Upgrade of the spoke test cavity station

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Abstract. Originally the spoke test cavity cryostat was designed to test exclusively SSR1 cavities. The goal of this upgrade is to extend this capability to SSR2 cavities, and to the low and high beta 650 MHz cavities. These cavities are the last elements of the superconducting linac architecture which is the main component of the Proton Improvement Plan-II (PIP-II) at Fermilab. The size of SSR2 and 650 MHz cavities being much bigger than SSR1, extensions of the vacuum vessel and of all the cryogenic lines have been necessary. Mechanical, thermal and cryogenic analyses have been performed to ensure proper operation. This paper summarizes the design choices which have been made by describing the main elements of this upgrade and the interface between cryogenic lines and cavities.

1. Introduction
The spoke test cavity station has been in use at Fermilab since 2014 to test SSR1 cavities. The test conditions are very close to what we will have during the cryomodule operation. Each cavity is tested with its coupler and tuner, and is supported in the same way as it will be inside the cryomodule. From the beginning of next year, all SSR1 cavities should be fully qualified and ready to begin the assembly of the beam line [1] [2]. Then the next steps will be to qualify the high and low beta 650 MHz cavities and SSR2 cavities for which no test station exists to qualify them.

1.1. The existing test station
To prevent radiation, the test station is surrounded by concrete blocks. During the test preparation, people will have access through a narrow corridor around 35” wide. We can see below a picture of the existing test station. The main cryogenic components are located just above the test station [3].

Cryogenic components
(Heat-exchanger, Joule Thomson valve, cool down warm up valve, check valve, relief valve, …)

Vacuum vessel

Figure 1. Existing test station
The test station consists of the following main components, which can also be seen figure 2 [3]:

- The stainless-steel vacuum vessel is composed of two hinged domes on each side in order to have access to set the cavity inside the test station.
- A cavity support post is bolted to the vacuum vessel and to the thermal shield in order to support the shield and to get a thermal intercept around 80K. This support post is a press fit assembly composed of a tube in G10 in order to reduce the heat-loads.
- The magnetic shield is located on the inner surface of the vacuum vessel.
- The thermal shield is actively cooled with liquid nitrogen at 80K. The connection to the top part of the vacuum vessel is done with VCR connectors.
- The two-phase helium pipe is located right above the cavity and is bolted to the chimney. At one end is the instrumentation to measure the level of helium and the pressure inside the pipe.
- The cool down - warm up line comes from the top part of the vessel with a long flexible tube and a VCR connector.

**Figure 2.** Cross section of the existing test station

1.2. Requirements and strategy

By upgrading this test station, we want to have the capability to test SSR2 cavities, and low and high beta 650 MHz cavities which have a geometry bigger than SSR1 cavities. For example, SSR2 cavity has a diameter 2” bigger than SSR1 cavity [4], and the high beta 650 MHz cavity [5] has a chimney making an angle with the vertical axis and a length around 55” compared to 39.5” for the length of the existing vacuum vessel. Therefore, an upgrade of the test station is necessary.

**Figure 3.** SSR1 cavity (left) and HB650 cavity (right)
In order to reduce the cost and the time of the project, it has been decided to re-use the components of the existing test station as much as possible and also to minimise the number of components to disassemble. Therefore, it has been decided that the top part of the cryogenic components including the heat exchanger designed for a maximum flow rate of 1.25 g/s should not be changed. Another important constraint was the room available inside the test station:

- The vacuum vessel and thermal shield can be extended but we still want to be able to have access on both ends of the vessel
- The design needs to consider an assembly process matching with the room available

2. Mechanical design

2.1. Description of the test station

The vacuum vessel, the magnetic shield, and the thermal shield of the existing STC have been extended. Figure 4 presents a cross section of the new test station. The vacuum vessel’s extension is 30” long. It also has been decided to add a support post on this extension in order to support the 650 MHz cavities due to their length. Moreover, the height of this support post has been reduced by 1.9” in order to fit SRR2 cavity inside the test station.

