OPERATIONAL EXPERIENCE WITH THE SOLEIL SUPERCONDUCTING RF SYSTEM

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The 352 MHz superconducting (SC) RF system of the SOLEIL storage ring consists in two cryomodules, each containing a pair of SC Nb/Cu cavities, cooled with LHe at 4K from a single 350 W cryogenic plant. In order to store 500 mA, a power of 575 kW and voltage of 3-4 MV are required. The RF power is provided by 4 solid state amplifiers delivering up to 180 kW each. The original cavity input power couplers, which are LEP-type antennas, designed to handle up to 200 kW, were replaced by upgraded versions, able to transmit up to 300 kW CW. This opens the possibility to operate at full beam current with only one active cryomodule. The SC RF system operational experience over the past ten years as well as the different upgrades will be reported here.

SOLEIL Storage Ring RF system

➢ SOLEIL storage ring parameters :

- E = 2.75 GeV, ΔE = 1.2 MeV, I_b = 500 mA
- P_{RF} = 575 kW & V_{RF} = 3-4 MV @ 352 MHz
- 4 x 352 MHz SC cavities, 4 x 180 kW amplifiers, 4 LLRF systems, 1 cryogenic plant

➢ Cryomodule

The SOLEIL cryomodule (CM) contains a pair of single-cell "HOM-free" SC cavities, equipped with input power couplers (antennas), capable to transmit up to 200 kW in their original version, and two types of HOM couplers (loops).

➢ 180 kW CW Solid State Power Amplifier

The solid state power amplifier (SSPA) consists in a combination of four towers of 45 kW and a total of 726 elementary modules of 315 W, with LDMOS transistor (LR301 from Polyfet), integrated circulator and individual 28 V dc power supply (600 W dc/dc converters).

➢ Cryogenic Plant

Both CM's are supplied with LHe @ 4.5 K and LN_2 from a single cryogenic plant, based on the HELIAL 2000 from Air Liquid. The cold box unit, a 2000 litre LHe Dewar, the cryogenic valve box distributing the LHe and LN_2 towards each CM are located in 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.

➢ Low Level RF System

The analog low level RF (LLRF) system 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. It can achieve a voltage stability of ± 0.1 % in amplitude and 0.03 degree in phase.

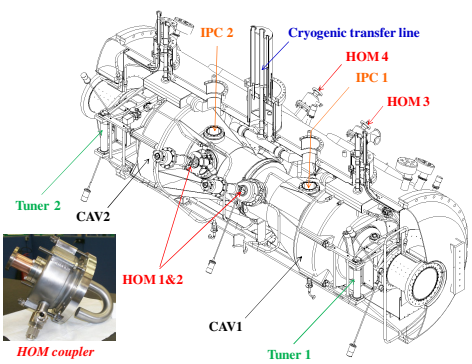
Description of the SOLEIL Cryomodule (CM)

The SOLEIL CM consists in a cryostat which contains two 352 MHz single-cell cavities, made of copper with a Niobium layer 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, housed inside the CM, works under vacuum and in cryogenics environment.

Four HOM couplers (loops), located on central tube, strongly damp the cavity parasitic HOM impedances; they are made of bulk Niobium and cooled with LHe circulating through their coupling loop.

Two input power couplers (antennas) are also located on the central tube; they have been upgraded and can now feed each cavity with up to 260 kW.



Input Power Coupler (IPC)

HOM coupler

Main upgrades of the SOLEIL RF systems

➢ Frequency tuner upgrade

The main difficulty that was encountered with the RF system came after 2 years of operation from repetitive jams on the frequency tuning mechanism. Fortunately, the impact on the user runs remained quite marginal.

The original version was using a standard screw-nut in Copper-Beryllium with a MoS2 lubricant coating, compatible with vacuum and cryogenic environment, coupled to a Harmonic Drive strain wave gear box.

Its repetitive failures led us to develop a new version, based on the combination of a "planetary roller screw" with a "planetary gear box", which was validated after an endurance test on CryHolab test bench at CEA.

The upgraded tuners were implemented on each cavity in 2009 and they have worked properly for more than 6 years without trouble.

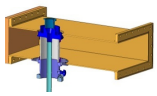
Planetary roller screw

Planetary gear box

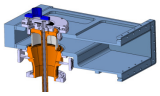
At the end of 2015, one of these tuners showed signs of fatigue and it was replaced during the January 2016 shutdown. Although six years of lifetime for such systems could be considered as acceptable, we decided to use a new version of the planetary roller screw without preloading (not needed with the planetary gear box) in order to improve the lifetime. A first one was implemented for validation in April 2017 on a cavity of CM2. This system will be extended progressively to all cavities in 2018.

