OPERATIONAL EXPERIENCE WITH THE SOLEIL SUPERCONDUCTING RF SYSTEM

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Abstract

In the SOLEIL storage ring, two cryomodules provide to the electron beam an accelerating voltage of 3-4 MV and a power of 575 kW at 352 MHz. Each cryomodule contains a pair of superconducting 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. Seven years of operational experience with this system, as well as its upgrades, are reported.

INTRODUCTION

During the SOLEIL design phase, it was decided that the RF system of the storage ring (SR) will be based on the use of "HOM free" superconducting (s-c) cavities in order to optimise the transfer of power to the beam and prevent coupled bunch instabilities that could be driven by parasitic HOM's of the RF cavities. Besides, 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 (IPC) design and open the possibility of a future implementation at ESRF [1, 2].

In 1996, a collaboration agreement between CEA, CNRS and CERN was concluded for the design, fabrication and test of a cryomodule (CM) prototype.

End of 1999, during the first power tests at CERN, the CM prototype housing two 352 MHz s-c cavities could provide an accelerating gradient of 7 MV/m with 120 kW (fully reflected) through each IPC [3].

In 2001, the CM prototype was installed on the ESRF SR in order to validate its performance in high intensity beam. The results were quite satisfying : with 3 MV of accelerating voltage and 190 kW of RF power through each cavity IPC, it contributed to store up to 180 mA of electron beam at 6 GeV [4].

On one hand, the achieved performance met the SOLEIL requirement for the 1st phase of operation (stored beam current of 300 mA and reduced number of insertion devices); on the other hand, these tests pointed out a few weak points that could be improved before the installation in the SOLEIL SR. Therefore, it was decided that, after a refurbishment [5], the prototype will become the CM n°1 (CM1) of SOLEIL, the only one for the 1st phase of operation. Modifications of the IPC's and dipolar HOM couplers as well as the replacement of the internal instrumentation and of the cryogenic manifold with the insertion of a LN_2 cooled copper shield, required full disassembling, reassembling and testing of the CM. That was carried out, using the clean room and power test-stand at CERN, where, beginning of 2005, each IPC was conditioned up to 200 kW CW with full reflection and an accelerating voltage of more than 2.5 MV was achieved in each cavity [6]. Finally, the CM n°1 was delivered at SOLEIL and installed in the SR by the end of 2005.

In the meantime, another CM, identical to the modified prototype, was ordered to ACCEL (now RI), to be implemented in a 2nd phase for storing up to 500 mA.

Each cavity is powered with a 180 kW solid state amplifier (SSA), developed in house [7] and both CM are fed in liquid Helium (LHe) and Nitrogen (LN_2) from a single cryogenic plant, supplied by Air Liquide [8].

In the next sections, we review the SR RF equipment and report about the operational experience.

DESCRIPTION OF THE RF EQUIPMENT

Cryomodule [6, 9]

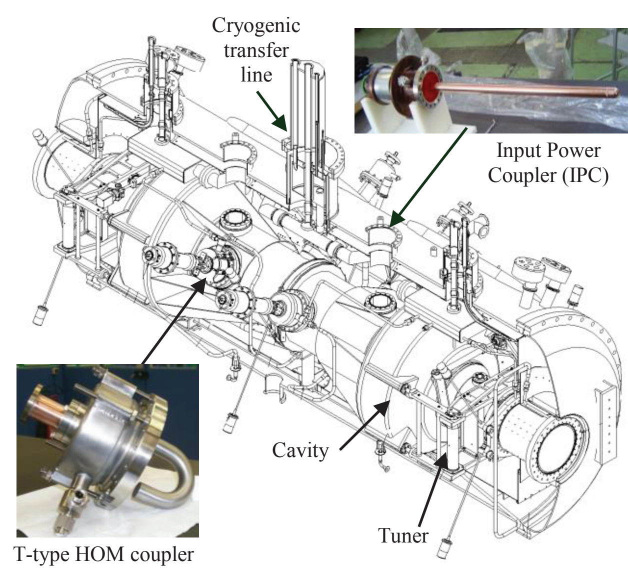

Figure 1: 3D-layout of the SOLEIL cryomodule.

