel. Figure 10 shows the jacketed cavity with the prototype tuning mechanism installed.

Figure 6 : Cut out view of the SSR1 cavity inside the helium vessel.

Two SSR1 prototypes have been fabricated. SSR1-01 was manufactured by Zanon [11] and SSR1-02 by Roark [12]. One significant difference in the fabrication techniques is the treatment of the interior weld beads. For SSR1-01 all interior beads were ground flat, with the exception of the final welds between the endwalls and shell. For SSR1-02 the interior weld beads were left intact, and where possible the welds were completed with a cosmetic pass.

At this point both prototypes have undergone chemistry and have been continuous-wave (CW) tested at high gradient without a helium vessel. SSR1-01 has subsequently undergone 600º C degassing, inelastic tuning, and has been welded inside its helium vessel. It is now being prepared for pulsed testing at high gradient.

CHEMISTRY PROCEDURES

In preparation for the chemistry, the cavity is immersed in a bath of ultra-pure water (UPW) with a degreasing agent and ultrasonically cleaned at FNAL. The Buffered Chemical Polishing (BCP) and High Pressure Rinse (HPR) operations are performed at the ANL G150 facility.

Buffered Chemical Polishing

The BCP uses the standard $HF:HNO_3:H_3PO_4$(1:1:2) acid mixture. During BCP, acid flow and temperature are controlled in the following manner. The bare cavity is immersed in a bath of UPW initially cooled to 7.5ºC. The cavity interior, sealed from the water bath, is connected to a pump for acid circulation. The cavity is oriented with the power coupler port and the vacuum port along the vertical axis and the beam pipes along the horizontal axis. In order to begin etching, acid (earlier chilled to 14ºC) is pumped up through the bottom port to fill the interior of the cavity. After shutting off the source of acid, the closed loop circulation pump draws acid from the top of the cavity and sends it back to the cavity through flanges on both beam pipes. For SSR1-02 acid was also injected into the cavity near the top and bottom ports in order to break up potentially stagnant regions at the bottom and gas pockets at the top. Heat generated by the etching is dissipated through the cavity walls (including the spoke walls) to the continuously cooled water bath.

In order to obtain a total etching of ~120 µm and keep the niobium content in the acid below 10 g/l, spent acid is replaced with fresh acid about half way through the etching. Given the asymmetry in the acid flow pattern, the cavity is flipped top to bottom between the two etching sessions. The reduction in wall thickness is monitored at 20 locations using an ultrasonic thickness gauge.

High Pressure Rinse

After BCP, the cavity is moved to the class 10 clean area for HPR. The G150 UPW distribution consists of a long wand with a nozzle at the end that produces six water jets, two each at +45º, 90º, and -45º to the wand axis. The wand rapidly rotates about the axis and travels along the axis (into or out of the cavity) at ~3 cm/min. In order for a jet to directly spray on all the interior cavity surfaces, including ports and beam pipes, the orientation of the SSR1 is changed six times with the HPR lasting ~20 minutes at each orientation for a total of 2 hours.

HIGH GRADIENT MEASUREMENTS

The Fermilab Vertical Test Stand (VTS), a liquid helium dewar designed for CW high-gradient testing of bare 9-cell ILC cavities, was used for the cold tests of the bare SSR1 prototypes.

SSR1-01

In its third cold test, SSR1-01 reached E_{acc} = 18 MV/m at 4.4 K [9]. Here E_{acc} is the total accelerating voltage divided by L_{eff}, where $L_{eff} = (2/3)\beta\lambda$ = 135 mm, the distance between the edges of the accelerating gaps at the two endwalls. A planned specific check for Q disease, a decrease in Q_0 due to hydrogen in the niobium [10], was not performed due to a leak that developed in the feed-through for the RF input antenna.

After the feed-through was replaced, a fourth VTS test was performed, and the resulting Q_0 vs. E_{acc} curves are shown in Figure 7. The upper Q_0 vs. E_{acc} curves at 2.0 K and 4.4 K were taken after the usual fast cool-down (~15 minutes from 150 K to 75 K) of the VTS. They exhibit a large slope as in earlier tests (except for the first), which prompted the concern for Q disease. The bottom curve was taken after warming up and cooling down again with a seven hour hold at 100 K to explicitly test for Q disease. The large drop in Q_0 clearly indicates the need for hydrogen degassing, and the cavity has subsequently undergone a 10 hour, 600 °C vacuum bake at Thomas Jefferson National Accelerator Facility. In all cases the maximum accelerating field (e. g., 20 MV/m at 2 K) was limited by the 200 W RF power supply.

