HIGH-VACUUM SIMULATIONS AND MEASUREMENTS ON THE SSR1 CRYOMODULE BEAM-LINE*

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Abstract

In order to guarantee an effective cool-down process for the SSR1 cryomodule, a high-vacuum level must be achieved at room temperature in the beam-line before introducing gaseous and liquid helium. The SSR1 cavities in the beam-line have a small beam aperture compared to the size of their internal volume. To avoid unnecessary complications for the vacuum piping of the cryomodule cold-mass, a pilot study was conducted on the string prior to processing and qualification of the components to investigate the vacuum level achievable by pumping only through the beam-line. To estimate the pressure distribution inside the cavity string we used a mathematical model implemented in a test-particle Monte-Carlo simulator for ultra-high-vacuum systems.

INTRODUCTION

The SSR1 cryomodule [1] will be part of the 800 MeV linear accelerator complex that Fermilab is planning to build in the framework of the Proton Improvement Plan-II (PIP-II) project. The cavity string assembly of this cryomodule which constitutes the beam-line volume, contains eight superconducting Single Spoke Resonators type 1 (SSR1) with their cold-end input couplers and four solenoids, see Fig 1. The connections along the beam-line are made using aluminum diamond seals and stainless steel flanged joints and bellows. At each end, the beam-line is terminated with ultra-high-vacuum gate valves through which the beam-line will be pumped down. The planned pumping system for the cryomodule consists of two turbo pumps with a pumping speed of $S = 300\,\mathrm{L/s}$ and an ultimate pressure of $1 \cdot 10^{-8}$ Torr at the pump inlet.

The cavity string will be assembled in a class 10 clean-room to minimize particle contamination in the beam-line known to cause field emission and therefore degrading cryomodule performance. Limiting the number of beam-line components and sub-assemblies from the initial stages of design simplifies greatly the installation procedure promoting a cleaner assembly approach. The goal for this study was to prove that a vacuum level of $5 \cdot 10^{-5}$ Torr or lower can be achieved in each section of the beam-line by pumping down the cavity string simply through the beam aperture without any additional manifold connected to the cavities. The pressure threshold of $5 \cdot 10^{-5}$ Torr was chosen to avoid negative effects such as increased field emission [2] and residual resistance due to condensed gases [3]. This level of vacuum must be reached in less than 12 hours to minimize the down-time associated with thermal cycles for the cryomodule.

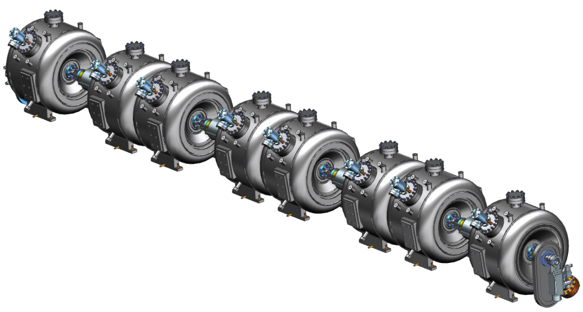

Figure 1: SSR1 cavity string assembly.

PILOT STUDY

A series of measurements was performed on the cavity string to evaluate the feasibility of pumping down the SSR1 string assembly from the beam-pipe ports only.

Vacuum Test

The test was performed on a half-string (four cavities) thanks to the symmetry of the problem. A turbo pump with cold trap was connected to the first cavity. Two pressure gauges (gauge 1 and gauge 2), calibrated for UHV, were installed on the first and last cavity to monitor the trend of pressure as function of time, see Fig. 2.

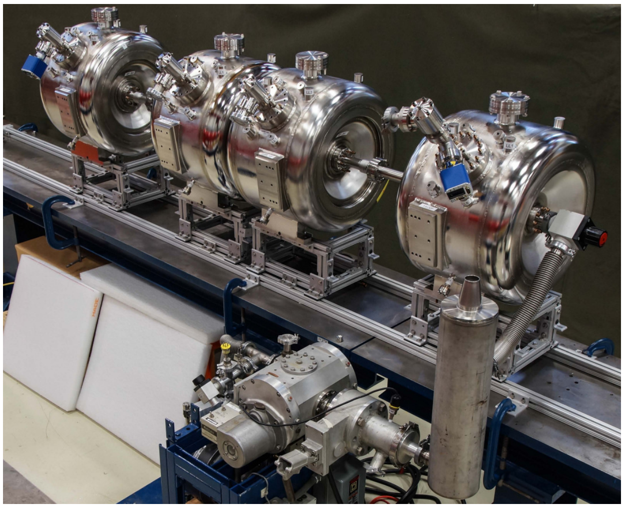

Figure 2: Half-string setup for the vacuum test.

The study is conservative for several reasons:

- niobium cavities were exposed to atmosphere and not yet baked;

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- the pump cart utilized for the test (nominal pumping speed of 160 L/s measured ultimate pressure at the pump inlet of $1.5 \cdot 10^{-7}$ Torr) has a lower performance compered to what will be used in the accelerator;
- O-rings were used in several connections instead of standard aluminum seals, increasing the outgassing rate;
- other beam-line components such as the bellows were not subject to the rigorous cleaning procedure which will be followed during the final assembly.

