SUPERCONDUCTING RF CAVITIES FOR SYNCHROTRON LIGHT SOURCES

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Abstract

Super-conducting (s-c) RF systems are already operational or planned at several 3rd generation synchrotron Light Sources (LS). In these machines, which require relatively low RF accelerating voltage and high RF power, the advantage of using the s-c technology essentially resides in the fact that one can achieve an efficient damping of the cavity parasitic Higher Order Modes (HOM) while still maintaining a high fundamental shunt impedance.

Strong damping of the HOM is practically realised following two approaches :

- introducing absorber material inside the cavity cut-off tubes, through which the HOM propagate and are then damped (CESR/KEK designs);
- two-cell cavity with coaxial HOM dampers located on the tube connecting the two cells (SOLEIL design).

SOLEIL type cavities are already operational at 1.5 GHz (3rd harmonic) at the Swiss Light Source (SLS) and ELETTRA. The main RF system (500 MHz) of these machines relies on normal-conducting (n-c) cavities and the purpose of the 3rd harmonic s-c system is to lengthen the bunches in order to improve the electron beam lifetime and stability (additional Landau damping).

Recently, several 3rd generation LS have also planned to use s-c cavities as main accelerating RF systems. The operational conditions of the existing systems as well as the status of the planned ones are reported here.

INTRODUCTION

The electron storage rings of the LS generally require rather modest RF accelerating voltage but quite high RF power. That can usually be achieved with a reasonable number of room temperature copper (n-c) RF cavities while keeping relatively low the dissipation in the cavity walls (typically < 1/3 of the total RF power). This is why, until recently, the LS were all run with n-c RF cavities.

With the search for very high brilliance, higher beam currents are required and one of the main issues of these machines comes from the parasitic impedances of the cavity HOM that can drive multi-bunch instabilities; the lower the ring energy, the more critical the problem. On the existing n-c RF systems, it could be overcome for intensity up to several hundreds of mA, by applying one - or combining several - of the following cures: HOM frequency tuning, passive impedance attenuation, multi-bunch feedbacks, generation of additional damping from "Landau cavities" or proper bunch filling pattern [1-9].

An alternative approach consists in using strongly HOM damped ("HOM free") s-c cavities. SOLEIL was the first LS project adopting that approach and which developed its own design, based on a 352 MHz two-cell-cavity; the HOM are damped by means of coaxial couplers, located on the tubes connecting the 2 cells [10,11]. More recently a few new LS (CLS, NSRRC, Diamond) have adopted the design made at CESR: a 500 MHz single-cell-cavity with ferrite absorbers located inside the cavity cut-off tubes, through which the HOM can propagate and then be damped [12]. Both types of designs proved to be capable of achieving efficient damping of the HOM impedances.

At the KEK B-factory, beam intensity larger than 1A are achieved using another variant of s-c "HOM free" cavity with ferrite absorbers inside the cut-off tubes [13].

The higher achievable accelerating field in the s.c cavities also allows to reduce the number of cavities – provided that the input coupler is capable of transferring the larger amount of power. In return, this could tend to affect the reliability in operation, particularly when the RF system reduces to a single plant. For comparison, most of the LS running with n-c RF cavities can still operate at almost full performance when one of the cavities is out of use.

One also has to consider that the s-c cavities operate at Q_{loaded} of about 10^5 (typically one order of magnitude more than n-c cavities) with nearly zero stability margin in the matched condition at full beam current. As a consequence, fast feedback systems on the fundamental mode are generally required to ensure a Robinson stable operation of the s-c cavities [14, 15].

