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OPERATIONAL EXPERIENCE WITH THE SOLEIL SUPERCONDUCTING RF SYSTEM

L. Nadolski, P. Marchand, J.P. Baete, R. Cuoq, H. Dias, M. Diop, J. Labelle, R. Lopes, M. Louvet, C. Monnot, S. Petit, F. Ribeiro, T. Ruan, R. Sreedharan, K. Tavakoli,
Synchrotron SOLEIL, Gif-Sur-Yvette, France

Abstract

In the SOLEIL storage ring (SR), two cryomodules provide to the electron beam an accelerating voltage of 3 - 4 MV and a power of 575 kW at 352 MHz. Each of them contains a pair of superconducting (SC) cavities, cooled with liquid helium at 4.5 K, which is supplied by a single 350 W cryogenic plant. The RF power is provided by four solid state amplifiers, each delivering up to 180 kW. The parasitic impedances of the high order modes (HOM) are strongly mitigated by means of four coaxial couplers, located on the central pipe connecting the two cavities. Eight years of operational experience with this system, as well as its upgrades, are reported.

INTRODUCTION

In the SOLEIL storage ring (SR), two cryomodules (CM's) provide the required 352 MHz voltage of 3 - 4 MV and power of 575 kW at the nominal energy of 2.75 GeV with the full beam current of 500 mA and all the insertion devices. Each CM contains two 352 MHz SC single-cell cavities, made of copper with a niobium deposit and cooled with liquid helium (LHe) at 4.5 K. Each cavity has its own frequency tuning, a mechanism driven by a stepping motor, which changes the cavity length. The HOM impedances are strongly damped thanks to four couplers of coaxial type, terminated with a loop (two for the monopole modes, two for the dipole modes) and located on the central tube that connects the two cavities. On the central tube, stand also the input power couplers (IPC's), two antennas of the LEP2 type, from CERN, which can transmit up to 200 kW CW.

Each of the four SR cavities is powered by a 180 kW SSA, developed in house [1], which is a combination of four 45 kW towers; the tower itself consists in a combination of 180 amplifier modules of 300 W with LDMOS transistors and integrated circulators.

A single cryogenic plant supplies both CM's in LHe and LN_2. It is based on a HELIAL 2000 unit from Air Liquide, operated in a dual liquefier/refrigerator mode [2].

One fully analog low level RF system is dedicated to each cavity [3]. It comprises three relatively slow loops, which control the cavity resonant frequency and its accelerating field in amplitude and phase; besides a fast direct RF feedback copes with the Robinson instability at high current. This system can ensure a cavity voltage stability of $\pm$ 0.1% in amplitude and 0.03 degree in phase.

More detailed descriptions of the equipment, as well as reporting about the commissioning and phase 1 operation using a single CM can be found in references [4, 5].

EIGHT YEARS OF OPERATIONAL EXPERIENCE AND UPGRADES

Cure of the CM Frequency Tuner Weakness

The main difficulty that was encountered with the SR RF system came after about two years of operation from repetitive jamming's of the CM frequency tuning mechanism. Fortunately, the impact on the user runs remained quite marginal. The tuning device consists of a double lever and a screw-nut assembly, driven by a stepper motor with a gear box, which changes the cavity length. This system is fully housed inside the CM, where it works under vacuum and at cryogenic temperature. The original version was using a standard screw, made of Copper - Beryllium with a lubricant surface treatment, compatible with vacuum and cryogenic environment and a Harmonic Drive type gear box. The repetitive failures, in spite of a few cure trials (change in screw-nut threads and backlash), led us to develop a new version, based on more suitable components. Indeed the combination of a "planetary roller screw" (fig. 1 - left) with a "planetary gear box" (fig. 1 - right) was validated after an endurance run equivalent to more than 20 years of SOLEIL operation, in the CryHolab test bench at CEA. The upgraded tuners were implemented inside each CM in 2009 and since then they have run without any failure.

Figure 1: Planetary roller screw (left) and planetary gear box (right).

Towards More Powerful IPCs

The cavity IPC is another component of the CM which was subject to R&D. The original version is a LEP2 type antenna [6], which consists of a waveguide to coaxial transition with a doorknob and a cylindrical vacuum ceramic window (fig. 2 - left). It can handle up to 200 kW CW. The cooling is ensured by a fan forcing the air circulating through the antenna and by returning the cold gas from the cavity He tank through the double wall of the outer tube. An improved version of this design, capable of transmitting higher power, was later developed by CERN at 400 MHz for the LHC [7]. That led us to conclude in 2011 a collaboration agreement with CERN and ESRF to develop a new 352 MHz version, based on the LHC design and capable of handling up to 300 kW.