![Figure 4. New test station - SSR1 configuration](image)

2.2. Two phase helium pipe design

In order to fit the high beta and low beta 650 MHz cavity inside the thermal shield it has been necessary to re-design the two-phase pipe. Its length has been increased in order to let the helium container at one end and a removable interface has been designed in order to make the connection with the cavity. Figure 5 shows the new design of the two-phase pipe with its interfaces.

![Figure 5. New two-phase helium pipe](image)
Finite element analysis of the two-phase helium pipe has been performed in order to estimate what will be the stress state and the displacement considering several scenarios, especially the loss of insulating vacuum. On the existing station the two-phase helium pipe was fixed just to a flange on the top of the vacuum vessel (Figure 2). Calculations have shown that another support is needed in order to follow ASME B31.3 requirements.

2.3. High beta 650 MHz configuration
In order to test high or low beta 650 MHz cavities, an aluminum plate is set on the two support posts inside the vacuum vessel as shown in Figure 6. On one side, the plate is directly bolted to the support and on the other side the plate is able to slide via two Teflon plates. The figure 7 presents the HB650 cavity with its insertion tooling. Outside the vessel, the cavity including the cold part of the coupler, the cool down - warm up line and the interface with the two-phase helium pipe is set on an aluminum structure which slides inside the vessel thanks to a rail and adjustable wheels. Finally, the cavity will be inserted inside the vacuum vessel.

![Figure 6. Test station with the aluminum plate connecting the two support posts](image1)

![Figure 7. High beta 650 MHz cavity on its insertion tooling](image2)

Figure 8 shows that the high beta 650 MHz cavity fit inside the thermal shield. The main difficulty was to design the interface between the cavity and the two-phase helium pipe. Calculations have been done in order to estimate what will be the displacement during the cool-down between these two elements in order to design properly the bellows.

![Figure 8. New test station - High beta 650 MHz cavity configuration](image3)
3. Cryogenic design

The goal of this upgrade is to have the capability to test spoke and elliptical cavities. Due to the fact that the high and low beta 650 MHz cavities have a chimney making an angle with the vertical axis contrary to SSR1 and SSR2 cavities, it has been necessary to design a dedicated interface. A schematic of the cryogenic lines according to the kind of cavity tested is presented in Figure 9. Note that the VCR connections are indicated with an “X”.

![Figure 9. Schematic of the cryogenic lines](image)

The 80 K line with a design pressure of 80 psig will be cooled by liquid nitrogen. The two-phase helium pipe and the cool down - warm up line will be cooled to 2 K with liquid helium considering a design pressure of 59.5 psig.

3.1. Heat-loads

In order to be sure that the test station upgrade will be compatible with the current cryogenic devices and especially with the heat exchanger, it is necessary to estimate the heat-loads. Due to the fact that the vessel and the thermal shield are longer, and that two shorter support posts are used the heat loads are more important. The heat loads on the 80 K and 2 K stages should increase around 7.5 W and 3.3 W respectively. Based on this analysis the helium mass flow should be close to the maximum flow of the exchanger: 1.25 g/s (Table 1). Nevertheless, we should have some margin considering that the heat loads on the 2 K stage have been slightly over-estimated due to the fact between one supporting post and the 2 K stage there will be some Teflon. In this way, the thermal contact won’t be perfect, and the heat loads should be lower.

|                                          | Existing test station | New test station |
|------------------------------------------|-----------------------|------------------|
| Heat loads on 80 K stage (W)             | 16.3                  | 23.9             |
| Heat loads on 2 K stage in static (W)    | 1.30                  | 4.6              |
| Heat loads on 2 K stage in dynamic (W)   | 24.0                  | 24.0             |
| Latent heat of helium (J/g)              | 23.0                  | 23.0             |
| Helium mass flow (g/s)                   | 1.10                  | 1.24             |