A 3D-layout of the SOLEIL CM is shown in fig. 1. It consists of a cryostat which contains two 352 MHz single-cell cavities, made of copper with a Niobium deposit and enclosed in their tanks where they are immerged in a LHe bath at 4.5 K. Each cell has its own frequency tuning, a mechanism driven by a stepping motor, which changes the cavity length. The tuning assembly is housed inside the CM, where it works under vacuum and in cryogenics environment.

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The HOM impedances are strongly damped thanks to four couplers of coaxial type, terminated with a loop (2 L-type for the monopole, 2 T-type for the dipole modes) and located on the central tube that connects the 2 cavities. Both type of HOM couplers are made of bulk Niobium and cooled with LHe circulating through the loop. Their design is rather similar except for two main specificities : different orientations of the coupling loop as referred to the cavity axis (parallel for L-type, perpendicular for T-type); only the T-type ones, which stand closer to the cavity iris, are equipped with a tunable notch filter for the rejection of the fundamental mode (fig. 1).

On the central tube, stand also the IPC's, two antennas of the LEP2 type, from CERN, which can transmit up to 200 kW CW. Fig. 2-t shows the CM1 in the SOLEIL SR.

Cryogenic Plant

A single cryogenic plant supplies in LHe and LN_2 both CM's. It is based on the use of a HELIAL 2000 from Air Liquide, operated in a mixed mode, liquefier/refrigerator. The cold box unit, a 2000 litre LHe Dewar, the cryogenic valve box for distributing the LHe and LN_2 towards each CM and the manifold for warm gas return are located in the technical gallery of the accelerator building. The compressor plant is housed in a dedicated room of the utilities building and nearby, outdoors, stand two 50 m^3 GHe buffers. More details about the cryogenic system, its performance and upgrading phases are reported in [8].

180 kW Solid State Amplifiers (SSA's)

Each of the four SR cavities is powered by a 180 kW SSA, which is a combination of four 45 kW towers (fig. 2-b) [7]. The tower itself consists in a combination of 180 amplifier modules of 300 W with LDMOS transistors and integrated circulators. The amplifier modules and their individual 28 V dc power supplies are bolded on both sides of water cooled dissipaters. The components for the power splitting and recombination stand in the centre of the tower. All the SSA components were designed in house and then the mass production was contracted to the industry; the assembly was also performed by SOLEIL.

Low Level RF System

One fully analog low level RF (LLRF) system is dedicated to each cavity [10]. That comprises three relatively slow loops which control the cavity resonant frequency and accelerating field, in amplitude and phase; besides a fast direct RF feedback copes with the Robinson instability at high beam current (see next section). This LLRF system can ensure a cavity voltage stability of ± 0.1 % in amplitude and 0.03 degree in phase. Similar performance was achieved with a LLRF unit using a FPGA and a I/Q modulation [11].

COMMISSIONING AND PHASE 1

During summer 2006, one half of the SR RF system (CM1, 2 SSA's, the associated cryogenic plant, control and LLRF systems) was commissioned, as scheduled for the first phase of SOLEIL with I_{beam} < 300 mA and a reduced number of insertion devices [12].

At the beginning of the commissioning, difficulties were encountered with the cryogenic system, in particular with pressure instabilities inside the cavity He tank, due to thermal oscillations. After a few slight modifications on the cryogenic valve box, the system has become very reliable and the pressure variations could be kept below ± 1 mbar, namely ± 0.1° in phase. Then the goal of storing up to 300 mA of stable beam, using a single CM, was quickly achieved [13].

At first, without RF feedback and with the tuning loop automatically set for full compensation of the reactive beam loading, the beam was lost at a current threshold of 230 mA, which is the theoretical Robinson stability limit under such conditions. That could be easily overcome by introducing a small tuning angle offset of 4°, at the expense of some extra power : at 300 mA, with 1 MV on each cavity, 145 kW incident power, of which 10 kW reflected (1 kW from mismatch + 9 kW from detuning). Later on, the implementation of the RF feedback enabled to store up to 300 mA of stable beam without any tuning offset, hence saving 9 kW of reflected power.

