OPERATIONAL EXPERIENCE WITH SRF CAVITIES FOR LIGHT SOURCES

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Abstract

Third generation light sources require modest accelerating voltages, however this is offset by a need for high reliability, to serve users on a continual basis with minimal interruption. The high Q of the superconducting (SC) cavities means that cavities are designed such that higher order modes are effectively damped using external loads, offering stable high current, multi-bunch operation. Fundamental mode SC cavities for light sources were initially used in CESR and KEKB, followed by Taiwan Light Source and Canadian Light Source and third harmonic systems are used for bunch lengthening at SLS and ELETTRA. The successful operation of those machines led to the choice of SC cavities in the design of Soleil, Diamond Light Source and Shanghai Synchrotron Radiation Facility, all now in operation. Additionally, Taiwan Photon Source, Pohang Light Source II and National Synchrotron Light Source II are currently in construction and all employ SC cavities. In this paper we will review recent operational experience of SC cavities in light sources and will describe recent developments related to the cavities and their auxiliary systems.

INTRODUCTION

For nearly 40 years light sources have attracted enormous interest and funding and the design and development has resulted in light sources of exceptional brightness, stability and reliability. More than 50 light sources have already been built and since the mid 1980s, the focus has been on third generation light sources. Third generation light sources are generally considered to consist of a low emittance electron storage ring with insertion devices. Recent upgrades and new light sources have tended to push the beam current up to the point where beam instabilities caused by parasitic higher order cavity impedances of normal conducting cavities can limit the stored current. It is the modest requirement for accelerating voltage, high beam power and the higher order mode absorbers which makes superconducting (SC) cavities particularly attractive. The fact that a smaller amount of valuable straight section space is needed is another important factor. For these reasons, many of the latest electron storage rings (SR) have been designed with SC cavities. The early development of SC cavities for use with light sources has been reviewed previously, see for example [1, 2, 3] and the references within.

RECENT OPERATIONAL EXPERIENCE

There are three distinct designs for fundamental frequency SC cavities in use in SR light sources. They are the CESR single cell 500 MHz cavity developed at Cornell [4], the two-cell 352 MHz cavity developed at SOLEIL [5] and the single cell 508 MHz KEK cavity [6]which has been adapted to operate at 500 MHz. In addition, there are SC third harmonic cavities for bunch lengthening in order to improve the beam lifetime and reduce instabilities They are in use at SLS and ELETTRA [7] and are under consideration and fabrication for TPS and NSLS-II [8].

The CESR Style Cavity

Cornell developed the single cell 500 MHz cavity in the late 1980s to early 1990s for the proposed B-factory. This cavity is aperture coupled to the RF waveguide which results in a fixed Q_{ext}. HOM damping is by means of ferrite absorbers on the beam pipes. The first module was incorporated in the CESR luminosity upgrade, CESR-III, with the first cavity in 1997 and in 1999 CESR became the first SR to operate entirely with SC cavities. CESR has been operating successfully since then and currently typically operates the SR at 400 mA. A three stub tuner is used to provide an optimum match for the various operating conditions. The forward power is typically 180 kW per module with one module being operated at 110 kW due to a higher trip rate. Only one persistent cavity trip mechanism exists: a window trip, which occurs on one module, which is mitigated by weekly pulsed RF conditioning.

In 2003, the Canadian Light Source (CLS) became the first dedicated light source to use a SC cavity. CLS operates using a single cavity with a second module available as a spare and future upgrade. The cavity typically operates at relatively high field for these cavities at 2.2 – 2.4 MV, 8 MV/m with forward power around 229 kW. Operation is generally reliable although a rupture on a bellow on the multi channel line (MCL) has occurred twice. Now the MCL is normally kept cold at all times and only warmed to LN2 temperature during maintenance periods. The CLS modules do however suffer with a gradual reduction in the Q_0. After a warm up and conditioning the dynamic loss is 40-50 W rising, after 2 weeks operation with beam, to 90-100 W. Operation is maintained by regular pulse conditioning and partial warm ups to release hydrogen. The pulse conditioning takes around 4 hrs. In the longer term, the plan is to install the second cryomodule to allow an increase in beam current to 500 mA.

