SUPERCONDUCTING RF SYSTEM PLANS AT CLS

C. N. Regier†, Canadian Light Source Inc., Saskatoon, Canada

Abstract

Canadian Light Source (CLS) in Saskatoon, Canada has several cryogenic systems. One of the most critical is a 4.4 K liquid helium system for a superconducting RF cavity. This system consists of a Linde TCF-50 liquid helium plant coupled to a Cornell-designed CESR-B 500 MHz cavity and cryomodule via a 52 metre multi-channel transfer line. Over the years CLS has evaluated failures on the system as well as risks for downtime, and has come up with plans for a major upgrade to the superconducting RF system to improve reliability. An overview of performance and issues to date is presented. Some of the specifics of the risk analysis and upgrade plan will be examined, and details of the process flow discussed.

INTRODUCTION

The Canadian Light Source (CLS) uses a superconducting radio-frequency (SRF) cavity to replace energy lost by the electron beam due to synchrotron radiation. The SRF system operated by CLS consists of a 500 MHz Cornell-designed Cornell Electron Storage Ring B-factory (CESR-B) cryomodule [1] [2] connected via a 52 metre multi-channel transfer line (MCTL) to a Linde TCF-50 liquid helium cryogenic plant. Along with Taiwan Light Source, CLS was one of the first synchrotrons to use SRF for storage ring applications, with the system initially commissioned in 2003. Since then, several other synchrotrons including Diamond Light Source, SSRF, PLS, and NSLS-II have chosen to use the CESR-B design for storage ring radio-frequency (RF) [3] [4] [5]. SIRIUS in Brazil is also planning to use the CESR-B as its storage ring SRF platform.

As with most other synchrotron facilities CLS is a user facility, meaning that operational consistency and reliability are of critical importance. While the SRF system has generally been reliable, over the last 13 years of operation CLS has experienced some problems. Cryogenic transfer line ruptures, cryoplant and compressor issues, and SRF cryomodule vacuum leaks have all occurred at CLS between 2007 and 2013. Based on these experiences, CLS has undertaken several avenues to increase system reliability. Two major projects are planned: The purchase of a third CESR-B cryomodule and a "Cryo Upgrade" project that will see a second cryomodule installed in the storage ring and an additional compressor installed at the plant.

THE CLS SRF SYSTEM

The SRF system at CLS comprises of a single CESR-B cryomodule in Straight 12 of the storage ring, coupled via a cold valve box and a 52 metre multi-channel transfer line (MCTL) to a Linde TCF-50 liquid helium cryoplant. The arrangement of this system is shown in Fig. 1, and a schematic of the system is shown in Fig. 2.

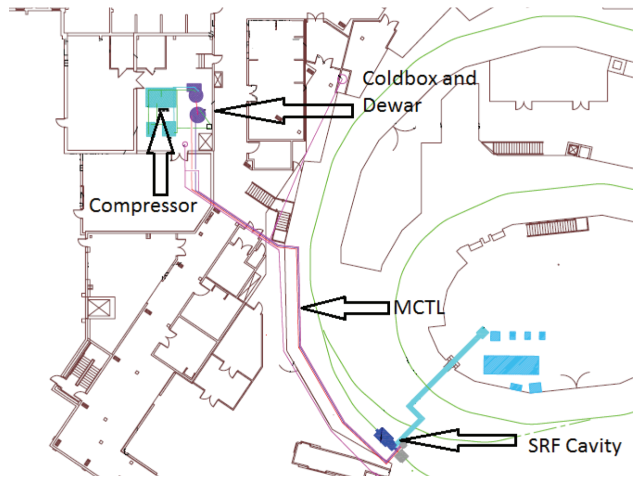

Figure 1: The layout of the CLS SRF system.

The cryoplant is located off of the experimental floor to prevent vibrational interference with ongoing experiments. A 200 kW compressor feeds oil through an oil recovery system (ORS) and gas management panel (GMP) to the coldbox, which deposits liquid into a 2000 L dewar. Pressure head drives liquid down the MCTL to the valve box on top of the storage ring concrete shielding, where a control valve regulates the level in the cryomodule below. Boil-off is returned to the valve box, where a second control valve meters flow back to the plant to regulate the cryomodule helium pressure. Both the liquid supply from the plant and the cold gas return to the plant are piped through the MCTL, along with a liquid nitrogen supply line for the cryostat. The liquid nitrogen is used to cool a thermal shield for the helium along the MCTL and in the cryomodule. A complete spare cryomodule is kept at CLS so that in the event of a cryomodule failure CLS is not required to wait for repair before continuing service. The cryomodules are identified as Cavity 1 and Cavity 2, with Cavity 1 being the first one delivered to CLS.

