TEST OF THE SOLEIL CRYOMODULE PROTOTYPE WITH BEAM AT ESRF

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Abstract

A cryomodule housing two strongly HOM-damped 352 MHz superconducting (SC) Nb/Cu single-cell-cavities has been developed within the framework of the SOLEIL project design phase. In 2002, the prototype was installed in the ESRF storage ring and tested with beam in the accelerating regime, the cavities being cooled down to 4.5 K by means of liquid helium from Dewars. Four series of tests have been carried out at the end of scheduled shutdowns. In order not to disturb the ESRF machine performance during the user mode of operation, the cavities were maintained detuned at room temperature. In this passive regime, they remained transparent to the beam with less than 100 W of deposited power, evacuated by a warm helium gas flow.

Up to 170 mA of beam could be accelerated with a peak RF voltage of 3 MV and a power of 360 kW from the SC module. This corresponds to the performance required for the first SOLEIL operation phase. The concept of effective HOM damping was validated up to the maximum ESRF intensity of 200 mA. A few weak points already identified at previous CERN tests were confirmed: high static cryogenic losses, poor cooling of one HOM coupler and too high fundamental power through the dipolar HOM couplers.

INTRODUCTION

In June 1996, a collaboration project between CEA, CNRS, CERN and ESRF was launched to develop, build and test a strongly HOM damped SC cavity for the SOLEIL project [1]. The frequency of 352.2 MHz was chosen in order to benefit from a possible transfer of CERN technology, including the coupler design, and to open the possibility of a future implementation at the ESRF. The prototype was successfully tested at CERN in December 1999 up to 7 MV/m of accelerating gradient [2].

In December 2001, the SOLEIL module was installed in the ESRF storage ring for a period of one year, in order to validate the design with a high intensity beam [3]. For the limited test period, it was decided to feed the cryostat with liquid helium (LHe) from Dewars. Tests with the cavity at 4 K have been carried out following the four shutdowns of March, May, August and October 2002 [4]. After one week of pre-cooling with cold helium gas, the first machine restart days were dedicated to the tests at 4 K. The cavity was then warmed up, kept in the ring at room temperature (300 K) and cooled with warm helium gas for the normal user operation, its resonance being thermally shifted off beam harmonics.

The successful operation at 300 K with high beam intensity - not initially foreseen in the cavity design - opens the possibility of increasing the availability of SC RF systems if the ring can be operated with a reduced number of modules.

The cooling with LHe from Dewars was also a success: during the four series of tests, the module was kept stable at 4 K between 17 and 20 hours. With the resonance detuned from the main RF frequency, 200 mA could then be stored without any sign of HOM excitation. The SOLEIL cavity module was successfully operated in the accelerating regime as well: with 3 MV of accelerating voltage, a maximum of 360 kW could then be transferred into 170 mA of beam.

In December 2002, the cavity module was removed from the ESRF storage ring as the space was required for a new beam line. Taking into account the results of the test, it is now planned to modify the existing prototype and to prepare it for the first commissioning phase of the SOLEIL storage ring starting in April 2005 [5].

It is also planned to build a second unit, which is required and will be installed in the SOLEIL ring for a second phase in order to reach full performance of the machine in 2006: 500 mA at 2.75 GeV, the ring fully equipped with insertion devices [5].

TEST OF THE HOM DAMPED SC SOLEIL CAVITY AT THE ESRF

Cavity Concept

The main design aspects that have been optimised for a reliable HOM-free operation in high intensity rings [1, 2, 3, 4] are briefly reminded below:

- On the 400 mm diameter beam tube connecting two cells in a single cryostat, the HOMs are effectively coupled with conventional coaxial couplers, which extract the power from the structure. As no ferrite absorbers are needed in the beam tubes, possible vacuum contamination is avoided.
- The open structure exhibits an excellent conductance for a very efficient vacuum pumping directly on the main tapers at each side.
- A high reliability is thus expected, which is essential for light sources with an expected MTBF better than 50 hours and more than 96 % beam availability.

