SUPERCONDUCTING RF IN STORAGE-RING-BASED LIGHT SOURCES *

S. Belomestnykh#, CLASSE, Cornell University, Ithaca, NY 14850, U.S.A.

Abstract

Third generation synchrotron light sources are small storage rings operating in the energy range of 1.5 to 3.5 GeV. These machines require relatively low total accelerating voltage and high RF power to compensate particle beam energy losses to X-rays. Strong damping of Higher-Order Modes (HOMs) is also necessary for stable operation of high-current multi-bunch beams. Superconducting HOM-damped single-cell cavities are ideal for such applications. Their ability to transfer almost all RF power to the beam and to operate at high accelerating gap voltages reduces the number of installed cavities thus improving overall efficiency of the RF systems. In the past many laboratories were reluctant to use superconducting RF (SRF) technology as it was considered more complex than conventional copper accelerating structures. Proliferation of superconducting insertion devices made having a cryogenic plant the necessity for every contemporary light source thus providing infrastructure for SRF as well. With the successful and reliable operation of HOM-damped cavities at CESR and KEKB, technological developments at CERN and other laboratories and the technology transfer to industry, SRF has become the readily available technology of choice for new and small labs with no prior experience in the field. In this paper we will describe the use of superconducting cavities in fundamental RF systems and as passive structures for bunch lengthening. Operating experience and recent achievements from light sources around the world will be discussed.

INTRODUCTION

There are about 20 third generation light sources in operation around the world and another 10 intermediate energy light sources are in various development stages [1]. These facilities produce and will continue to produce the vast majority of research results in the field of X-ray science for years to come. The third generation intermediate energy light sources are dedicated storage rings operating in the energy range from 1.5 to 3.5 GeV, where high-brightness, stable X-ray beams are generated in insertion devices, wigglers and undulators, by low-emittance short electron bunches. The requirements imposed on RF systems in these user facilities are quite demanding. Although the required total accelerating voltage is relatively low, hundreds of kilowatts of RF power have to be delivered to compensate particle beam energy losses to synchrotron dariation. Strong damping of Higher-Order Modes (HOMs) is also necessary for stable operation of high-current multi-bunch beams. Superconducting HOM-damped single-cell cavities are ideal for such applications. Their ability to transfer almost all RF power to the beam and to operate at high accelerating gap voltages reduces the number of installed cavities thus improving overall efficiency of the RF systems. For more details we refer the readers to previous review papers [2, 3, 4, 5, 6].

While in the past many laboratories were reluctant to use a superior, but "unproven" technology, a qualitative change has happened over the last decade. First, single-cell HOM-damped superconducting cavities, developed for CESR and KEKB and suitable for high-current storage rings, demonstrated stable and reliable operation [7, 8]. Second, the SRF technology was successfully transferred to industry [9] thus becoming readily available as turn key units. Third, other designs were developed via inter-laboratory collaborations [10, 11]. These important developments enabled new and small user facilities with limited resources to use SRF technology, which was previously accessible only to large research laboratories. Several light sources have chosen to employ SRF systems either as main RF systems or as third harmonic systems for bunch lengthening. Recent operating experience with these systems is discussed in subsequent sections.

EXPERIENCE WITH FUNDAMENTAL ACCELEARTING SYSTEMS

Table 1 lists parameters of the fundamental SRF systems in operation or under construction. There are three types of cryomodules in use: CESR-, KEKB- and SOLEIL-type cryomodules.

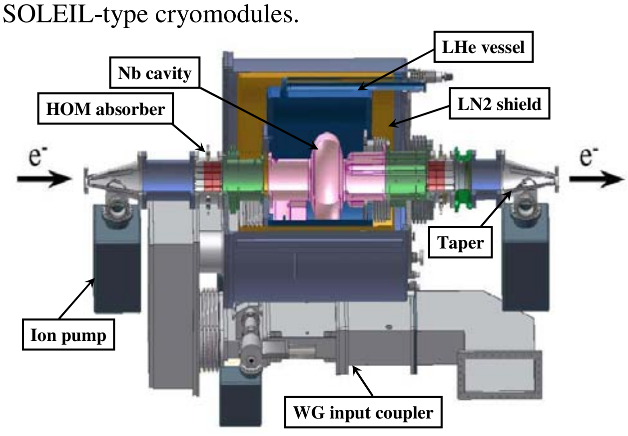

Figure 1: CESR-type cryomodule.