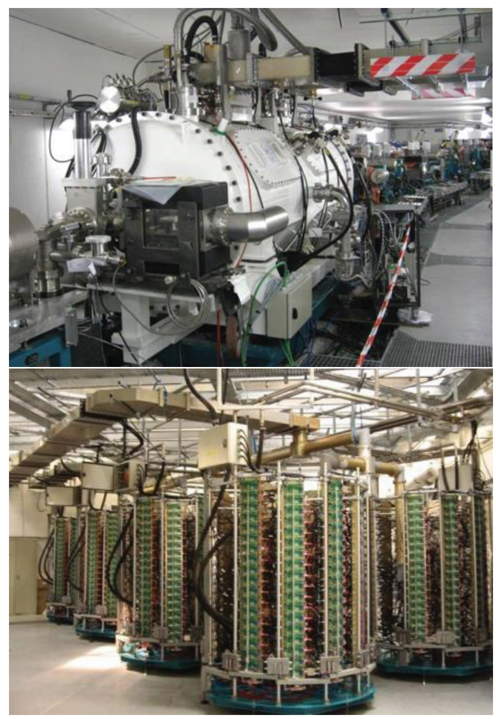

Figure 2: CM1 (t) and its two 180 kW SSA's (b).

Injection at Constant Tuning

The blue plot of fig. 3 shows the required RF power versus beam current for a cavity voltage of 1 MV, with the tuning loop continually active, compensating for the reactive beam loading: 28 kW, fully reflected (from mismatch) at 0-current, up to 135 kW at 300 mA (matched and tuned). Under these conditions, frequency changes of ~ 4 kHz, corresponding to about 10 000 motor steps, are required at each injection.

Considering the difficulties encountered on the Super-3HC cavities at ELETTRA with a similar tuning system, which happened to get stuck after roughly fifty millions of motor steps [14], we early anticipated a possible issue. We therefore decided to develop an upgraded version of the tuner (see next section) and in the meantime to operate at constant tuning during the injection, in order to use the tuners more sparingly [12]. However, as shown by the graph of fig. 3, injecting at constant tuning requires a ramping of the voltage; otherwise this would result in too large amount of reflected power at low beam current (red/black plots). Ramping the cavity voltage from 650 kV at 0-current, up to 1.4 MV at 300 mA, with a fixed tuning angle of 60°, allows to maintain the reflected power below 50 kW and the maximum required power at 145 kW (green plot). In return, with an overall voltage as low as 1.3 MV (650 kV per cavity), the energy and phase acceptance are significantly reduced [15]. Indeed, the experience has demonstrated that it remains acceptable as the injection efficiency is nearly unaffected.

The injection at constant tuning and ramped voltage then became the standard way of operating. A software application, programmed in the PLC dedicated to the RF control, automatically set the cavity voltage and phase as a function of the stored beam current.

The RF system has operated very reliably under such conditions for 2 years and more than 10 000 hours, delivering 250 mA in user runs and up to 300 mA for machine studies. The 2[nd] half of the RF system (CM2 and two other SSA's) was implemented and commissioned in summer 2008, which enabled storing up to 500 mA.

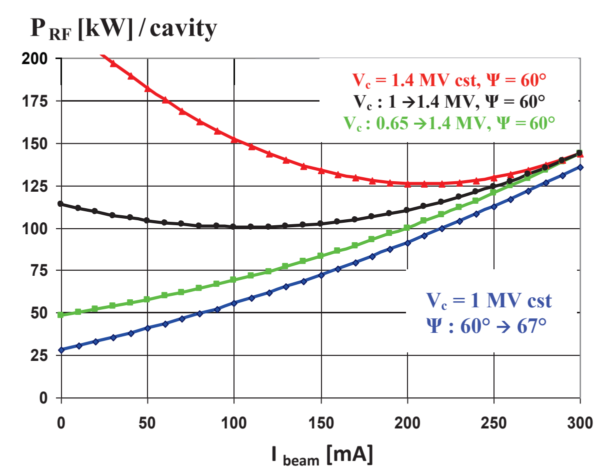

Figure 3: Cavity RF power vs I_{beam} for variable (blue), and constant (red, black, green) tuning cases.