Another challenge of the new generation of LS is the achievement of extremely high brightness, principally through the reduction of the electron beam transverse dimensions (emittance). Unfortunately, the associated enhancement of the bunch charge density results in significant degradation of the beam lifetime (Touschek scattering). The use of a harmonic RF system for lengthening the bunches is widely regarded as the most efficient way of improving the beam lifetime and stability. This approach has been applied at several places, using n-c cavities (SUPER-ACO, BESSY II, MAX II, ALS) [6]. More recently 3rd harmonic RF systems using s-c cavities (more or less a scaling to 1.5 GHz of the SOLEIL cavity) were implemented in the SLS and ELETTRA [16,17]. It is also planned to install in BESSY II a 1.5 GHz s-c cavity of the CESR type for replacing the existing n-c "Landau cavities" [18]. In all cases, the harmonic systems have significantly improved the LS performance and particularly, they proved to be very efficient for stabilising the multi-bunch instabilities in providing extra Landau damping [6,8].

In the following sections, the results achieved at LS operating s-c RF systems are reported and the status of the planned ones are reviewed for different projects. They are of two types : main accelerating RF systems and harmonic RF systems for bunch lengthening.

S-C MAIN ACCELERATING RF SYSTEMS

The SOLEIL RF cryomodule

Design

In June 1996, during the SOLEIL design phase, a collaboration agreement between CEA, CNRS, CERN and ESRF was concluded to develop, build and test a "HOM free" s-c cavity for the SOLEIL project [10]. The frequency of 352.2 MHz was chosen in order to benefit from a possible transfer of CERN technology, in particular the input power coupler design and to open the possibility of a future implementation at the ESRF.

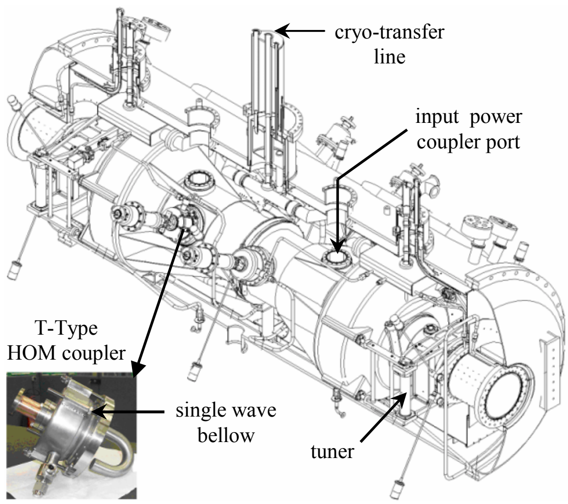

Figure 1: SOLEIL cryomodule and T-type HOM coupler

A 3D-layout of the SOLEIL cryomodule is shown in Figure 1. It consists of a cryostat containing 2 single-cell cavities, made of niobium deposited on copper and enclosed in their tanks where they are immerged in a bath of liquid helium (LHe) at 4.5K. The LHe from the Dewar, enters the cryomodule through a phase separator and then fills up the cavity He tanks from the bottom. On top of each cell a reservoir, acting as a second phase separator, collects the cold He gas (GHe) which is returned back to the refrigerator through the external transfer line. A small fraction of it is used to cool the 4-300 K transition tubes and the input power couplers. A part of the LHe is also derived for the cooling of the HOM couplers.

Each cell has its own frequency tuning system, a mechanism, driven by a stepping motor which changes the cavity length within the limit of elastic deformation (range of ± 150 kHz; accuracy of ~ 1 Hz). The tuning assembly is housed inside the cryostat and works under vacuum and cryogenic environment.

The HOM impedances are strongly damped by means of 4 coaxial couplers, 2 L-type for the longitudinal modes and 2 T-type for the transverse modes, which are located on the central tube (ϕ 400 mm). Both types of HOM couplers are made out of bulk niobium (RRR > 200), cooled with LHe circulating through the loops; their design is rather similar, except for two main specificities :

- different orientation of the coupling loops, as referred to the cavity axis; parallel for the L-type, perpendicular for the T-type;
- only the T-type HOM couplers, which stand closer to the cavity iris, are equipped with a notch filter for rejection of the fundamental mode coupling; an external mechanism and a single wave bellow allows to tune the filter, once the coupler is bolted on the cavity (Fig. 1).

All the HOM impedances are damped largely below the multi-bunch instability thresholds [11,23].

The HOM couplers are connected to external loads through coaxial lines housing a vacuum ceramic window. They are designed to extract up to 5 kW of power.