CESR-type cryomodules produced by ACCEL

The Cornell CESR cryomodule, shown in Figure 1, is a single cavity cryomodule with a waveguide input coupler and two beam pipe ferrite HOM load, operating at room temperature. The 500 MHz single cell cavity is made of high RRR niobium sheets and has large beam pipes for higher order modes extraction [12]. Starting in 1997, CESR RF system was gradually upgraded from four

*Work supported by the National Science Foundation
#sab@lepp.cornell.edu

Table 1: Parameters of fundamental SRF systems used in storage-ring-based light sources (CESR-CHESS and BEPC-II are operating as light sources only part time; CESR-CHESS is a second generation light source, all other machines are third generation light sources).

Machine	*CESR-CHESS*	*TLS*	*CLS*	*DIAMOND*	*SSRF*	*BEPC-II*	*SOLEIL*	*NSLS-II*	*TPS*
Cryomodule	CESR-type					KEKB-type	SOLEIL	CESR or KEKB	CESR or KEKB
Beam energy [GeV]	5.3	1.5	2.5 / 2.9	3.0	3.5	2.5	2.75	3.0	3.0 – 3.3
Beam current [mA]	500	500	250 (500)	300 (500)	200 (300)	250	500	500	400
Frequency [MHz]	500	500	500	500	500	500	352	500	500
***R/Q* [Ohm]**	89	89	89	89	89	93	90	–	–
***Q*ext**	1.4×10^5	2.2×10^5	2×10^5	2×10^5	1.7×10^5	1.7×10^5	1×10^5	1.2×10^5 (6.7×10^4)	–
Cavity voltage [MV]	1.3	1.6	2.4	2.0 (1.3)	1.3 (2.0)	1.5	1.1	1.7 (2.5)	0.9 – 1.2
Number of cavities	4	1	1 (2)	2 (3)	3	2	4	4 (2)	4
RF input coupler type	Waveguide	Waveguide	Waveguide	Waveguide	Waveguide	Coaxial antenna	Coaxial antenna	–	–
Power per coupler [kW]	160	82	245	270 (300)	200	96	150	225 (500)	180
HOM damper type	Ferrite beam line	Ferrite beam line	Ferrite beam line	Ferrite beam line	Ferrite beam line	Ferrite beam line	Loop	Ferrite beam line	Ferrite beam line
Status	Operational	Operational	Operational	Operational	Construction	Operational	Operational	Planned	Planned

normal conducting 5-cell copper cavities to four SRF cryomodules and in 1999 CESR has become the first storage-ring based light source to run entirely on superconducting cavities. During the same year a technology transfer agreement was signed between Cornell University and ACCEL allowing industrial production of CESR-type cryomodules. Since then ACCEL has delivered two cryomodules for CESR, two cryomodules for Taiwan Light Source (TLS) at NSRRC laboratory in Taiwan [13], two cryomodules for Canadian Light Source (CLS) [14], three cryomodules for DIAMOND Light Source in UK [15] and two cryomodules for Shanghai Synchrotron Radiation Facility (SSRF) in China [16]. One more cryomodule for SSRF is under assembly.

In 2003 Canadian Light Source has become the first dedicated light source to use superconducting RF for normal operation. At the first stage only one cryomodule was installed in the machine. Most of the problems encountered were typical for the commissioning and initial operation phase of a new facility. Among those problems are input coupler vacuum and arc trips, need for RF conditioning with beam and several partial or complete warm-ups of the cryomodule. After overcoming these initial problems, the storage rings routinely operates now with beam current of 250 mA, accelerating voltage up to 2.4 MV and RF power up to 225 kW. The operation of the SRF system is robust and generally trouble-free. During an early test the beam current of 300 mA was achieved, with 270 kW of RF power. The plan is to begin routine operation at 300 mA soon. Longer term plan includes installation of the second cavity with an additional RF amplifier for 500 mA operation.

Installation of the SRF cryomodule was part of an upgrade project for TLS, which has been operating with normal conducting DORIS cavities since 1982. NSSRC was the first laboratory to order a turn key system from industry. In 2004 the DORIS cavities were replaced with one CESR-type cryomodule. The second module is a spare unit. Upgrading to the SRF system allowed TLS to double the photon intensity by increasing beam current to 300 mA and using top-up injection. During machine studies 400 mA was stored. Lower HOM impedance of the superconducting structure cured longitudinal coupled-bunch instabilities. The system operates reliably with low trip rate.

Three cryomodules were delivered for DIAMOND, two of which were installed in the storage ring (Figure 2) and met the specifications during commissioning without beam. During initial operation though one of the cryomodules developed a leak and had to be removed from the ring for repair so the initial commissioning was performed with only one cryomodule. The second cryomodule was eventually installed during March/April 2007 shutdown. 300 mA beam current was achieved to date although not yet with insertion devices operational.