TLS became the next light source to upgrade the existing normal conducting (NC) cavities, and the first SC module was successfully installed in 2004 and has been in continuous operation since 2005 [9]. A second module was also procured and is available as a spare. The upgrade allowed the current to be increased and the TLS now operates at 300 mA in top-up. The module is typically used with an accelerating voltage up to 1.6 MV but compared to other light sources, only at a relatively low power of 70 kW, required to maintain the stored beam. The cavity generally operates well, although currently some problems associated with the tuner assembly are under investigation.

Diamond Light Source (DLS) started operation with Users in 2007. Initially two modules were installed in the SR where up to three cavities can be installed into a single 8.3 m straight section. Unfortunately one module (cavity three) developed a leak during the initial machine commissioning, which meant that initial operation, with users, was with a single cavity. The spare module was installed in the spring of 2007 whilst cavity 3 was being repaired under warranty. The second cavity did however suffer from poor reliability resulting in beam losses and was not taken into regular operation until July 2008. From then on, the beam current was gradually increased to 250 mA. Unlike previous experience with these cavities at other light sources, the DLS batch has suffered with frequent beam trips. A variety of trips have been encountered, many of which have effectively been eliminated. These include problems with the water flow meters, trips in the window region, trips with spikes on insulation vacuum and false trips due to the arc detectors misfiring. However, the most troubling and by far the most frequent cavity trip, results in a loss of RF field in 2-4 µs. This is then followed by gas spikes observed on the beam pipe vacuum gauges in the whole of the RF straight and in the window region of the cavity which tripped. The gas produced does not migrate through the cold waveguide bend on the module which did not trip. To improve our understanding of the trip, various data acquisition systems have been installed which record data from a variety of sources. The trip rate appears to increase strongly with increasing accelerating field. These difficulties resulted in disappointing mean-time-between-failure (MTBF) statistics for the cavities which resulted in MTBF values for 2009 and 2010 of around 42 hrs for the complete SR RF system.

At Christmas 2009, cavity 2 was damaged during a cavity warm up and was subsequently removed from operation. Cavity 3 was installed in March 2010, however the reliability did not improve significantly. In October 2010, significant steps were taken to improve the vacuum conditions in the RF straight and the ion pumps on the make up vessels were upgraded and Titanium Sublimation Pumps (TSP) were added. Regular firing of the titanium filaments and partial or complete cavity warm ups, has resulted in steady improvements in the MTBF. Cavity 3 is currently partially warmed up to 35 K to release hydrogen during the shutdowns and a short partial warm up is being trialled in the middle of long user runs. In addition, pulse RF conditioning is done for both cavity 1 and cavity 3 every week for up to 2 hrs. The results are promising and the MTBF is continually improving. The MTBF for the year to date, > 2500 hrs of User Mode operation, for all the SR RF systems, is > 140 hrs. Approximately 50% of the RF trips this year, have been caused by the cavities with the remainder split between the LLRF, the high power amplifiers and the cryo plant. The plan is to replace half of the TSP pumps with NEG pumps which have yet superior pumping capacity. Cavity 2 is still under repair by the manufacturers having recently failed during the first trial cooldown in the RF test facility. During the repair a number of improvements have been carried out, including new copper plating, due to poor adhesion of previous platings, figure 1, new pickup probes to eliminate short spikes observed on existing probes, believe to be caused by charging up and breakdown of the existing insulators and a high temperature bake of the niobium parts to 600°C to reduce hydrogen desorption. In parallel, steel components adjacent to the modules are also being baked at temperatures up to 450°C. Current operation is at 250 mA, 1.1 and 1.4 MV on cavity 1 and 3 respectively and 160-180 kW forward power per module.