On the central tube connecting the 2 cavity cells, stand also the main couplers, 2 antennas of the LEP type, from CERN, that will transmit up to 200 kW, each. Before their mounting on the cavities, they are conditioned per pair on a test bench at CERN [19] up to 300 kW in transmission and 200 kW in full reflection.

Experimental results

The prototype of SOLEIL cryomodule was successfully tested up to 7 MV/m, in December 1999, at CERN [20]. End of 2001, it was installed in the ESRF storage ring for a campaign of tests, scheduled over one year, in order to validate the design with high intensity beam [21]. For this limited test period, it was decided to feed the cryostat with LHe from Dewars. The first restart day following each scheduled shutdown (March, May, August and October 2002) was dedicated to the tests at 4K; a pre-cooling with cold GHe during the preceding week allowed to speed up the final cool-downs. After the tests, the cavity was warmed up, kept in the ring at 300K and cooled with warm GHe for the normal user operation, its frequency being thermally shifted off resonance. In warm state, as well as at 4.5K, the (detuned) cavity proved to be transparent for the beam, without any sign of HOM excitation, up to the maximum ESRF current of 200 mA.

In October 2002, the SOLEIL cryomodule contributed to store up to 170 mA, by generating an RF voltage of 3 MV with a power of about 190 kW through each input coupler; 4 MV RF voltage was simultaneously provided by the ESRF n-c cavities.

At voltage above 3.5 MV, overheating of the T-type HOM couplers led to quench-like events with pressure bursts in the LHe tank. The static losses were evaluated at 120 W, 50 % higher than expected.

Strategy and schedule

It is worthwhile to note that the level of performance, achieved at the ESRF by the cryomodule prototype, should allow to store up to 400 mA with a lifetime of more than 30 hours for the phase 1 of SOLEIL (reduced number of insertion devices). On the other hand, the tests pointed out a few weaknesses that could be easily improved before the installation at SOLEIL. It was therefore decided that :

- after refurbishment, the prototype will become the RF cavity of SOLEIL for the commissioning in May 2005;
- a 2nd module will be fabricated and installed early 2006 in order to achieve the requirements for phase 2, with all insertion devices (5 MV of RF voltage , 600 kW of total RF power in the 500 mA beam at 2.75 GeV) [22].

A collaboration agreement was concluded between CEA-Saclay, CERN and SOLEIL for the realisation, during the year 2004, of the refurbishment program, including the following tasks [23]:

- partial re-design and replacement of the T-type HOM couplers (cooling and bellow improvement);
- insertion of a copper thermal shield, cooled with LN2;
- lengthening of the input coupler antennas for better matching to the maximum beam loading conditions;
- partial replacement of the internal instrumentation and He circuitry.

The cryomodule prototype was removed from the ESRF storage ring, by the end of 2002, for transportation to CERN where it has been dismounted in a dust-free environment (Figure 2).

Figure 2: Cryomodule disassembling at CERN

The new HOM couplers as well as the copper thermal shield are under fabrication. All components should be available in Autumn 2004 for the assembling, followed by RF power and cryogenic tests, before the end of the year and the installation on the SOLEIL ring early 2005.

The 2 cryomodules will be supplied in LHe by a single cryo-plant, based on a Helial-2000 refrigerator from Air Liquide, specified to provide simultaneously 40 l/h of liquefaction and 350 W of refrigeration at 4.5K [24].

Each of the 4 cavities will be powered with a 352 MHz solid state amplifier capable to provide 190 kW CW [25]. In phase 1, the cavity RF voltage will be controlled with conventional "slow" frequency, phase and amplitude loops, complemented with a fast RF feed-back on the fundamental mode; fast amplitude and phase loops will be developed for phase 2 [14,15].