Figure 3 shows a simple cut-away of the CESR-B cryomodule. Radio-frequency (RF) energy is supplied to the cryomodule via waveguide. The RF passes through a ceramic window located under the cryomodule to transition from the air-filled waveguide into the ultra-high vacuum (UHV) required for the cavity. From there, the RF passes through a pump-out box, which is the point at which turbomolecular pumps can be attached to the UHV, and travels into the waveguide elbow. The elbow curves

† chris.regier@lightsource.ca

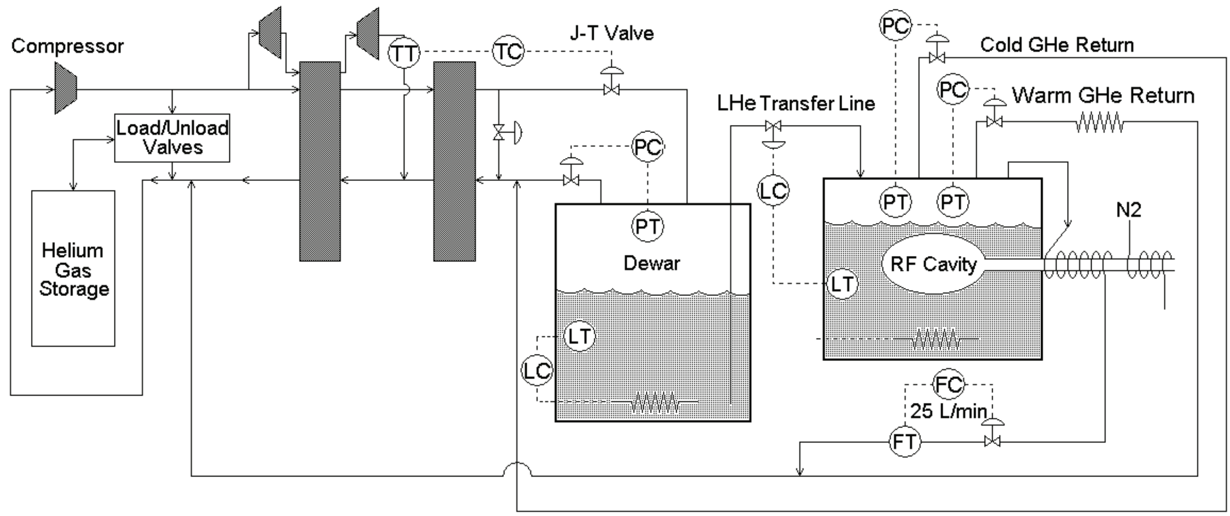

Figure 2: Schematic of the CLS SRF system.

upward and then backward, steering the RF through 180 degrees. The vertical section of the waveguide elbow is also wrapped in a coil through which the liquid nitrogen flow passes before exiting the cryomodule. This provides a thermal transition for the waveguide, going from near room temperature to liquid nitrogen temperature.

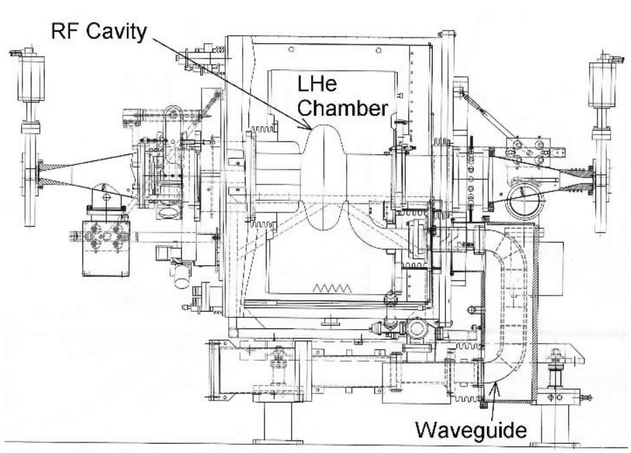

Figure 3: Cut-away view of the CESR-B cryomodule.

A short helium heat exchange (HEX) section connects the top of the elbow to the wall of the helium vessel. This section is similar to the liquid nitrogen section, but uses boil-off helium gas for cooling to provide a thermal transition from liquid nitrogen temperatures to liquid helium temperatures. Inside the helium vessel, the waveguide is niobium and is part of the cavity.