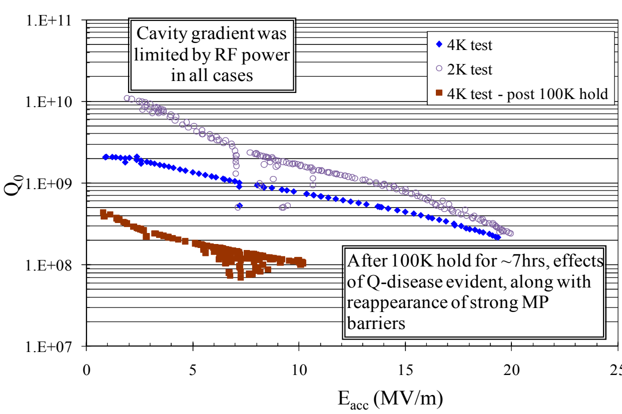

Figure 7 : Q_0 vs. E_{acc} at 2.0 K and 4.4 K from the fourth cold test of SSR1-01.

SSR1-02

SSR1-02 has undergone one cold test. The first cold test of a cavity should be free of the effects of Q disease [10]. Figure 8 shows the surface resistance, R_s, as a function of 1/T, indicating a residual resistance near 5 nΩ. Figure 9 contains the Q_0 vs. E_{acc} curves at 2 K and 4.4 K. As with SSR1-01, many multipacting barriers had to be processed when initially raising E_{acc}, and some are shown in the 2 K curve. Eventually the field reached 33 MV/m at 2 K and was limited by quenching (from Table 1, B_{peak} = 128 mT at E_{acc} = 33 MV/m).

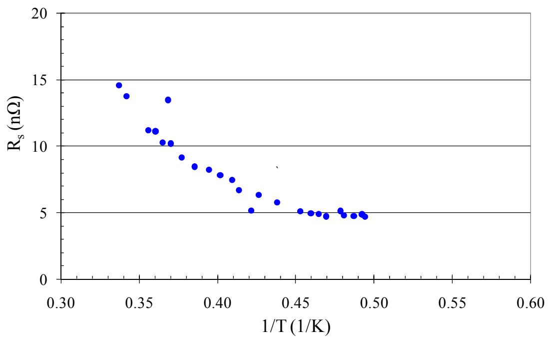

Figure 8 : R_s vs. 1/T from the first cold test of SSR1-02.

The subsequent scan at 4.4 K reached 25 MV/m and was limited by the 200 W RF power supply. Also shown in Figure 9 is the X-ray intensity as measured by a sensor near the top of the VTS. During the 2 K scan, the intensity decreased after jumping through a multipacting barrier.

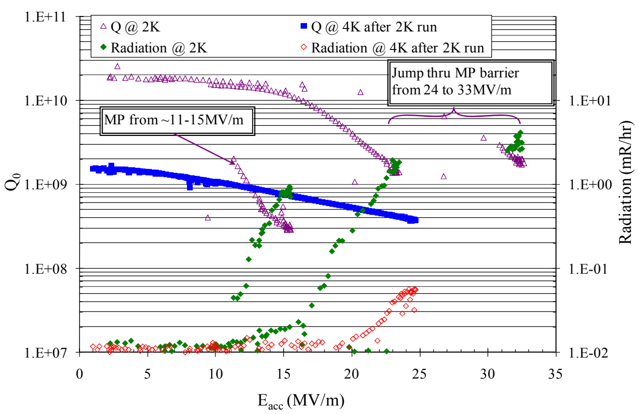

Figure 9 : Q0 vs. Eacc from the first cold test of SSR1-02.

INELASTIC TUNING

After the VTS tests and the 600ºC degassing, SSR1-01 was placed in a fixture where its resonant frequency was adjusted by permanently deforming the two end walls. The fixture holds the resonator by its vacuum port and coupler port and allows pushing or pulling of the beam pipe flanges while measuring both the forces and the displacements. The initial frequency of the cavity in warm conditions at one atmosphere was 324.960 MHz. The target frequency being higher, the cavity had to be extended. The cavity was first stretched permanently to a frequency of 325.220 MHz by cycling between a load and the relaxed state, each time with a higher load. Later the cavity was compressed permanently following the same cycling method to a final frequency of 325.036 MHz.

The tuning was performed in this manner because the cavity operates in a compressed state inside the cryomodule. Throughout the stretching operations, the elastic range increased expectedly due to work hardening. When the load was reversed to squeeze the cavity, the elastic range dropped with the first cycles and rose finally to about a factor of four larger than the initial value. This confirmed that the procedure had been effective. Table 2 shows other parameters extracted from the tuning data.

Table 2 : Parameters extracted from the tuning data.

Spring constant of end wall	18.9 N/μm
Frequency sensitivity / total deformation	540 kHz/mm
Elastic range (0-3400 lbs, 0-0.783 mm)*	871 kHz

* measured at the end of tuning operations.

TUNER DESIGN AND FIRST TESTS

As with other pulsed superconducting cavities, each spoke cavity will be equipped with slow tuning and fast tuning devices to compensate for static detuning and Lorentz force (dynamic) detuning respectively.