The CESR RF cryomodule

Design and performance [12]

The CESR RF cryomodule is another example of "HOM free" s-c cavity. It consists of a cryostat containing a 500 MHz single-cell cavity, made of bulk niobium and immerged in a bath of LHe at 4.5 K (Figure 3). Thanks to the cavity bell shaped geometry and the large diameter (24 cm) of the cut-off tubes, the HOM can propagate and be absorbed in ferrite loads which are housed in the beam tube, outside the cryostat, on both sides of the cavity. In addition, one of the 2 cut-off tubes is "fluted" for ensuring the propagation of the lowest dipole modes towards the absorber. The HOM absorber consists of a stainless steel ring housing 18 water cooled Elkonite plates to which the ferrite tiles are bonded; each plate can handle at least 600 W, that ensures a 10.8 kW dissipation capability per absorber (Figure 3-c).

The RF power is fed into the cavity by means of a waveguide housing a vacuum ceramic window and coupled via a slot in the cut-off tube, next to the cell iris.

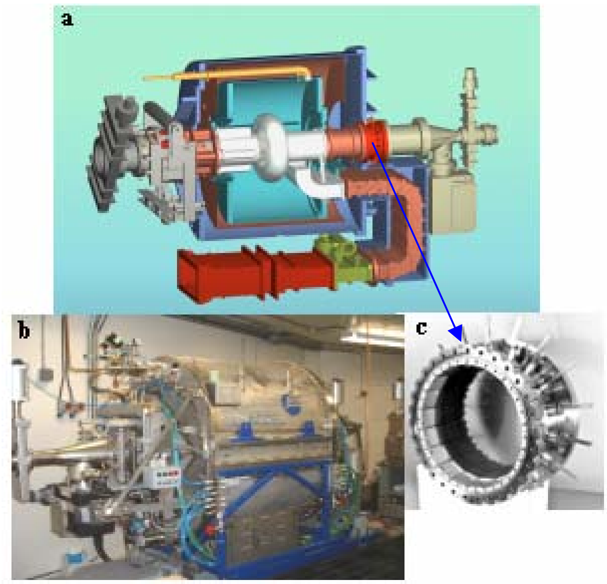

Figure 3: CESR cryomodule (a, b) and ferrite load (c)

Technology transfer to the industry [26]

In 2000, Cornell and ACCEL concluded a technology transfer agreement for the industrial production of two CESR type cryomodules with the goal to extend the use of this technology to other high current storage rings or e-/e+ colliders [27]. The possibility of ordering a "turn-key" product in the industry, together with the successful and reliable operation of the CESR and KEK s-c cavities at high beam current, led a few new LS to adopt this technology. Up to date, nine CESR type cryomodules were thus ordered to ACCEL, two for Cornell, two for the Taiwan Light Source (TLS), two for the Canadian Light Source (CLS) and more recently, three for Diamond. The conditions under which they will operate in these machines are listed in Table 1.

Table 1: Operating conditions for s-c accelerating systems

	Ncell	Energy	Current	E_{acc}	Power
CESR	4	5.3 GeV	0.75 A	6.7 MV/m	350 kW
CLS	1*	2.9 GeV	0.28 A	8 MV/m	250 kW
TLS	1*	1.5 GeV	0.45 A	5.3 MV/m	80 kW
Diamond	2*	3 GeV	0.3 A	6.7 MV/m	280 kW

** + another one available as spare part or for further upgrade*

The cavities are manufactured at ACCEL, shipped to Cornell for tests and measurement of Q_o vs E-field in vertical cryostat, shipped back to ACCEL for complete assembling of the cryomodules; then the RF and cryogenic tests are performed either at Cornell or at the final user laboratory. The measured Q_o at 4.5K and 2.4 MV (8 MV/m) were all around $1.\ 10^9$ [28].

The two cryomodules for Cornell have already been delivered and are operational at CESR [29].

A ceramic window failure at high power occurred on the first TLS cyomodule, due to a wrong coupling caused by a waveguide buckling [30]. It is being repaired while the other one should be soon power tested. The installation and commissioning in TLS is scheduled for the end of 2004.