At CLS the SRF cavity is typically operated at an accelerating voltage of 2.05 MV and at RF power inputs of 260 to 270 kW or more. To consistently achieve these high voltages and power inputs, the cavity must be well-conditioned and be kept free of contaminants. This is made more difficult by the fact that the cold cavity will cryo-pump any storage ring vacuum contaminants. Build-up of these contaminants on the cavity inner walls will cause increased liquid helium consumption due to an increase in the electrical resistance seen by the RF, and can create emitters. An emitter is the equivalent of a steel tower in a thunderstorm – it provides a path of reduced resistance for current flow, and can cause arcing across the cavity. If this happens then a quench occurs and the entire cavity quickly becomes normal-conducting, causing cryogenic system oscillations and tripping the RF off.

Two methods are used to prevent this increased helium use and quenching: pulse conditioning and partial warm-ups. Pulse conditioning is done by pushing high-power pulses of RF into the cavity to burn off any potential emitters. Partial warm-ups are more effective, and involve removal of the liquid helium from the cryostat and warming the cavity to roughly 50 K. This allows cryo-pumped gases, largely hydrogen and air, to sublime off of the inner wall of the cavity and into the vacuum space, from which they can then be removed by vacuum pumping with a turbomolecular pump.

CLS CESR-B HISTORY

Cavity 1 was delivered to CLS in May 2003 and commissioned in August 2003 in the storage ring. While Cavity 1 was commissioned in the CLS storage ring, it was used to commission the storage ring as well. After conditioning a cavity voltage of 2.4 MV was achieved.

Cavity 2 was delivered in mid-2004. During the fall maintenance outage in 2004 Cavity 1 was removed from the storage ring and Cavity 2 was installed. Cavity 2 was also successfully commissioned, however a leak into the insulation vacuum of Cavity 2 was noted. While the leak was small and was controlled by continuous pumping, it was decided that Cavity 2 should be removed and Cavity

1 reinstalled. This was done in the fall maintenance outage in 2005.

While Cavity 2 was being commissioned, Cavity 1 was stored with dry nitrogen gas in the UHV space. This was done to avoid any potential issues that could arise with vacuum maintenance during storage. When Cavity 1 was reinstalled in the storage ring in late 2005 it took only four hours after cool-down to achieve 2.2 MV across the cavity. Because of this Cavity 2 was also stored with dry nitrogen in the UHV space when it was removed in late 2005.

In January 2013 a problem with Cavity 1 forced CLS to remove it from the storage ring and bring Cavity 2 out of storage. Cavity 2 was installed in the storage ring and Cavity 1 was shipped to Research Instruments in Germany for repair. While Cavity 1 had quickly come back to normal operating conditions after storage, Cavity 2 required six months of regular conditioning and partial warm-ups to achieve full operation again. During this period CLS was forced to operate with reduced beam current, slowly working up from 150 mA to 250 mA over the six-month period.

When Cavity 1 was disassembled it was found that there were vacuum leaks at two small RF pickup flanges on the cavity. While the repair of these seals was a relatively minor job in itself, it required complete disassembly of the cryomodule to complete, which is quite time-consuming. Because of this, it was roughly 27 months from the time the failure occurred until Cavity 1 was returned to CLS.

Since 2013 CLS has operated with Cavity 2, and while there have been a few minor issues that have caused some concern, operation has been reliable over the last 3 ½ years.

PAST PROBLEMS

In 2007 the CLS experienced a failure of the MCTL. A helium leak into the insulation vacuum formed on the cold gas return line. This was found to be due to a manufacturing issue with the transfer line: a bellows was used in place of a solid piece of pipe as an elbow. A slight overpressure resulted in deformation of this bellows, causing several pinhole leaks. A second bellows developed a leak one year later, but this bellows was installed correctly and the leak is thought to be a delayed result of the first problem.

In 2012 there were several issues with the airend in the compressor. After several airend changes in a short period of time, it was determined that a misprint in the compressor maintenance manual had caused CLS to underfill the compressor with oil. Once this misprint was discovered, the airend issues ceased.

Soon after the compressor issues it was discovered that there was oil in the coldbox. This was unusual in that the oil was in the return, or low-pressure side of the coldbox. With assistance from Linde, an acetone flush was performed on the low-pressure side of the coldbox and the system was placed back into operation. The supply side was found to be completely clean and dry. This oil was forced into the coldbox during the compressor airend issues, and once removed the plant was restored to normal operation. Roughly 15 L of oil was removed from the coldbox, and plant performance is now slightly better than it was before any issues were noticed.