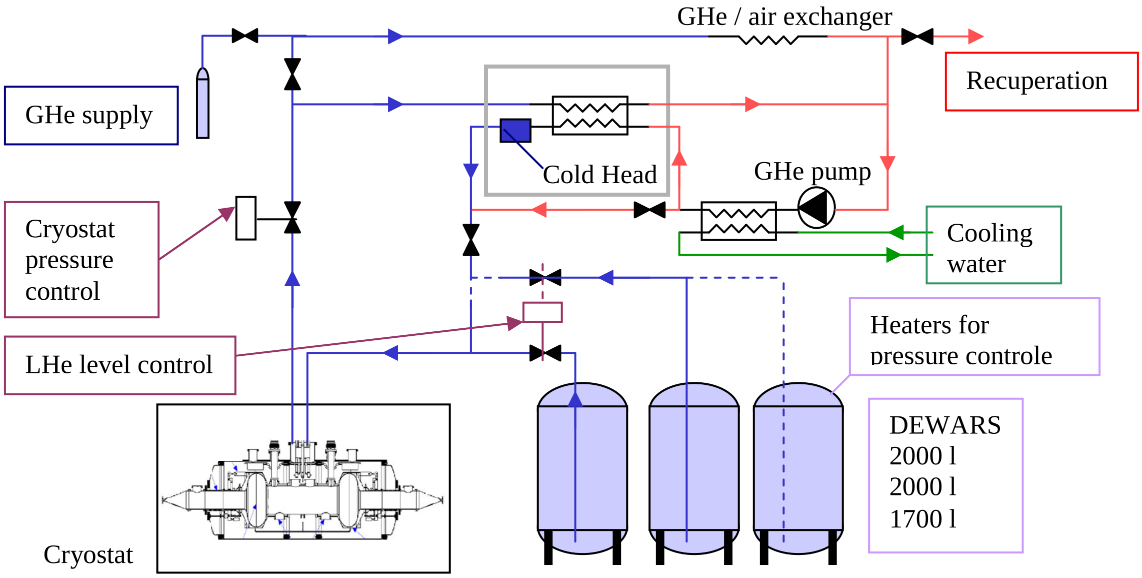

Figure 1: Liquid Helium (LHe) and Helium Gas (GHe) cooling circuits for the SOLEIL cavity at ESRF.

- The CERN technology using niobium coated copper cells has been adopted for the SOLEIL cavity. It is the first application to a cavity designed for high beam current.

Cooling System

Fig. 1 gives a schematic view of the cooling system that was implemented at the ESRF for these tests.

For the operation at 300 K, the heat deposited in the accelerating structure was evacuated by means of helium gas (GHe). About 15 m^3/h were pumped through the cryogenic lines to the cryostat and were re-circulated. The GHe/water heat exchanger after the compressor pump cooled the injected GHe to 22°C and a GHe bottle kept the pressure at 1140 mbar, above atmospheric pressure. With a modest consumption of about 2.8 bars/day, the bottle was exchanged every two months. The isolation vacuum was vented with a permanent small flow of dry nitrogen in order to add some convection and avoid any possible hot point inside the cryostat.

At the beginning of the one week long shutdowns, the cryostat isolation vacuum was pumped and the **pre-cooling** started. The GHe was then cooled by means of the cold head of a cryocooler, which extracted 280 W at 80 K . The gas incident on the cold head was pre-cooled with the cold return GHe by means of a heat exchanger built in the same cryostat. With a time constant of 36 h, the Nb/Cu cells reached their limit temperature of 110 K after six days.

The CEA and CNRS in Grenoble, who liquefied the helium, started filling 5700 l of liquid helium (LHe) into the Dewars about three weeks before the tests. The day before the machine restart, the whole LHe was available and the cooling to 4 K started. Details of the operation at 4 K are given in the next section.

Vacuum Configuration

In order to absorb the high frequency HOM above 1.5 GHz, which couple to the tapered transitions towards the vacuum vessel, these tapers are made of magnetic lossy stainless steel 430 and are water cooled. The main 500 l/s ion pumps are connected to the tapers, close to the accelerating structure. They are equipped with Ti sublimation pumps, which were regularly activated during machine interventions. On each taper, an isolation valve, a shielded bellow and a water cooled photon absorber were mounted. The absorber prevented synchrotron light from hitting the accelerating structure and was directly pumped with a 150 l/s ion pump.

Penning gauges were mounted on the tapers and on each RF power coupler. Their analogue signal was processed by the fast RF interlock system to cut the RF and protect the RF windows against sputter deposition of metal.