The design for a fast/slow tuner has been developed and two prototypes have been tested in warm conditions as described in [13].

Each cavity will have two identical tuners (one per side) allowing the mechanical loads to be applied symmetrically and also providing redundancy.

The mechanism (visible in Figure 10) uses a stepper motor to control the position of the slow tuner arm via a harmonic drive (1:100 ratio), this arm pivots around bearings fixed to the helium vessel wall with a mechanical advantage of 5:1. The loads are transmitted to the beam pipe flange through two piezo actuators.

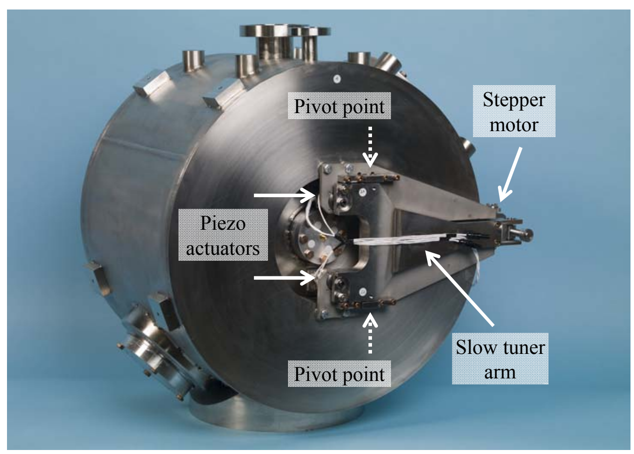

Figure 10 : Jacketed SSR1-01 prototype with tuner mechanisms installed.

During the first tests, a tuning range of 200 kHz was reached meeting the design requirements. The load on the piezos remained in a safe range of 200-2200 N (20-80% of blocking forces).

The measured sensitivities for the slow and fast tuners were 0.9 Hz/step and 60 Hz/V respectively.

COUPLER DESIGN AND TESTS

The RF design of the main power coupler was performed by using the Ansoft HFSS software. Two types of couplers were considered and the antenna coupler was preferred to the loop coupler.

The optimum position of the antenna coupler is located in the plane perpendicular to the spoke, where the surface magnetic field is minimum and the electric field is strong.

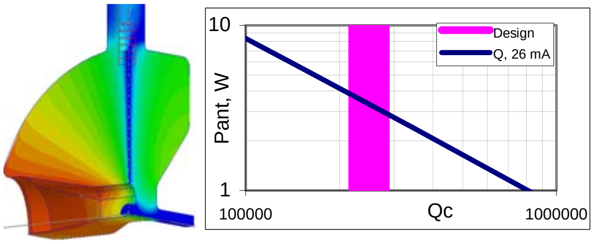

Figure 11 Left: magnetic field amplitude in 1/8 of the cavity with an antenna coupler. Right: pulse power dissipation on the coupler tip vs. external Q of the coupler.

The input coupler is a 50-ohm coaxial design with inner and outer conductor diameters of 33.4 and 78.4 mm respectively and supplies 250 kW peak and 750 W average pulsed power to a single cavity. The coupler contains two ceramic windows, one warm, one cold, which protect the integrity of the interior of the cavity and which enable us to break the coupler into warm and cold sections. During cryomodule fabrication, the cold section can be installed on the cavity in the clean room prior to assembly of the string. The warm section can then be installed from outside the vacuum vessel during cryomodule final assembly. The inner conductor is solid copper. The outer conductor is 304-stainless steel. A short section of hydro-formed bellows in the cold section of the outer conductor allows a small amount of tuning – 1 to 2 mm – to be performed from outside the vacuum vessel.

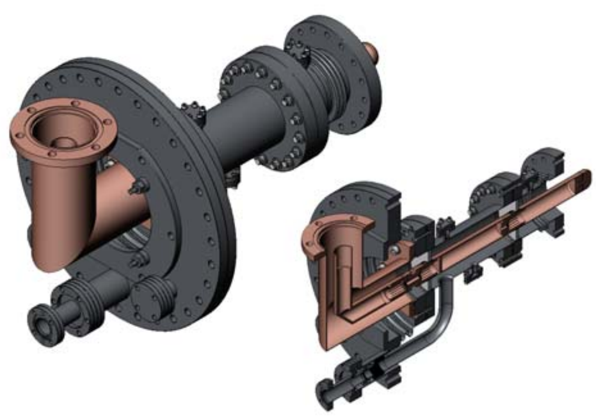

Figure 12 : Input coupler assembly and cross sectional view.

Initial heat load estimates don't suggest a significant penalty for not copper plating the outer conductor so to preclude potential problems with copper plating the bellows, the prototype will not include plating. Figure 12 shows the most recent coupler design. The copper elbow connects to the RF distribution system. The small stainless steel elbow and tube visible in the cross section view is the vacuum pumpout for the section between the two ceramic windows. Instrumentation ports are included for vacuum monitoring and multipacting detection.

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