Finally, in early 2013 Cavity 1 developed the leak from the helium vessel into the cavity UHV space as mentioned in the previous section. The leak was slow, but enough to keep the system from operating. Cavity 2 was installed in the storage ring, and the damaged unit was removed and sent back to the manufacturer for repair. The removal of a cryomodule can be completed in roughly three days, but the installation of a new cryomodule requires almost two weeks. This is due to the quantity of instrumentation connections, and the time taken to properly ring-out these connections to establish that all instrumentation is functioning properly.

These failures have cost the CLS roughly 12 weeks of downtime. Figure 4 shows a breakout of the SRF cryogenic system failures and the percentage of the overall system downtime for which each is responsible. Included is the “Cryostat Reduced Ops” category. This describes the period after the spare cryomodule had been installed in 2013 during which much conditioning and many partial warm-ups were required before a full 250 mA of beam current could be consistently run in the storage ring. While users had beam during this time, the flux was substantially reduced and there was significant impact on both experimentation and operations.

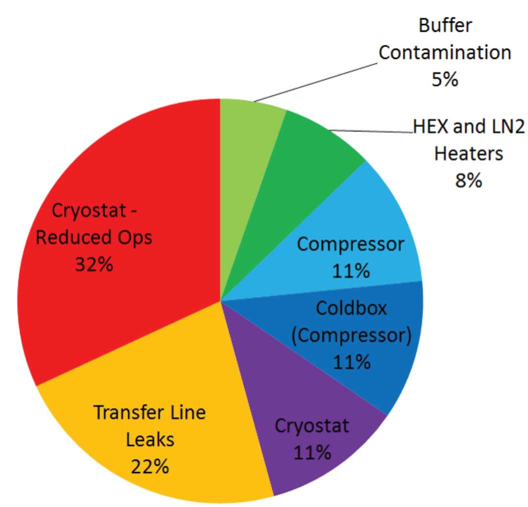

Figure 4: Downtime contributions for CLS SRF cryogenic system problems.

While the system has been repaired and has operated very reliably for the last 3 ½ years, many of the weaknesses in the system still exist. For this reason, current risk mitigation strategies for the SRF cryogenic system at CLS are focused both on reducing the chance of occurrence of the issues shown in Fig. 4 and in reducing the risk of having a double cryomodule failure.

THE CRYO UPGRADE

CLS has planned an upgrade to the SRF cryogenic system that would eliminate many of the system weaknesses that could cause downtime. The upgrade consists of putting the spare SRF cryomodule into the storage ring in another straight section (Straight 2), and installing a second compressor and ORS/GMP system. Space for the second compressor would be gained by moving the coldbox and dewar onto the top of the storage ring shielding bunker to a central location between the two cryomodules. Figure 5 shows the proposed layout for this upgrade.

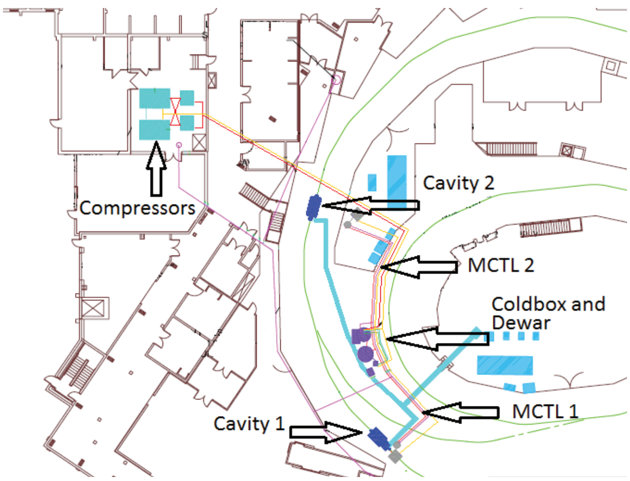

Figure 5: The layout for the proposed upgrade for the CLS SRF cryogenic system.

Several benefits are realized from the cryo upgrade proposal. First, a second compressor is in-line and available in event of a compressor failure, or if maintenance is required on a compressor. This would reduce cryoplant downtime to roughly 3 hours from multiple days in event of a problem. The same principle is valid for the second ORS/GMP unit. The proposal calls for cross-piping the compressors and ORS/GMP skids, so that either ORS/GMP can be used with either compressor. This provides further redundancy.