Connection to the ESRF 3rd RF Transmitter

Figure 2 shows the module in the straight section of cell 23 in the ESRF storage ring. A special waveguide feeder with waveguide switches was connecting the SOLEIL module to the 3rd RF transmitter instead of the existing normal conducting cavities 5 and 6 of cell 25. The standard RF control system design had easily been adapted to monitor and interlock the SC cavity, and to integrate it into the ESRF control system.

The temperatures at several strategic points within the SC module were monitored and interlocked for the operation at 300 K, as well as the vacuum, the Helium gas cooling, the coupler air cooling, and other relevant parameters. When the system was switched to 4K operation, an interlock signal from the existing SOLEIL cavity control cabinet was validated. This system was already developed by the CEA to control the cryogenic processes for the CERN tests [2] and was slightly modified for the operation with Dewars at the ESRF.

The existing software tuning system of the ESRF cavities was also easily adapted to control the resonant frequency of the two SC cells.

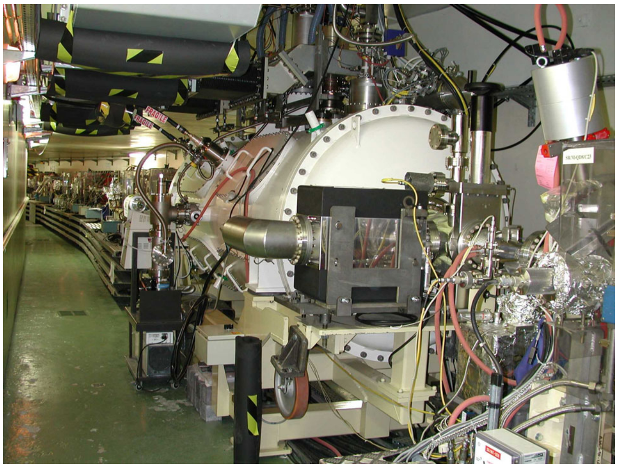

Figure 2: SC SOLEIL cavity in the ESRF storage ring.

ACHIEVEMENTS

Passive Operation with Beam at 300 K

At 300 K, due to thermal expansion, the SC cells are naturally de-tuned by *1209 MHz = 3.4* $f_{revolution}$. This constituted an excellent parking position, with only little power extracted from beam harmonics, including revolution sidebands in partial filling. Following a thorough computation of the HOM power distributed among the HOM dampers, the tapers and, to a small proportion, the warm Cu/Nb structure, the maximum total power to be extracted from the cryostat had been estimated between 200 and 300 W. This pessimistic analysis had been used to dimension the GHe pumps for up to 40 m^3/h GHe flow. It then turned out that with only 15 m^3/h GHe flow, the measured temperature increase and the maximum corresponding power dissipation was:

ΔT = 5 °C,	P = 26 W for	19 mA	in single bunch fill,
ΔT =16 °C,	P = 83 W for	90 mA	in 16 bunch fill,
ΔT = 8 °C,	P = 42 W for	200 mA	in uniform fill.

Considering that the SC cells had never been baked, the expected advantage of the open geometry resulted in a vacuum pressure as low as 10^{-9}, 10^{-8} and 3 10^{-9} mbar in these three filling modes, respectively.

A maximum HOM power of 50 W was measured on monopole HOM couplers in 16 bunch at 90 mA. Finally, as expected from this strongly HOM damped cavity, no sign of HOM driven coherent multibunch instability was ever observed up the maximum ESRF current of 200 mA.

The system proved to be very reliable and transparent to machine operation, causing only three beam trips over a full year, which could not clearly be attributed to the cavity itself.

Cryogenic Cooling

To cool down from 110 K and saving as much LHe as possible by exploiting the evaporated cold gas, only a moderate flow of about 45 l/h of LHe was set for about 24 hours. The superconducting parts were then below 10 K and the bulky tuning system at about 30 K. A LHe flow of 200 l/h was then required for about 3.5 hours before the cryostat filled up with LHe. At this time, the first 1700 l Dewar was already empty. Including all the transfer losses, about 160 l/h, corresponding to a recuperation of 114 m3/h or 117 W losses, were drawn from the Dewars in automatic mode keeping the LHe level stable in the cryostat. During the four series of test, the cavity remained in stable superconducting state for about 17 to 20 hours until the Dewars were empty. The unexpected high static losses may be explained by a degradation of the super-isolation following many manipulations during the development phase at CERN. Nevertheless, a cold radiation shield seems necessary for the final design.