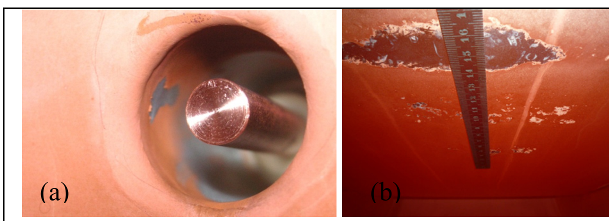

Figure 1: (a) Peeling copper plating around the field pick-ups. (b) Large areas of missing plating in the copper plated waveguide after the RF window.

SSRF became the next and most recent light source to become operational with the CESR cavity design. The cavities were delivered and installed into the test cave in May 2008. At that point it was found that each of the three modules had developed leaks on the ion pump welds in the window region during shipping. Fortunately the module and the pumps were shipped under N2 and the pumps were isolated from the cavity volume by angle valves so the high field regions of the cavities were not compromised. The welds were fixed on site. In September 2008, the modules were installed into the SR and put into operation, Figure 2.

Initial SR commissioning had already taken place using NC cavities due to delays with the cryogenic refrigerator pipework. The design current of 300 mA, was reached in July 2009 during a machine shift. All three cavities were in operation, each operating at 1.7 MV with 128 kW, 166 kW and 190 kW RF power for modules one to three respectively. Shortly thereafter, in September 2009, during a 24 hr machine development shift, 300 mA was stored for 12 hrs in top-up mode following 12 hrs cavity conditioning. The SSRF recorded its longest uninterrupted run > 200 hrs in November 2010.

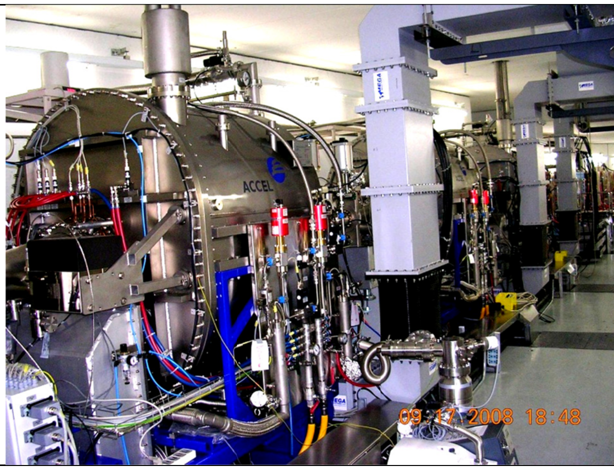

Figure 2: Picture of three installed cavities cryomodules at the SSRF.

Typical operation with users is in decay mode with 210 mA peak, with a total accelerating voltage of 4.5 MV split evenly across the three cavities and a total RF power of 326 kW. Despite early problems with frequent beam trips, the SSRF RF system now operates reliably having achieved an MTBF of 43 hrs in 2009 and 79 hrs in 2010. Many of the early trips were similar to the experience at DLS, including problems with false triggers on the arc detectors, gas spikes in the window region and problems with water flow meters. The trips with a similar fast loss of cavity field have also been observed but no longer appear to be a significant problem. Similar to the experience at DLS, the trip rate appears to increase for higher accelerating voltages, so to minimise the number of beam trips caused by the cavities, the accelerating voltages have been reduced to 1.5 MV and 120 kW per cavity. Pulsed RF conditioning has also been found to be beneficial.

Due to the presence of Q-disease observed on the DLS cavities, which causes the Q_0 to drop if the module is cooled down slowly, some tests were carrying out by RI during the vertical test of the first SSRF module. Figure 3(a) shows how the Q_0 was degraded by the cavity being held at a temperature 70-130 K for 10 hrs. The cause of the Q-decease is generally believed to be an excess of hydrogen in the bulk niobium, therefore to reduce the hydrogen content, the niobium parts were baked in a vacuum furnace at 600°C for 10 hrs. The same Q_0 test, as for SSRF1, by holding the temperature between 70-130 K for 10 hrs, was carried out on SSRF2 after the high temperature bake, with no evidence of any Q_0 degradation or Q-disease. Additionally, on the first cavity, SSRF1, the Q_0 was up from 7×10^8 before the bake to 1.05×10^9 at 8 MV/m after the bake, Figure 3(b).