Figure 3 shows that the vacuum level of $5 \cdot 10^{-5}$ Torr was reached in less than 12 hours in all points of the beam-line volume. Considering the penalizing testing conditions, this result allows to conclude that the cavity string can be pumped down from the beam-line port only, without any additional manifold.

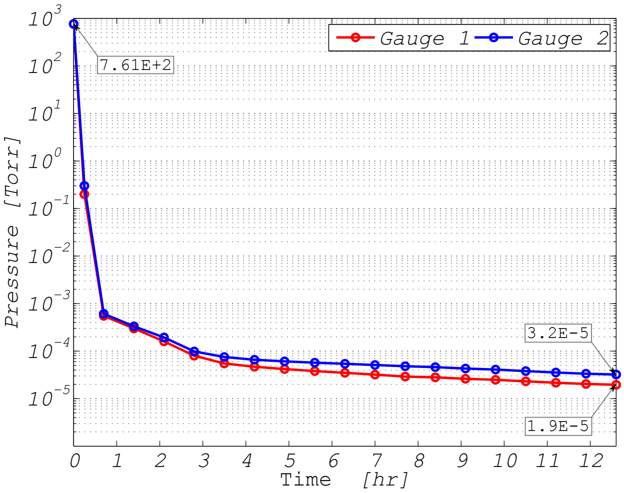

Figure 3: Pressure as function of time measured in the upstream cavity (gauge 1) and downstream cavity (gauge 2).

Outgassing measurement

In a vacuum system the components release any gas which was previously adsorbed at the surfaces or entrapped in the volume of the material. A measurement of the outgassing rate (q) for the assembly (Fig. 3) was done by actively pumping for 12 hours. After this period of time, the pump was valved off and the pressure in the first and last cavity was monitored using the gauge 1 and gauge 2. Figure 4 shows the pressure profile up to the maximum scale of the gauge: 10^{-2} Torr, as function of time.

The following equation defines the outgassing rate (q) according to [6]:

$$q = \frac{\Delta P \cdot V}{A \cdot t} \tag{1}$$

where,

- ΔP is the pressure drop measured by the gauges after certain amount of time t;
- V is the beam-line volume that was pumped down: 192 L (half-string);
- A is the total surface of the components in the beam-line exposed to vacuum: 43 240 cm^2 (half-string);

Outgassing rate measured in the upstream cavity (gauge 1) after one hour:

$$q = \frac{(6 \cdot 10^{-3} - 1.9 \cdot 10^{-5}) \cdot 192}{43240 \cdot 3600} = 7.4 \cdot 10^{-9} \frac{Torr \cdot L}{s \cdot cm^2}$$

Outgassing rate measured in the downstream cavity (gauge 2) after one hour:

$$q = \frac{(2.3 \cdot 10^{-3} - 3.7 \cdot 10^{-5}) \cdot 192}{43240 \cdot 3600} = 2.8 \cdot 10^{-9} \frac{Torr \cdot L}{s \cdot cm^2}$$

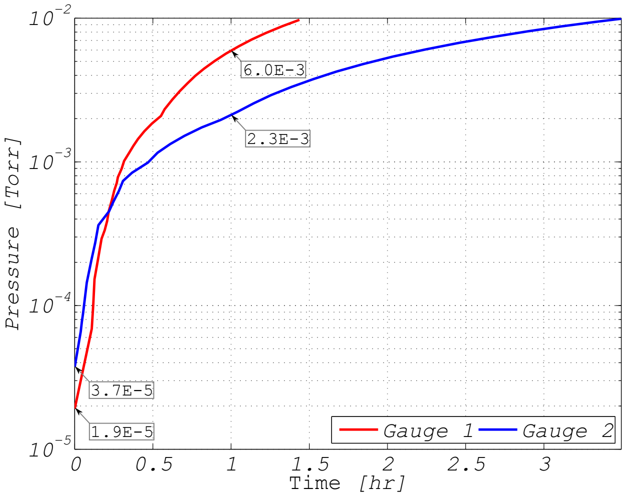

Figure 4: Pressure profile as function of time during outgassing measurement during the pilot vacuum test.

VACUUM SIMULATION

It was of great interest to provide an estimate for the achievable pressure level in the beam-line after clean assembly in the cleanroom. A model was developed to perform a best guess vacuum simulation in Molflow [4]. The previously described vacuum test was performed in conservative conditions and exceeded the requirements setting the lower limit of the achievable vacuum level. The vacuum simulation aims instead at predicting the higher limit by utilizing parameter values based on assumptions for the most part optimistic.

Model The 3D model of the cavity string beam-line volume (Fig. 2) was made using NX CAD software. The geometry was simplified omitting details not contributing to the results. The model consists of a series of eight cavity volumes joined by cylindrical sections having diameters equal to the apertures of the BPMs, solenoids, bellows and tubes.