One of the CLS cryomodule was quickly (~ 40 hours) conditioned up to 2.4 MV with $Q_o = 8\ 10^8$; since October 2003, it is reliably operated at 2 MV for the commissioning of the storage ring. In March 2004, the initial goal of 100 mA stored beam was achieved. The cryo-source is a TCF-50 refrigerator from Linde with a capacity of more than 275 W at 4K [31].

The fabrication of the other cryomodules is under progress at ACCEL.

S-C HARMONIC RF SYSTEMS

Electron beam lifetime and stability in LS

In the 3rd generation LS, the high brightness is achieved at the expense of a reduction of the electron beam lifetime through Touschek scattering that can be compensated essentially following two approaches: either enlarging the energy acceptance by increasing the RF voltage, but the transverse energy acceptance becomes then the limiting factor, or reducing the charge density by lengthening the bunches. The two methods were compared as possible upgrades of the SLS [32]. It was proposed to complement the existing 500 MHz n-c system with a passive (beam-driven) s-c cavity operating either at 500 MHz for enlarging the energy acceptance or at 1.5 GHz (3rd harmonic) for lengthening the bunches. In both cases, the beam powering is fully achieved by the n-c system and the passive s-c cavities only contribute to the potential well for bunch lengthening (or shortening). This separation of the functions allows to optimise the performance of each system.

Such a scheme, in its bunch shortening version, was first proposed in 1990 for the projects of European B-factory [33-35]. The principle was recently experimented with success at CESR, where one of the four installed s-c cavities was operated in passive mode for shortening the bunches [36].

For the LS, the other alternative, which consists in lengthening the bunches with a harmonic RF system, is regarded as the most attractive solution, with multiple beneficial effects :

- increase in electron beam lifetime;
- generation of additional Laudau damping through the non linearity of the RF voltage, that contributes to stabilise the beam;
- increase of the current threshold for microwave instability which is a source of energy spread;
- bunch shortening as an option (if needed).

This approach was applied at several LS, using n-c cavities [6] and more recently passive 3rd harmonic s-c cavities were successfully implemented at SLS and ELETTRA where they are routinely operated [8,37].

For such application, s-c cavities with very high Q_o, present significant advantages [32]:

- fewer cavities (with lower R/Q but higher impedance);
- no extra power to be supplied by the main RF system;
- easier to make "invisible for the beam" by detuning;
- wider Robinson stability range (towards lower I_{beam});
- weaker transient beam loading effects [38].

The SUPER-3HC cryomodule (S3HC)

Design and fabrication

After investigation of the different possible ways of improving the electron beam lifetime and stability in the SLS [32] and ELETTRA [39], the two laboratories decided to adopt a common approach: complement their existing 500 MHz n-c RF systems (4 single-cell cavities) with a 3rd harmonic system, based on the use of a s-c cavity of the SOLEIL type, "scaled to 1.5 GHz" and operated in passive mode. Within this context, in October 1999, Sincrotrone Trieste, PSI and CEA-DAPNIA-Saclay concluded a collaboration agreement, the so-called SUPER-3HC project, with the objectives to design and build two complete cryomodules, one for SLS and one for ELETTRA [16].

The S3HC design is more or less a scaling to 1.5 GHz of the SOLEIL cryomodule, previously described. The major changes from the original design are:

- a more stringent specification on the HOM damping that finally led to the implementation of two additional D-type HOM couplers (total of 4 T-type + 2 L-type per cryomodule); this involved new computer simulations and optimisation on a copper cavity model before launching the fabrication [40];
- the HOM couplers are only conduction-cooled at 4.5K (no He circulation);
- thermal shield, cooled with a circulation of GHe;
- no input power coupler (operation in passive mode).

The Nb/Cu cavities were fabricated and measured in a vertical cryostat at CERN. Q_o at 4.5K and 5 MV/m was above 1.10^8 for the 4 cells. Then the complete cryo-modules were assembled (Fig. 4) and tested (cryogenics and RF) at Saclay before shipment to SLS and ELETTRA.

The S3HC cryo-plant [41] is based on a Helial-1000 refrigerator from Air Liquide which can provide simultaneously 10 l/h of LHe and 150 W of refrigeration.