Figure 2: SRF cryomodule at DIAMOND.

SSRF is still under construction. Two cryomodules have been delivered by ACCEL after cryogenic tests at the factory. RF commissioning/processing is under way. The third cryomodule is scheduled to be delivered in early 2008.

KEKB-type cryomodules at BEPC-II

Institute for High Energy Physics (IHEP) in Beijing, China, has chosen KEKB-type cryomodule for BEPC-II, the upgrade project of the Beijing Electron and Positron Collider. BEPC-II is re-configurable for two modes of operation: a two-ring collider operating at 1.8 GeV per beam and a 2.5 GeV single-ring light source.

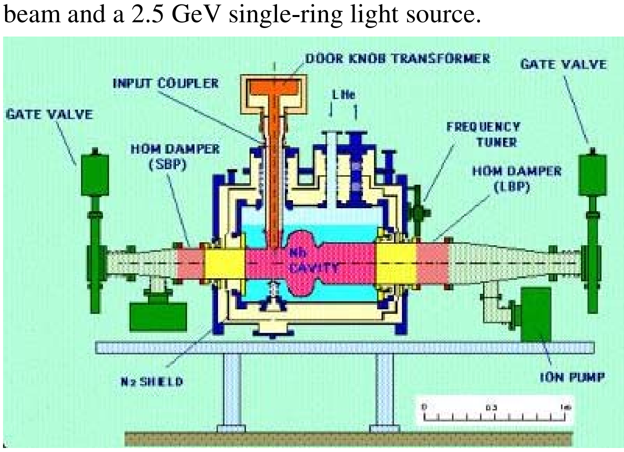

Figure 3: Schematic of the KEKB cryomodule.

KEKB cryomodule contains one single-cell 509 MHz niobium cavity [8]. Main general features of this cryomodule (Figure 3) are similar to those of the CESR cryomodule though specific designs are very different and it has a coaxial rather than waveguide input coupler.

As RF frequency of BEPC-II is different from KEK, the cavity was redesigned from 509 MHz to 500 MHz. All other components were the same as in the KEKB cryomodules. Two cryomodules for BEPC-II were produced by Mitsubishi Electric Company (MELCO) in collaboration with KEK (Figure 4). The vertical cavity tests and high power tests of input couplers and HOM dampers were carried out at KEK. During the final acceptance test at IHEP both cavities has reached accelerating voltage of 2 MV [17].

Figure 4: KEKB cryomodule (blue) and IHEP cryomodule (white).

Upon installation in the ring and commissioning [18], the cavities are operating stably and reliably with the beam current of 180 mA during the user run. 250 mA beam current was stored in a test run.

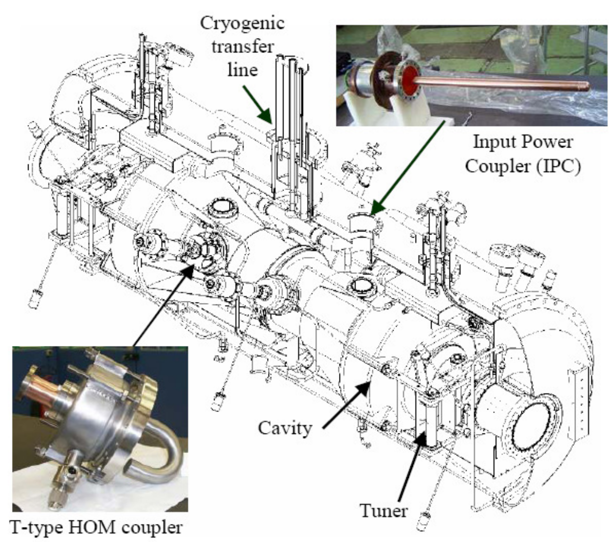

Figure 5: 3D layout of the SOLEIL cryomodule.

SOLEIL cryomodules

The SOLEIL cryomodule was developed by collaboration between CEA, CNRS, CERN and ESRF. The frequency of 352 MHz (LEP RF frequency) was chosen to benefit from transfer of CERN technology, in particular the input coupler design. The cryomodule (Figure 5) houses two single-cell niobium-sputtered-on-copper cavities. Unlike in CESR or KEKB cryomodules, here the HOMs are strongly damped by four loop couplers located on the central large diameter tube between the cavities. Two of the couplers are designed for longitudinal modes and the two others are used for transverse modes [19].