Second, the coldbox and dewar will be on top of the storage ring enclosure. This elevates the coldbox relative to the compressors, making it much more difficult for oil to transfer into the coldbox from the compressor circuits. The coldbox and dewar are also elevated relative to the SRF cryomodules, meaning additional pressure head is available via this elevation to supply liquid helium to the cryomodules. This will help with system stability.

Third, the distance from the dewar to each cryomodule will be far less than the current setup, meaning the length of each MCTL will be smaller. This will help reduce chances of an MCTL failure, and will also reduce heat leak into the liquid helium. It is better to use a longer pipe run for the room-temperature gas and a shorter pipe run for the cold fluids, as room-temperature piping is simpler, cheaper, and easier to construct and maintain.

Fourth, the second cryomodule in the storage ring will reduce downtime in event of a cryomodule problem. While a cryomodule must be removed from the storage ring if it cannot be kept cold, removal is much faster than the current removal and replacement required if there is a problem with the single cryomodule. As an added benefit, the second cryomodule will reduce the load on the first. The power being put into the beam can be spread over two cavities instead of all going into one. This will decrease the chance of an RF window fracture on the cryomodules, increasing their reliability, and will also allow CLS to pursue higher beam current operation in the range of 350 to 500 mA in the future.

CLS began preliminary work on the cryo upgrade in 2013, but because of other priorities the project did not make as much progress as desired. In mid-2015 the project was put on hold while CLS analysed the possibility of spending the money and effort installing a normal-conducting RF cavity system instead. While the decision has been made to proceed with the cryo upgrade, the project has not progressed since mid-2015 because resources have been diverted to other higher-priority work.

SUPERCONDUCTING VERSUS NORMAL CONDUCTING

In mid-2015 CLS considered the possibility of removing the superconducting RF system and installing normal-conducting cavities instead. Normal-conducting cavities have some advantages in that they do not require a complex liquid helium system, they don't require time-consuming warm-up and cool-down procedures to repair problems, and they don't have quenching or arcing issues because normal-conducting cavities operate at lower accelerating voltages than superconducting cavities do. Also, the Euro cavities considered take up less space because they do not require vacuum insulation, magnetic shielding, or liquid nitrogen shielding.

Disadvantages of normal-conducting cavities are that they are more susceptible to beam interference from higher-order modes (HOMs) in the cavity, they are much less efficient and create large amounts of heat that must be removed, and they are only capable of accelerating voltages in the 0.6 to 0.8 MV range for 500 MHz cavities, whereas the CESR-B is capable of 2.4 MV. Because of the HOMs CLS would need to implement longitudinal feedback for the beam to compensate. The heat generation would add a significant load to the CLS cooling water systems, requiring additional fluid cooler capacity and increased cooling water supply to the storage ring. In addition, the inefficiency of normal-conducting cavities would necessitate an increase in RF power input from 300 kW to 600 kW to compensate. The lower accelerating voltages mean three to four times as many normal-conducting cavities would be required as compared to SRF cavities, negating the benefits in size.

Several facilities have done analyses comparing superconducting and normal-conducting storage ring cavity options. These analyses typically come out very close, with the increase in cost and complexity for superconducting equipment and the helium plant being offset by the reduced HOM effects on the beam, the smaller required investment in RF system capital due to lower RF power requirements, and the reduction in operating costs due to greater efficiency. In the case of CLS, the increases in size and capacity that would be required to the cooling water and storage ring RF systems to implement normal-conducting cavities are significant and expensive. In the end this fact along with the longitudinal feedback system requirement resulted in the CLS decision to remain with SRF.

ANOTHER SRF CRYOMODULE

When cryomodule 1 failed in early 2013, CLS installed the spare cryomodule in the storage ring. At that point there was not a spare cryomodule at CLS, meaning another failure would result in loss of beam. Total time between the failure and the return of the repaired cryomodule to CLS was 27 months. This length of time meant that the possibility of another failure during this period, while low, was significant. In fact, of total of 30 new or refurbished CESR-B modules that have been installed, five have failed upon initial cool-down or shortly thereafter.

Roughly two months before the return of cryomodule 1 to CLS, the insulation vacuum space on cryomodule 2 began to show signs of problems. Additional turbo pumping was added to attempt to combat this problem, but there were concerns at CLS that cryomodule 2 would become inoperable before cryomodule 1 was returned. Because of this concern, along with the extended repair times required for cryomodules, CLS has decided that another cryomodule is necessary to ensure continued operation in event of a double cryomodule failure. While a chance of a triple failure still would exist, this chance is statistically small enough that it is an acceptable risk.