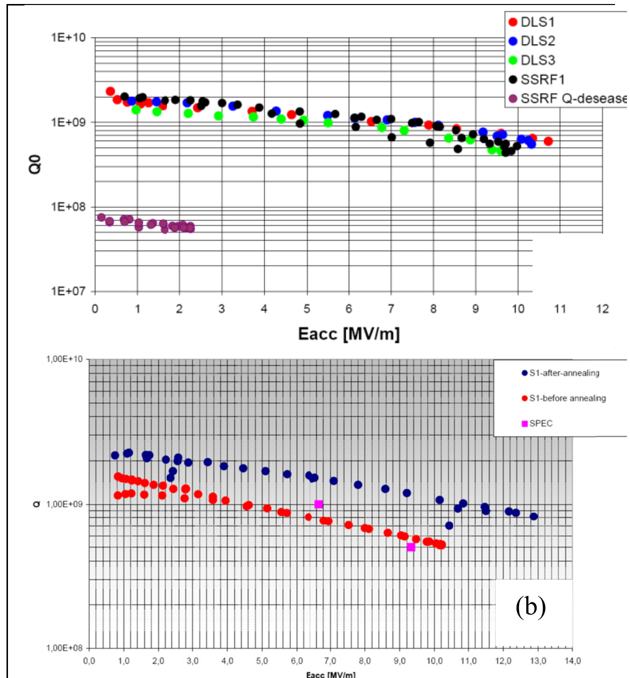

Figure 3: (a) Plot of how the Q_0 degraded on SSRF1 following 10 hrs at a temperature 70 – 130K. (b) Comparison of Q_0 of SSRF1 before and after the high temperature bake

The SOLEIL Cavity Design

The SOLEIL studies started in 1996 with the launch of a cryomodule design in a collaboration between CEA, CNRS, CERN and ESRF. The cavity has a resonant frequency of 352 MHz, predominantly to benefit from the experience from CERN and ESRF [5]. The cryomodule contains two single cell cavities, and unlike the solid niobium CESR design, the Soleil cavity is made of niobium deposited on copper. HOM coupling is achieved with 4 loops connected to external loads placed on the beam pipes to couple to transverse and longitudinal modes. The first prototype was initially tested at CERN without beam and later at ESRF, where it was installed and operated with beam. The first cryomodule was delivered and installed in the SOLEIL SR in 2005. Cool down and conditioning started in May 2006 and by September 2006 SOLEIL had stored 300 mA. Thereafter, as originally planned, SOLEIL operated with the first cryomodule for two years. The second cryomodule was ordered from industry and delivered by ACCEL Instruments in May 2008 and already in November 2008, it had been installed and SOLEIL achieved 455 mA. By 2009, the design current of 500 mA was achieved during machine development shifts and typical operation is currently at 400 mA in top-up mode. The module performance has been good with few cavity trips. Earlier, repeat failures involving the tuner resulted in a tuner re-design. The tuner is mounted in the cold space making maintenance and repair difficult. Initially the cavity voltage was ramped during injection whilst managing the reflected power, such that re-tuning of the cavity was minimised between low current during injection and the final detune required at the target current. Finally, the problematic screw-nut assembly was replaced by a planetary roller screw which offers less friction and is more robust. The upgrade was completed on cryomodule 2 in August 2009 and on cryomodule 1 in January 2010. Since then there have been no further problem with the tuners.

The power couplers on the SOLEIL cryomodules are limited to 200 kW each and a project in collaboration with CERN and ESRF has been started to design and develop power couplers capable for delivering 300 kW to the beam (Figure 4). Compared to the original coupler the main change is to upgrade the ceramic window to an adapted version of the window used on the LHC. The first such prototype is due to be tested at the ESRF by the end of this year. Following the test, the two power couplers on one cryomodule will be changed during the summer shutdown in 2012 and the second module will be upgraded the following year. The new couplers will allow SOLEIL to store the full 500 mA using a single cryomodule.