The first cryomodule had been RF conditioned with full reflection up to 200 kW per cavity at CERN and up to 80 kW, once installed in the SOLEIL storage ring (Figure 6). Re-conditioning with beam (in 2006) went quite smoothly: there were only a few coupler vacuum trips, at first when reaching power of approximately 150 kW per cavity. Further conditioning would be likely required for operating at this power level. However, with proper settings, require RF power is less than 145 kW for beam currents up to 300 mA with only one cryomodule installed, which is more demanding than 500 mA with two cryomodules [20]. No evidence of HOM excitation was observed so far.

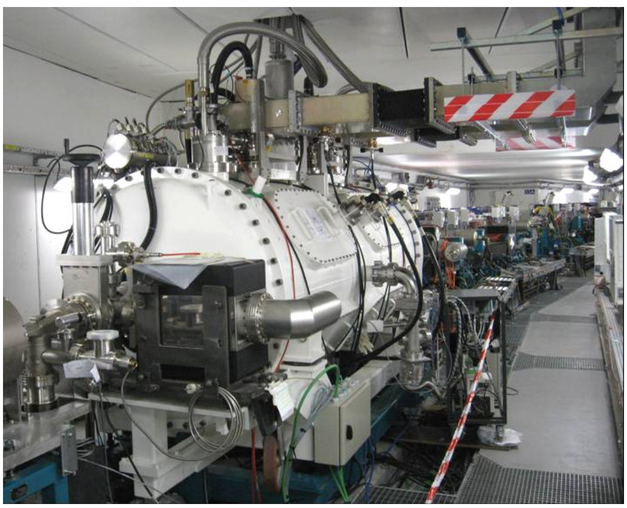

Figure 6: SOLEIL cryomodule in the ring.

The second cryomodule for SOLEIL is on order from ACCEL. The complete cryomodule test is scheduled for the beginning of 2008 at CERN and the installation and commissioning at SOLEIL is planned for May of 2008.

Future projects

Two new projects, NSLS-II (Brookhaven National Lab, USA) and Taiwan Photon Source (NSRRC, Taiwan) plan to use superconducting RF cavities. The base line design of NSLS-II has four CESR-type cryomodules and two third harmonic cavities for bunch lengthening, while considering KEKB design as an option. TPS also has four superconducting cavities in the machine layout though they still have not committed yet to a particular design and may even switch to normal conducting option.

THIRD HARMONIC SYSTEMS FOR BUNCH LENGTHENING

Beam lifetime in storage rings is very often limited by the Touscheck effect (large-angle intra-beam scattering). One of the methods of improving Tousheck lifetime is to reduce the charge density by lengthening the bunches. Passive harmonic cavities are effective instruments for bunch length manipulation and are in use at a number of light sources. Superconducting cavities, having high quality factor and low *R/Q*, enjoy a number of advantages over normal conducting ones, when used in an idle (passive) regime [4, 5].

Two third harmonic superconducting systems are operational at SLS and ELETTRA [21]. The systems have similar design, a "scaled to 1.5 GHz" version of the SOLEIL cryomodule. This SUPER-3HC cryomodule (Figure 7) was developed by collaborating efforts of CEA-DAPNIA-Saclay, PSI and Sincrotrone Trieste [11]. Utilization of the third harmonic SRF cavities allowed both SLS and ELETTRA to improve beam lifetime by factors of 2 to 3.5 depending on machine parameters, vacuum conditions, etc. Additional benefit of the bunch lengthening is suppressing of the longitudinal coupled-bunch instabilities.

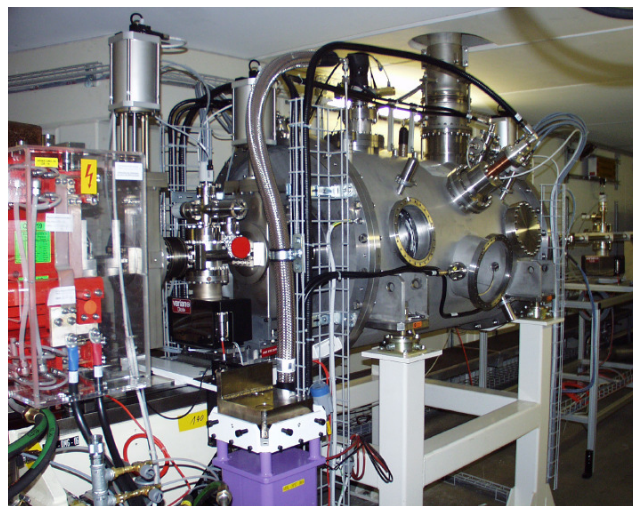

Figure 7: SUPER-3HC cryomodule at SLS.