Passive Operation at 4 K

In passive operation at 4 K, as at 300 K, the cavity remained transparent to the beam and no instability was detected up to 200 mA: along with the experience at 300 K, this demonstrates the validity of the concept for an effective HOM damping.

RF Voltage Conditioning at 4 K

The SOLEIL prototype module had already been powered in the CERN teststand prior to its installation at the ESRF, and it was relatively easy and fast to recondition the couplers up to the nominal total voltage of 4 MV in CW and 5 MV in pulsed mode.

After the second test window at 4 K in May 2002, a problem with the HOM coaxial feed-throughs was encountered, which limited the maximum voltage [3]. It turned out that the brazing joints close to the external RF connectors, between atmosphere and insulation vacuum, were leaking. As a consequence, some glow discharges occurred inside the coaxial lines and limited the voltage due to the spurious coupling to the fundamental mode. Once identified, the leaks were easily repaired. One of the coaxial lines showing strong traces of the discharges was cleaned up. At the August test, a decade was gained in the insulation vacuum and the accelerating voltage of the module could be raised to its nominal value.

The dipolar HOM couplers which are located close to the accelerating cells are equipped with notch filters for the rejection of the fundamental mode coupling. Due to an incorrect tuning of these filters and to the resulting spurious coupling to the fundamental mode, at 4 MV in CW, the extracted power was as high as 1650 W. Moreover, the LHe circuits feeding the HOM couplers were not yet fully optimised and the cooling efficiency was only moderate. Altogether this lead to strong overheating of the HOM couplers at high accelerating voltage and was probably the reason for some quench-like events, with pressure bursts on the LHe tank.

At 4 MV, the total cryogenic losses were evaluated around 140 W, which is slightly above the already high static losses of ca. 117 W.

Some multipacting was also observed in the main RF couplers around 4 MV, eventually leading to some pressure bursts on which the RF was tripped. The fast vacuum interlock had been implemented to protect the ceramic against sputter deposition of copper. It is expected that further conditioning of the couplers will help to overcome multipacting.

Beam Acceleration at 4 K

With 5 MeV energy loss per turn at the ESRF, a minimum of 7 MV of RF voltage is necessary for stable storage of a high intensity beam. At the end of the 4th test window, in October 2002, 170 mA of beam could be stored, achieving 30 hours of lifetime with 3 MV from the superconducting SOLEIL module and 4 MV from the existing normal conducting ESRF cavities. This corresponds to 360 kW of power transferred from the SC cavity module into the beam and meets the requirements for the commissioning of the SOLEIL ring with one module. Surprisingly, only little time was needed for conditioning so that the beam intensity and the beam loading of the module could be ramped within a few hours.

A run test of one hour was carried out at the end of the last test period, with a smooth beam decay from 155 to 149 mA, demonstrating that more than 300 kW can be fed to the beam over a longer period of time, without any thermal run away.

Refurbishment of the Prototype and Production of a Second Unit [5]

Before its installation in the SOLEIL storage ring, taking into account the numerous results from the beam tests at the ESRF, the prototype module will be refurbished as described in detail in [4, 5]. The intervention should be completed in the last quarter of 2004, allowing the SOLEIL ring to be commissioned with the refurbished prototype in spring 2005.

For the fabrication of a second HOM-free cavity module, SOLEIL will issue calls for tender with the aim of placing orders beginning of 2004. The fabrication, assembly and tests should be completed by October 2005. The installation and commissioning in the SOLEIL ring is scheduled at the end of 2005, allowing to reach full performance of SOLEIL in 2006.

CONCLUSION

The beam test of the strongly HOM damped superconducting SOLEIL cavity at the ESRF was extremely successful and brought all the expected results. The concept was validated, the voltage and power requirements of SOLEIL were reached. The tests also allowed the identification of a few design and fabrication weak points on the prototype, which can still be resolved before the installation of the module for the commissioning of the SOLEIL ring. With the planned modifications, the present performance limitations of the SOLEIL cavity are expected to be overcome. Based on these experimental results, the fabrication of a second module can now also be launched on a sound basis. Finally, the tests have also shown that this cavity constitutes a valuable option for a possible future intensity upgrade of the ESRF.

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