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Two other events have motivated this decision. Firstly, problems of ceramic aging were encountered at the ESRF, where LEP type IPC's are also in use [8]. Secondly, occurrences of discharge were experienced in one of the SOLEIL IPC's, at a rate of about once a week, when operating above 120 kW; although that was not detrimental insofar as the beam current was limited at 430 mA in user runs, it might disturb the future routine operation at 500 mA. Furthermore the ability of feeding up to 300 kW per cavity will open the option to SOLEIL of storing 500 mA using a single CM and consequently of taking benefit of the resulting redundancy.

In April 2013 the first pair of upgraded IPC's (fig. 2 - right), built at CERN for SOLEIL, was successfully conditioned with RF power in the ESRF test-stand, using a copper cavity from CERN as shown in fig. 3. The following performance was achieved: 300 kW CW, transmitted through each IPC into a water cooled dummy load; 200 kW CW and 365 kW in 160 µs pulses fully reflected with a short circuit plate.

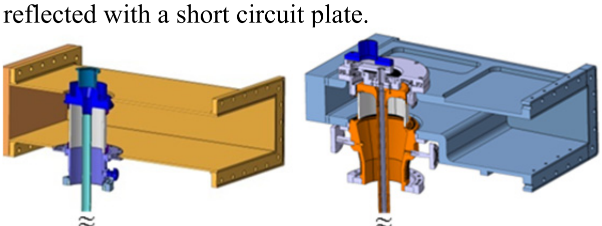

Figure 2: Original (left) and new (right) version of the SOLEIL cavity IPC.

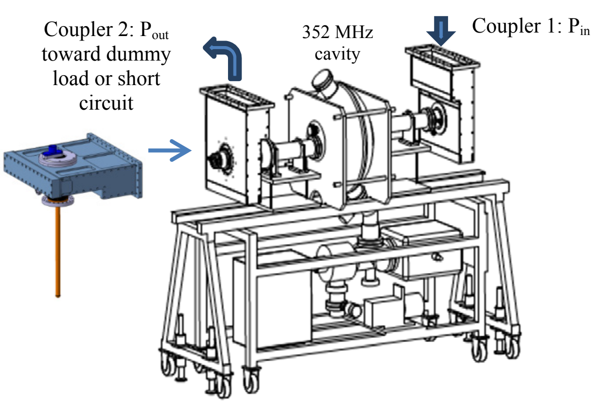

Figure 3: Layout of the coupler test bench.

Note that the antenna of the new IPC's is lengthened by 1 cm in order to double the coupling factor and hence match the optimum operating condition at 500 mA, which is actually obtained with an accelerating voltage of 3 MV (750 kV / cavity) instead of 4.4 MV as initially predicted.

During the scheduled SOLEIL shutdown in August 2013, one of the conditioned IPC was mounted on CM1 cavity-2. That was performed in situ, without removing the CM out of the ring, under external laminar air flow and slight N_2 gas overpressure inside the cavity. Then after a few days of RF conditioning the cavity could provide up to 1.5 MV with 150 kW CW in full reflection, limited by the power amplifier. End of August when restarting the operation with beam, we could store quickly up to 500 mA. Nevertheless, after about one week of operation, multipacting process occurred around 110 kW, sometimes leading to vacuum interlocks. During the user sessions, the corresponding cavity was operated below this level, compensating with the other ones. After two successive reconditioning during shutdown periods, the same scenario repeated itself: no problem at the beginning of the following run, then a kind of “de-conditioning” after a couple of weeks. This was cured by implementing a device which enables to generate a DC bias voltage at the ceramic window location, aimed at destroying the multipacting resonant conditions. The multipacting indeed fully disappeared when applying a DC voltage above 1 kV.

The exchange of the 2nd IPC of CM1 is scheduled for the shutdown of August 2014 and the next pair, presently under fabrication at CERN, on CM2 in January 2015.

Success of the SSA Technology

The SOLEIL decision of using SSA's, instead of the usual vacuum tubes (klystron or IOT), for providing the high CW 352 MHz power required in its SR (4 x 180 kW), was quite innovative and challenging. So far, after about 45 000 running hours on CM1 and 35 000 on CM2, the four SSA's of the SR have proved themselves, featuring an outstanding reliability with a MTBF of 1.5 year (for the four amplifiers), which has largely contributed in the achievement of high beam availability for the users [9].