SEVEN YEARS OF OPERATIONAL EXPERIENCE AND UPGRADES

Upgrade of the CM Frequency Tuner

As anticipated, the main difficulty that was encountered with the 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 (fig. 4 - left), 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. 4 - right) with a "planetary gear box" 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 4: Standard stainless steel screw-nut (left) and planetary roller screw (right).

Towards More Powerful IPC's

The cavity IPC is another component of the CM which was subject to R&D. The original version is an LEP2 type antenna [16], which consists of a waveguide to coaxial transition with a doorknob and a cylindrical vacuum ceramic window (fig. 5 - 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 [17]. 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. 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 [18]. 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. 5 - 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. 6. 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.

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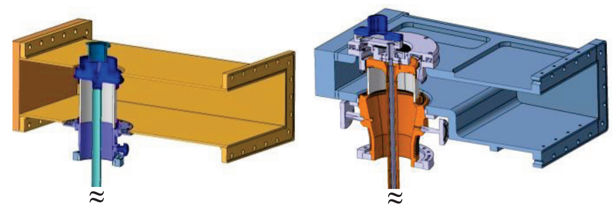

Figure 5: Original (left) and new (right) version of the SOLEIL cavity IPC.

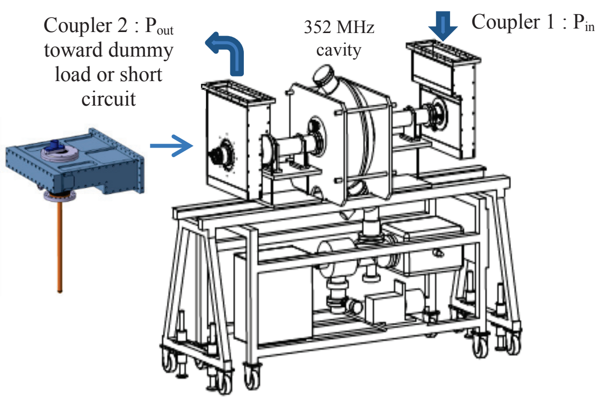

Figure 6: Layout of the Coupler Test Bench.

During the scheduled SOLEIL shutdown in August 2013, one of the conditioned IPC was mounted on CM1 cavity-2 (fig. 7). 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 only 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 without any trouble. Higher power with lower reflection will be later achieved under beam loading conditions.

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.

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

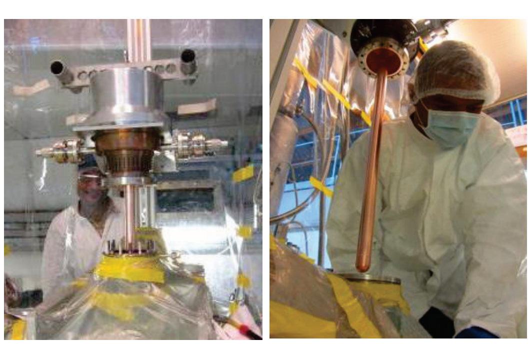

Figure 7: Mounting of the new IPC on CM1 cavity-2.

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 40 000 running hours on CM1 and 30 000 on CM2, the four SSA's of the SR have proved themselves, featuring an outstanding reliability with a MTBF > 1 year, which has largely contributed in the achievement of high beam availability for the users [19].

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

Figure 8: Amplifier module (LR301) failure distribution.

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

This upgrade process has already started. For 2013 we have planned to modify the 160 preamplifier modules (1st and 2nd stages) of our 4 amplifiers; 80 of them are already done and the other half will be completed by the end of the year. Then we intend to go on with the 3rd stages at a rate of about 2 towers a year.

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.

CONCLUSION

The RF system of the SOLEIL SR is quite innovative and challenging with the use of SSA's and HOM free s-c cavities, both developed in house. However, after more than 7 years of operation, it has demonstrated outstanding availability, reliability and flexibility [19]. 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 [20, 21].

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 is working quite satisfactorily; the three other cavities will be equipped as well in 2014.

Upgrades of the cryogenic system for improving its autonomy are also under way [8].

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. It is fully expanding and now adopted by other laboratories [22-26]. SOLEIL is thus involved in several collaborations and transfers of know-how [27].

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