While CLS was the first synchrotron to use SRF for normal storage ring operations, several others have chosen the CESR-B for their storage ring RF cavity system since. Each of these iterations of the CESR-B has seen improvements and design variations, particularly in the cryomodule, cryogenic connections, tuner, and heater systems. This complicates the process of specifying the new CLS CESR-B, as writing the technical specification becomes a balance between ensuring the new module will work with existing CLS infrastructure and taking advantage of improvements and lessons learned over the 12 years since the CESR-B was first delivered to CLS.

CLS is just in the process of releasing a request for expressions of interest in providing a new CESR-B cryomodule. Once potential vendors have been established CLS plans to go forward with a request for proposals this fall.

THE COLD RF TEST

After Cavity 1 was repaired in Germany, high power RF testing was done on it before it was returned to CLS. This testing was done at the Diamond Light Source RF test facility. An interface was constructed to allow connection of the CLS CESR-B to Diamond's RF test infrastructure, and the cryomodule was tested in January and February of 2015. During testing the cavity achieved 2.1 MV at 80 kW of RF. After testing, the Cavity 1 was returned to Germany before shipping to CLS.

The integrity of both the insulation vacuum and the UHV was tested in Germany before shipping, and again at CLS after being received. However, accelerometers mounted on the frame during shipping indicated some significant bumps and jarring during the unloading from the aircraft and during the 600 km truck trip from the airport to CLS. This has caused some concern that, while there are currently no leaks in the vacuum spaces, leaks may develop on cool-down. Even a small leak can easily stop operation of the cryomodule.

While a third cryomodule will reduce the risk to CLS in the event of a double cryomodule failure, to order and receive a new CESR-B takes roughly 24 to 30 months. Because of this CLS is planning a cold test of Cavity 1 during an upcoming maintenance outage in February, March, and April. Cavity 1 will be moved into the storage ring shielding and connected to the cryogenic system with instrumentation cable and cryogenic flex line connections. This will permit testing without moving the installed cryomodule, which could cause potential cavity contamination issues.

CONCLUSIONS

CLS has successfully and reliably operated a storage ring SRF system for over 12 years. While operation has proven reliable, there have been some issues over the 12 year operating period. The system is complex, and repair times for cryomodules are long, meaning that there are risks of significant downtime periods of multiple weeks in event of equipment failure, and a risk of extended downtime of months or even years in the event of a double cryomodule failure.

To reduce these risks, CLS has focused on four main areas. First, an assessment was completed examining whether a normal-conducting storage ring RF option was feasible and realistic. It was found that it was too complicated and expensive to switch from SRF to normal-conducting RF. Second, a cryogenic system upgrade has been proposed and conceptually designed. This would increase redundancy and reduce downtimes in the event of equipment failures. Third, a third cryomodule is being ordered. This will reduce the likelihood of extended downtime due to the chance of a double cryomodule failure. Fourth, a cold test is planned for the recently repaired Cavity 1 to ensure vacuum spaces will remain leak-free upon cool-down.

REFERENCES

[1] D. Moffat, P. Barnes, J. Kirchgessner, H. Padamsee, and J. Sears, "Preparation and Testing of a Superconducting Cavity for CESR-B," in *Proc. 1993 Particle Accelerator Conf.*, Washington D.C., USA, May 1993, pp. 763-765.

[2] S. Belomestnykh *et al*., "Commissioning of the Superconducting RF Cavities for the CESR Luminosity Upgrade," in

Proc. 1999 Particle Accelerator Conf., New York City, USA, Mar-Apr 1999, pp. 980-982.

[3] M. R. F. Jensen, “Operational Experience with SRF Cavities for Light Sources,” in *Proc. SRF2011 Conf.*, Chicago, USA, Jul 2011, pp. 27-31.

[4] S. Belomestnykh, “Superconducting RF in Storage-Ring-Based Light Sources,” *13th Annual Workshop on RF Superconductivity*, Bejing, China, Oct 2007, pp. 19-23.

[5] F. Gao *et al.*, “Commissioning and Early Operation Experience of the NSLS-II Storage Ring RF System,” in *Proc. Int. Particle Accelerator Conf. (IPAC’15)*, Richmond, USA, May 2015, pp. 3606-3608.