➢ Upgrade of the input power coupler (IPC)

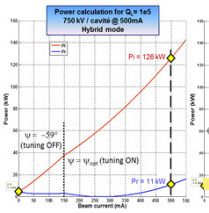
The upgrade of the IPC was motivated by the problems of ceramic aging encountered at ESRF with a similar design and by the occurrences of discharges, experienced on one of the SOLEIL IPC's, at a rate of once a week, when operating above 120 kW. Furthermore the ability of feeding up to 300 kW per cavity opens the option to SOLEIL of storing more than 450 mA using a single CM (→ redundancy).

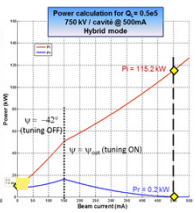


Original IPC (Q_L = 1e5)



Upgraded IPC (Q_L = 0.5e5)





In 2011, a collaboration agreement was concluded with CERN & ESRF to develop a new 352 MHz IPC, based on the LHC design and capable of handling up to 300 kW. The antenna of the new IPC's is lengthened by 1 cm to double the coupling factor hence matching the new standard operating condition, V_{RF} of 3 MV instead of 4.4 MV, which prevents from fast ion instabilities.

In August 2013, the first upgraded IPC, pre-conditioned in the ESRF test-stand using a copper cavity from CERN, was mounted on CM1 in situ. Then after a short reconditioning up to 150 kW (full reflection), we could quickly stored the full beam current .

Unfortunately, multipactor occurred about after one week of operation and led us to implement a DC bias voltage of 1 kV at the ceramic location. Multipactor has since then totally disappeared.

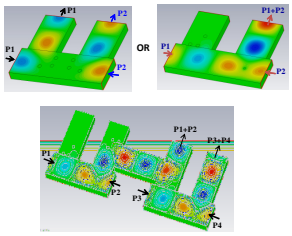
Upgraded IPC's are now installed on our four cavities and are routinely operated up to 150 kW without any problem. All of them have transmitted up to 270 kW to the beam during dedicated machine test sessions. That could be achieved in combining two of our 180 kW SSPA's.

➢ SSPA refurbishment (→ Specific talk by M. Diop)

In spite of excellent operational performance (MTBF ~ 1 year, downtime ~ 5 10^{-4}, cumulated by the 4 SSPA's), a refurbishment was undertaken. It consists in replacing the original transistors by 6th generation LDMOS (V_d = 50 V instead of 30 V), much more robust and with higher gain and efficiency. That should result in a drastic reduction of the module failures (less maintenance effort), higher power capabilities and a gain in efficiency leading to electrical power savings which will compensate the investment cost in < 3 years.

➢ Upgrade of the waveguide network

In parallel, the waveguide network is being modified for a fast and easy combining of 2 amplifiers into a single cavity. For this purpose, we have developed a new device that we called «Magic Switch». It is a 4 ports (2 inputs & 2 outputs) waveguide component with a number of holes into which one can insert metallic posts. Depending on the post configuration, one can transfer either each input power to each output or their sum to one or the other output. Furthermore connecting two Magic Switches, one can power one or the other CM with 260 kW per cavity from our four amplifiers, combined by pairs, which allows storing 450 mA using a single CM.



Conclusion

The RF system of the SOLEIL SR is quite innovative and challenging with the use of SSPA's and "HOM-free" SC cavities, both developed in house. However, after more than 10 years of operation, it has demonstrated outstanding availability, reliability and flexibility. Two operation modes with top-up injection are routinely delivered to the users: 450 mA multibunch in hybrid mode and 500 mA multibunch in uniform filling.

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

Cavity IPC's of higher power capability, have been developed. They are now implemented on the four cavities and are working quite satisfactorily when applying a 1 kV DC bias voltage for curing recalcitrant multipacting levels. They are able to feed more than 260 kW per cavity. Moreover the refurbishment of the SSPA's and modifications of the waveguide network with the implementation of "Magic Switches" open the option for SOLEIL of storing > 450 mA using a single CM or 2 CM's with only 3 running amplifiers/cavities and consequently of taking benefit of the resulting redundancy.

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

A special emphasis is put on the success of the SSPA technology, which has demonstrated that it could advantageously replace the vacuum tubes in such an application. Further R&D's, carried out by SOLEIL, allowed improving the original design in compactness, reliability and efficiency. SOLEIL was thus asked to share its experience through scientific collaborations and transfers technology. It is now being adopted by many other accelerator facilities.

ARW 2017
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