Parameters In order to perform vacuum simulations in Molflow it is necessary to define the pumping speed at the pump inlet (S) and the outgassing rate of the materials (q). The nominal pumping speed of the two pumps that will be used for the SSR1 cryomodule is 300 L/s. The maximum speed allowed by the software is 184 L/s and it was applied at the inlet of the pipe that connects the beam-line to the pumping system. Niobium material which has undergone routine preparation for SRF application (chemical processing, high-pressure rinsing and 120 °C baking) is considered outgassing-free and $q = 0$ was applied to the niobium surfaces [5]. The remaining surfaces are a mix of components made of oxygen-free copper, aluminum and stainless steel. Of all these materials, unbaked stainless steel has the highest outgassing rate: $q = 2 \cdot 10^{-10} \frac{Torr \cdot l}{s \cdot cm^2}$ [6, 7]. This value was applied to all non-niobium surfaces.

Result About 10 hours of simulation were necessary to reach convergence. Figure 5 shows the simulated pressure distribution in the beam-line of the SSR1 cryomodule. Figure 6 shows the simulated pressure profile along the beam axis. In all locations of the beam-line the level of pressure is well below the specification of $5 \cdot 10^{-5}$ Torr. This demonstrates that the conductance of the system is not limiting the achievable vacuum level in the system.

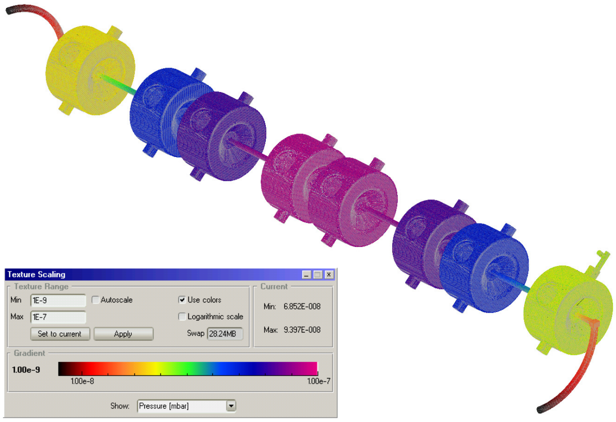
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Figure 5: Plot of the vacuum simulation using Molflow.

CONCLUSION

The vacuum test performed on the string has concluded that the high-vacuum level at room temperature can be achieved pumping down by the beam ports only, even in non-ideal condition. Furthermore, simulations performed on the entire string with ideally clean components show that the achievable pressure in the beam-line would be of $7 \cdot 10^{-8}$ Torr pumping from both ends. Thus, an additional vacuum manifold is not necessary to achieve the vacuum level of $5 \cdot 10^{-5}$ Torr in less than 12 hours.

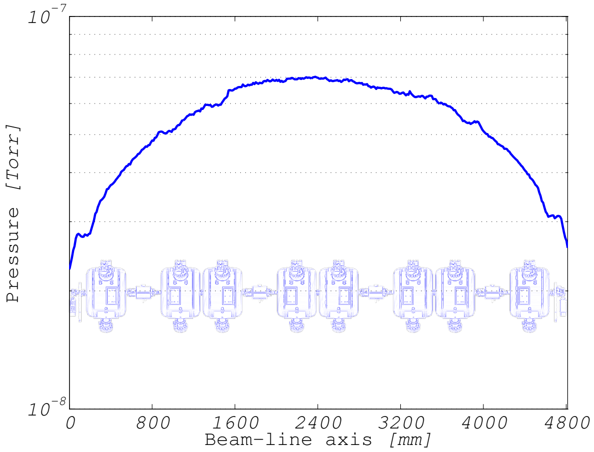

Figure 6: Simulated pressure profile along the beam axis when pumping down from both ends of the SSR1 cryomodule through the beam-line only.

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REFERENCES

[1] T. Nicol et al., “SSR1 Cryomodule Design for PXIE”, Proceedings of PAC2013, Pasadena, USA.

[2] P. Kneisel, “Effect of Cavity Vacuum on Performance of Superconducting Niobium Cavities”, Proceedings of the 1995 Workshop on RF Superconductivity, Gif-sur-Yvette, France.

[3] J. Knobloch, H. Padamsee, “Reduction of the surface resistance in superconducting cavities due to gas discharge”, Proceeding of 8th Workshop on RF Superconductivity, Padova, Italy.

[4] `https://test-molflow.web.cern.ch/`

[5] A.L. Cabrera et al., “Kinetics of Subsurface Hydrogen Adsorbed on Niobium: Thermal Desorption Studies”, J. Mater. Res., Vol. 17, No 10, Oct 2002.

[6] P. Chiggiato, “Outgassing”, TS-MME Coatings, Chemistry and Surfaces, 2006.

[7] P.A. Redhead, “Extreme High Vacuum”,National Research Council, Ottawa, Canada, `http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/32/011/32011645.pdf#page=224`

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