SUMMARY

Three different reliable and proven superconducting RF cryomodule designs for storage-ring-based light sources exist and can be purchased from industry. Six operational machines (CESR-CHESS, TLS, CLS, SOLEIL, DIAMOND, BEPC-II) use superconducting cavities in their fundamental RF systems. One more facility (SSRF) is under construction. Using passive third harmonic cavities for bunch length manipulation to improve the beam lifetime and suppress longitudinal coupled bunch instabilities is very efficient. First successful applications are at SLS and ELETTRA. Operating and commissioning experience with new SRF systems is in general very positive. The systems are robust, easy to operate and fulfill expectations. More new projects are coming.

ACKNOWLEDGEMENTS

The author would like to thank Ch. Wang (NSRRC), M. Pekeler (ACCEL), P. Marchand (SOLEIL), M. Jensen (DLS), M. de Jong (CLS), G. Wang (IHEP), G. Penco (ELETTRA), J. Liu (SSRF), J. Rose (BNL), A. Anghel (PSI) for the information provided on their facilities.

REFERENCES

[1] Z. T. Zhao, "Commissioning of New Synchrotron Radiation Facilities," *Proceedings of PAC'07*, Albuquerque, NM, USA, p. 17.

[2] H. Padamsee, "Review of Experience with HOM Damped Cavities," *Proceedings of EPAC'98*, Stockholm, Sweden, p. 184.

[3] D. M. Dykes, *et al.*, "Superconducting RF Systems for Light Sources?" *Proceedings of EPAC'00*, Vienna, Austria, p. 2034.

[4] S. Belomestnykh, "Operating Experience with b=1 High Current Accelerators," *Proceedings of SRF'2003 Workshop*, Luebeck, Germany.

[5] P. Marchand, "Superconducting RF Cavities for Synchrotron Light Sources," *Proceedings of EPAC'04*, Lucerne, Switzerland, p. 21.

[6] M. Pekeler, "SRF in Storage Rings," *Proceedings of SRF'2005*, Ithaca, NY, USA, p. 98.

[7] S. Belomestnykh and H. Padamsee, "Performance of the CESR Superconducting RF System and Future Plans," *Proceedings of SRF'2001*, Tsukuba, Japan, p. 197.

[8] K. Akai, *et al*., "RF Systems for the KEK B-Factory," *Nucl. Intr. & Meth*. **A 499** (2003) 45.

[9] M. Pekeler, *et al*., "Production of Superconducting Accelerator Modules for High Current Electron Storage Rings," *Proceedings of EPAC'04*, Lucerne, Switzerland, p. 638.

[10] A. Mosnier, *et al*., "Design of a Heavily Damped Superconducting Cavity for SOLEIL," *Proceedings of PAC'97*, Vancouver, Canada, p. 1709.

[11] M. Svandrlik, *et al*., "The SUPER-3HC Project: an Idle Superconducting Harmonic Cavity for Bunch Length Manipulation," *Proceedings of EPAC'00*, Vienna, Austria, p. 2052.

[12] H. Padamse, *et al*., "Design Challnges for High Current Storage Rings," *Particle Accelerators* **40** (1992) 17.

[13] Ch. Wang, *et al*., "Operational Experience of the Superconducting RF Module at TLS," *Proceedings of SRF'2005*, Ithaca, NY, USA, p. 535.

[14] R. Tanner, *et al*., "Canadian Light Source Storage Ring RF System," *Proceedings of SRF'2005*, Ithaca, NY, USA, p. 532.

[15] M. Jensen, *et al*., "Operational Experience of the DIAMOND SCRF System," *Proceedings of the SRF'2007 Workshop*, Beijing, China, WEP73.

[16] J. Liu and H. Hou, "SSRF Superconducting RF System," *Proceedings of the SRF'2007 Workshop*, Beijing, China, WEP38.

[17] Z. Li, *et al*., "Fabrication and Test of the 500 MHz SC Modules for the BEPC-II," *Proceedings of the SRF'2007 Workshop*, Beijing, China, WEP23.

[18] G. Wang, *et al*., "The Commissioning of BEPC-II RF System," *Proceedings of the SRF'2007 Workshop*, Beijing, China, WEP44.

[19] P. Bosland, *et al*., "Upgrade of the Cryomodule Prototype Before its Implementation in SOLEIL," *Proceedings of EPAC'04*, Lucerne, Switzerland, p. 2329.

[20] C. Madec, "300 mA Stored Beam in SOLEIL," *Proceedings of the SRF'2007 Workshop*, Beijing, China, WEP53.

[21] M. Pedrozzi, *et al*., "First Operational Results of the 3rd Harmonic Superconducting Cavities in SLS and ELETTRA," *Proceedings of PAC'03*, Portland, OR, p. 878.