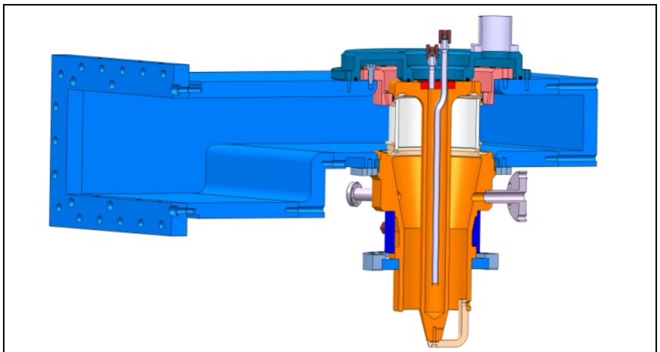

Figure 4: Picture of the new SOLEIL power coupler under development.

The KEK Cavity Design

The BEBC-II at IHEP operates at 500 MHz but other than a modification to reduce the fundamental frequency to 500 MHz, the cavities are nominally identical to the KEK cavities. Two cryomodules, both produced by Mitsubishi Electric Company (MELCO) have been in operation since 2006, although only one is in operation in synchrotron radiation mode and the other module is detuned [10]. Typically BEPC-II in synchrotron radiation mode operates with a cavity voltage of 1.8 MV, 250 mA with a maximum beam power of 92 kW although 313 mA, 115 kW has been demonstrated. To overcome multipactor (MP) on the coupler a DC bias of 1.5 kV is applied.

Recently, IHEP have manufactured and tested a second spare 500 MHz KEK style cavity successfully. The cavity voltage was tested to 2.3 MV with a $Q_0 = 1.2x10^9$ which is an improvement on the first cavity and is well within specification, Figure 5.

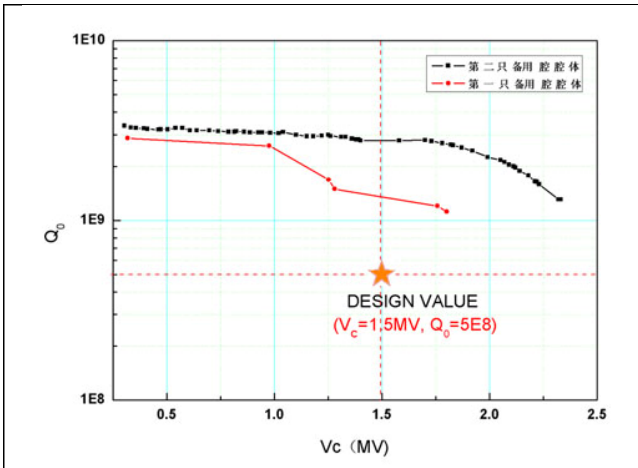

Figure 5: Plot of the Q_0 measurements for the first (red) and most recent (black) cavities manufactured and tested at IHEP.

NEW LIGHT SOURCES

Three new third generation light sources have been designed around SC cavities for the SR and construction has started. They are PLS-II, due to start operation in 2012, TPS due in 2014 and NSLS-II in 2015.

PLS-II is a 3 GeV machine designed for 400 mA. It is being built in stages; stage 1 (July 2011 – July 2012) will be with 5 NC cavities due to the long lead times for the SC cavities and the associated liquid helium refrigerator. Three NC cavities will be replaced by two SC cavities in a single straight in Stage 2. Ultimately it is hoped that budget will be available to replace all the NC cavities with three SC cavities. The SC cavities will be of the CESR cavity design under a contract let to Research Instruments. The cavities will be built with a lower external Q_{ext} of 1.7 (+/- 0.2) x 10^5 to provide a good match at high current without the use of a three stub tuner. The anticipated operating conditions are 1.65 MV and 223 kW per module.