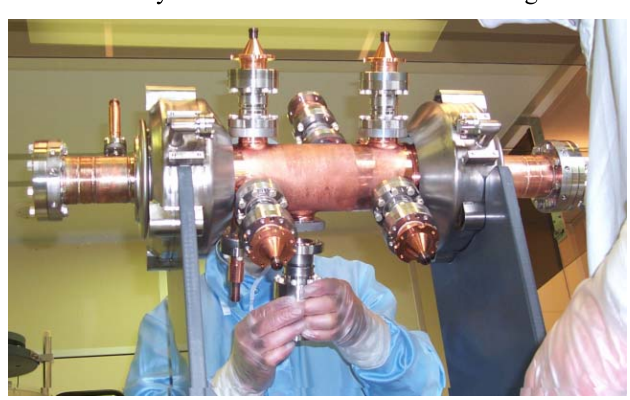

Figure 4 : S3HC cavity assembling at CEA

Commissioning and operation [8,37]

At both ELETTRA and SLS, S3HC first was operated "warm and detuned" with GHe cooling. This cooling was not effective enough to prevent temperature run-away effects that led to a Robinson instability, driven by the S3HC fundamental mode above 200 mA at SLS. Due to the same effect, ELETTRA had to be run for a few months at 2.4 GeV – 140 mA, instead of the scheduled 2 GeV – 300 mA user shifts.

Table 2 shows typical S3HC operating conditions at 4.5K.

	V_{1h}	V_{3h}	I_{beam}	δf	K_τ
SLS	2.1 MV	700 kV	0.32 A	60 kHz	2.2
ELETTRA	1.8 MV	600 kV	0.32 A	70 kHz	3

V_{1h} is the main RF voltage at f_{RF} = 500 MHz; the beam induced voltage in S3HC, $V_{3h} = (R/Q)\ I_{beam}\ 3\ f_{RF}\ /\ \delta f$, is controllable via the detuning, δf ($\delta f >> 3\ f_{RF}\ /\ Q_o$) by acting on the tuner; R/Q = 2 x 45 Ω.

The achieved performance at 4.5K is excellent for both machines: a lifetime increase factor K_τ of 2.2 at SLS, of 3 at ELETTRA and complete suppression of the longitudinal multi-bunch instability up to 400 mA at SLS (2.4 GeV), up to 320 mA at ELETTRA (2 GeV).

The transient beam loading due to the gap of empty buckets, created in the bunch train for ion-clearing, remains relatively low, as expected from a s-c system. The resulting modulation of phase and bunch length along the train (~ 35° and 40 ps, resp.) does not affect too much the gain in lifetime and contributes to Landau damping.

S3HC, which is now routinely operated at SLS and ELETTRA, has demonstrated that it is very effective for improving the beam lifetime and stability; it has also proved to be very flexible and easy to operate although both machines encountered "teething problems" with the cryo-plants, in particular turbine failures and ELETTRA had some trouble with the tuning system [37,42].

1.5 GHz CESR type cryomodule for BESSY II

In order to improve the performance of BESSY II, it is planned to replace the existing n-c Landau cavities by a CESR type cryomodule, scaled to 1.5 GHz. The s-c cavity is provided by Cornell and the cryostat is being fabricated and assembled by ACCEL [18,43].

CONCLUSION

Recently, the s-c RF technology came into the 3rd generation LS, as well for main accelerating systems as for harmonic systems. When compared to n.c cavities which, with proper cures against the HOM excitation, are running at many LS, HOM free s-c cavities are regarded as an attractive alternative, provided they prove to be as reliable in operation as the n-c version. In particular, the reliability of the medium power refrigerators, presently available on the market, is a key issue.

The advantages of using s-c systems for the bunch lengthening purpose are more evident. Their efficiency in improving the beam lifetime and stability was fully demonstrated at SLS and ELETTRA. Although the reliability of the cryo-plant is also important in this case, it is less critical since, in case of cryogenic system failure, the operation remains possible, at reduced performance, with the harmonic system in "warm and detuned" state.

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