3.2. Thermal shield design

The new thermal shield will be cooled actively at 80 K by expanding the existing lines. The interface will be done with flexible tubes and VCR connections in order to easily connect the two thermal shields. The thermal shield is welded to an extruded pipe both in aluminum 6061 in order to warrant a good heat exchange. The interface between this pipe and the cryogenic line in stainless steel is done by using bimetallic parts (Figure 10).
3.3. Cool down - warm up line
Each kind of cavity will have its own cool down - warm up line because the design of spoke and elliptical cavities is very different. For example, you can see in the Figure 11 the cool down - warm up line of the SSR1 cavities and HB650 cavities.

![Figure 11. Cool down - warm up line of the SSR1 cavities (left) and HB650 cavities (right)](image)

3.4. Venting requirements
Due to the use of an interface between the elliptical cavities and the two-phase helium pipe, it has been necessary to perform a new venting analysis. For this, three different scenarios have been studied:
- Loss of insulating vacuum at cold temperature
- Loss of vacuum of the cavity at cold temperature
- Warm cavity with full system flow

The maximum flow is iteratively calculated by keeping the cavity pressure at 110% MAWP while fixing the discharge to atmosphere at 14.7 psia. In addition, the FIKE technical bulletin TB102-1 Rupture Disk Sizing recommends multiplying the system calculated relief capacity by a factor of 0.9 to account for uncertainties. Table 2 summarizes these calculations.

|                         | 110 % MAWP or 3 psi above MAWP (psi) | Relief Temperature (K) | Available relief capacity (g/s) | FIKE Recommendation (g/s) | Required mass flow rate (g/s) |
|-------------------------|--------------------------------------|------------------------|-------------------------------|--------------------------|-----------------------------|
| HB650 Cavities at cold temperature | 65.4                                 | 6.8                    | 5400                          | 4860                     | 3850                        |
| HB650 Cavities at room temperature   | 32.7                                 | 289                    | 330                           | 297                      | 60.7                        |
4. Assembly process

4.1. Modifications of existing components
The upgrade of this new test station has been done in a way to avoid any welds inside the existing vacuum vessel. Therefore, it was not necessary to disassemble many components and to remove the MLI around the existing pipes. The assembly process will be the following:

- The cryogenic lines will be disconnected including the two-phase helium pipe, the cool down - warm up line and the 80 K line
- The existing thermal shield will be supported by temporary supports
- Due to design constraint, the only solution to remove the existing cavity support post will be to cut it
- Finally, the new two-phase helium line and the new cavity support post will be set up (Figure 12)

Figure 12. Modification of existing components

Figure 13. Extension of the test station

4.2. Installation of new components
Due to space constraint inside the test station, the extension of the vacuum vessel with the new magnetic shield and thermal shield will be assembled outside (Figure 13) and brought together inside the test station from the roof with a crane. Nevertheless, due to the cryogenic lines above the test station it is not possible to set the assembly directly on its posts. The assembly will be lowered to the area A and then moved to the area B with a portable crane (Figure 14). Then the dome of the vacuum vessel and the interfaces between the cryogenic lines will be connected.

Figure 14. Test station - Top view
5. Conclusion

The main challenge of this upgrade was to be able to fit the high beta 650 MHz cavity inside the thermal shield with regards to the room available. For this, the cavity will slide inside the vessel thanks to a structure on wheels and guided by a rail. As it was the case for SSR1 cavity, we will qualify the high beta 650 MHz cavities in “cryomodule” conditions by testing the tuner and the coupler together. By changing the plate on the cavity support post, we will be able to test and qualify all the cavities needed for PIP-II. Therefore, we will have more flexibility and adaptability to follow the project schedule. The design of this test station is now completed and the procurement is in process. The schedule is to upgrade this test station early 2018 and to start to qualify the high beta 650 MHz cavities.

6. References

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