The module failure rate is about 3.5% a year, divided up in two kinds, transistor breakdowns and damaged soldering by thermal fatigue effects; they are distributed as shown in fig. 4. After the starting period, affected by the “infant mortality”, the transistor failure rate has stabilized itself around 1%. In 2011, after 5 years of operation, as the soldering failure rate was becoming significant, we decided to carry out a preventive maintenance, consisting in re-soldering the transistor output leads in each amplifier module; that explained the steep decrease of this type of failure afterwards.

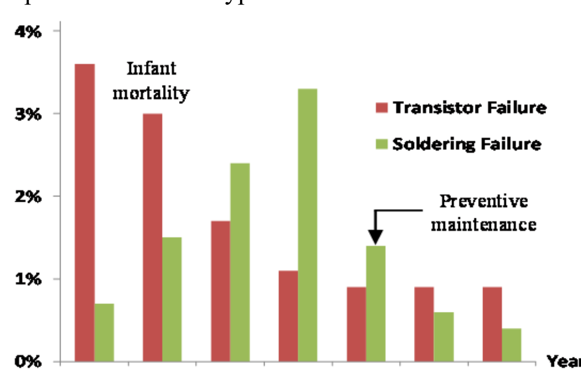

Figure 4: Amplifier module (LR301) failure distribution.

It is worthwhile mentioning that, thanks to the intrinsic modularity and redundancy of the design, these module failures do not impact the operation; it is only a matter of

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maintenance, typically 2 men . weeks of manpower and 5 k€ of repairing cost per year for the 4 SR SSA's.

Although that remains quite acceptable, we recently decided to take advantage of using a transistor of 6th generation, the BLF54XR from NXP, which is much more robust and has higher performance than the LR301 (Table 1). The module modification consists in replacing the transistors and a few matching components on the PCB. The cabling of the existing DC power supplies must also be modified in order to provide each module with 50 V instead of 28 V.

This upgrade process has already started. In 2013 we modified the 160 preamplifier modules (1st, 2nd and 3rd stages) of our 4 amplifiers. Then we intend to go on with the 4th stages at a rate of about 2 towers a year; the first one is scheduled for August 2014.

The electrical power savings resulting from the higher efficiency and lower number of preamplifier modules (larger gain) shall compensate for the investment cost after less than 4 years of operation. We also expect a significant reduction of the failure rate and therefore savings in maintenance costs. Moreover, the power capability of our SSA's will be significantly increased and thus provides additional operational flexibility, as for instance storing 500 mA with 3 out of 4 cavities.

Table 1: LR301 vs BLF574XR Performance

Parameters	LR301	BLF574XR	Benefits of BLF574XR
P_{nom}	315 W	330 W	
P_{max}	330 W	450 W	more powerful
Gain	13.5	20	less preamplifiers
Efficiency	62 %	68 %	better efficiency
Gain spread	± 0.8 dB	± 0.2 dB	no sorting
Phase spread	± 7.5°	± 2.5°	better combining efficiency
T_{max}	130 °C	80 °C	less thermal stress

CONCLUSION

The RF system of the SOLEIL SR is quite innovative and challenging with the use of SSA's and HOM free SC cavities, both developed in house. After more than 8 years of operation, it has demonstrated outstanding availability, reliability and flexibility [9]. A beam current of 430 mA in multibunch hybrid mode with top-up injection is routinely delivered to the users. The operation at the maximum current of 500 mA is already validated in uniform filling while in hybrid mode it is still limited by fast ion instabilities [10, 11, 12].

The difficulties encountered with the CM frequency tuners had only minor impact on the user operation and were quickly overcome by improving the initial device.

Cavity IPC's of higher power capability, have been developed. After a validation test at full power of 300 kW in CW, the first one has been recently implemented on cavity-2 of CM1 and it is working quite satisfactorily when applying a 1 kV DC bias voltage for curing a recalcitrant multipacting level; the three other cavities will be equipped as well in 2014 and 2015.

Upgrades of the cryogenic system for improving its autonomy and reliability are also under way [2].

A special emphasis is put on the success of the SSA technology, which has demonstrated that it could advantageously replace the vacuum tubes in such an application, thanks in particular to its extreme modularity and the resulting redundancy, the absence of high voltage and its very low phase noise. It is fully expanding, now adopted by several other laboratories [13-18] and taken up by the industry. SOLEIL is thus involved in several collaborations and transfers of know-how [19]. The French company, SIGMAPHI ELECTRONICS is SOLEIL licensee since December 2013.

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They also express their deepest respect and gratitude to Ti Ruan who passed away end of March 2014. He was **the** pioneer in the domain of high power RF SSA's, which would not have had such a fast expansion and success without his precursor work.

Ti Ruan
1936 - 2014

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