TPS is currently under construction and a contract is in place for two KEK style cavities. The cavities will be operated with 1.4 – 1.7 MV each with a total beam power < 500 kW. The modules are not being manufactured as part of a complete turnkey contract. Mechanical construction, including cell manufacture, is being done by Mitsubishi Heavy Industries (MHI) but then transported to KEK for surface treatment, high pressure rinsing, tuning and conditioning. Finally the cryostats and the associated beam pipe components including tapers, will be sent to NSRRC for final system integration and horizontal test. The limits of responsibility and the level of resource sharing for this construction therefore are very different from a complete turn-key contract. The first cryostat and the beam pipe components will be delivered to NSRRC in March 2012 with two more deliveries in July. System integration is expected to complete by the end of 2013. In the meanwhile, a pair of NC 5-cell Petra cavities will be used for early machine commissioning prior to the installation of the SC cavities in the spring 2014.

The NSLS-II is currently under construction and a contract for the first two modules has been placed. Due to budget constraints, the baseline design contains two SC cavities but ultimately the hope is to install a further two cavities in the future. The base line design assumes that the cavities will be operated at 1.65 MV and deliver up to 270 kW. The modules are being manufactured under a turn-key contract with Advance Energy Systems with a licence agreement with Cornell. The optimum external Q_{ext} of the cavity is lower still than SSRF and PLS-II, and further simulations have been undertaken to modify the coupling tongue of the waveguide coupler to achieve a value of 65000. Figure 6 shows the geometry of the coupling slot for the original Cornell design and the NSLS-II design.

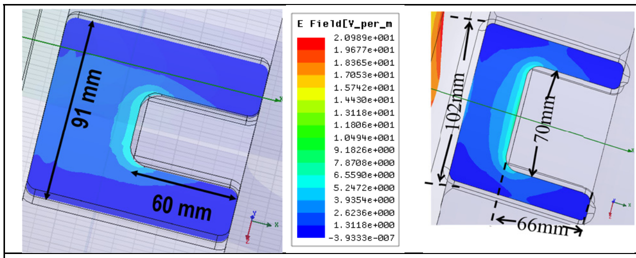

Figure 6. Original Cornell design with Qext = 250k (left) and NSLS-II design with Qext = 65k (right).

The NSLS-II will also have two two-cell SC 3rd harmonic cavities installed to improve lifetime. All parts have been manufactured and the niobium cavity turning is complete.

ON GOING RELEVANT WORK

SR light sources are designed with one principal aim, which is to provide a service to users. Although many of the machines are being built around fairly mature technology, the main focus during operation is to provide a high quality, highly stable and reliable beam. As such much effort is spent to improve the reliability and to reduce the number of beam trips. However, in addition there are a number of other R&D activities in progress. These include numerical modelling including MP simulations, development of horizontal testing to replace the typical vertical testing, horizontal high pressure rinsing, work to reduce fluctuations in the helium bath pressures resulting in phase noise, optimisation of LN2 cooling circuits, improvements to the mechanical tuners, improved arc detection to eliminate false trips, work on beam pipe HOM absorbers [11], work on the effect of DC conductivity of ferrites and high power window development [12]. In addition, work is ongoing to improve the quality of the vacuum systems by improved copper plating, hydrogen degassing of steel vessels, high temperature bake of niobium components and improved coatings, e.g. TiN coating, to reduce the risk of MP.

SUMMARY

Superconducting cavities have been chosen for the fundamental RF system in many of the most recent light sources. There are three main systems in use and further machines are being designed around the existing cavity designs. Despite the often limited R&D budget available for operational light sources, much effort to improve the operational reliability as well as further development and improvements to the auxiliary systems are in progress. Third harmonic cavities have been used successfully to improve lifetime and are being planned for future light sources. The cavity performance, higher order mode threshold stabilities have resulted in machines capable of storing high current and provide reliable beam of exceptional stability and brightness for a vast number of users.

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