Upgrade of the Cryomodule Prototype before its Implementation in SOLEIL

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Abstract

In the Storage Ring (SR) of the SOLEIL Synchrotron light source, two cryomodules will provide the maximum power of 600 kW required at the nominal energy of 2.75 GeV with the full beam current of 500 mA.

A cryomodule prototype, housing two 352 MHz superconducting single-cell cavities with strong damping of the Higher Order Modes has been built and successfully tested in the ESRF storage ring. Even though the achieved performance (3 MV and 380 kW) does meet the SOLEIL requirement for the 1st year of operation, the cryomodule prototype will be upgraded before its installation on the SR early 2005. Modifications will be made on the internal cryogenic system, and also on the power and dipolar HOM couplers. That requires a complete disassembling and reassembling of the cryomodule, which is being carried out at CERN within the framework of collaboration between SOLEIL, CEA and CERN.

Additional 3D RF calculations have been performed on the full SOLEIL RF structure in order to get a more detailed description of the damping of the dipolar modes and to optimise the tuning of the dipolar couplers.

A second cryomodule, similar to the modified prototype, will be built and installed in the SR about one year later.

INTRODUCTION

The SOLEIL cryomodule prototype was developed, realised and tested during the machine pre-study (1996 - 1999), in the frame of a collaboration between CEA, SOLEIL and CERN [1]. After the successful tests, performed in the CERN bunker in December 1999 (E_{acc} of 7MV/m achieved in both cavities, fully equipped in the cryomodule), a collaboration agreement was concluded with ESRF to test this prototype on their storage ring. The cryomodule was prepared for tests and installed in the ESRF storage ring in December 2001 for one year.

The goal of these tests, described in [2], was to validate the new design with a high intensity beam. The cavities were cooled down at 4K during the 4 shutdown periods of March, May, August and October 2002. The rest of the time the cavities were kept at 300K, their frequency being shifted between two beam spectrum lines.

The tests were successful for the different operating modes with high intensity beam: at 300K with detuned cavities, at 4.5K with detuned cavities and at 4.5K in the accelerating regime. No sign of HOM excitation was ever observed and 360kW could be transferred to a beam of 170 mA with an accelerating voltage of 3MV.

This level of performance meets the SOLEIL requirements for the 1st year of operation.

Nevertheless, the tests showed two weak points: the cryogenic static losses were significantly larger than predicted (117W instead of 80W) and the tuning of the dipolar HOM coupler was made impossible because of the too high rigidity of the single wave bellow [3].

It was therefore decided that the cryomodule prototype will be used for the commissioning of the machine, but that it needed first to be refurbished. The refurbishment tasks which require a complete dismounting in a dust-free environment are performed within the framework of a collaboration between SOLEIL, CEA and CERN.

The goal of this paper is to present the status of the cryomodule, half a year before its implementation in the SOLEIL storage ring.

REFURBISHMENT OF THE CRYOMODULE PROTOTYPE

The main modifications, already described in previous papers [2,3], are the following: the two dipolar HOM couplers will be improved and replaced, a copper thermal shield, cooled with liquid nitrogen, will be inserted in the vacuum tank and the length of the power coupler antenna will be slightly increased for better matching. Other minor modifications concern the cryogenic piping, the temperature sensors and the addition of copper thermal straps.

Power coupler modifications:

The fundamental power coupler (FPC) antenna will be lengthened in order to match the new beam loading conditions: 2 cryomodules instead of a single one and an energy increase from 2.5 to 2.75 GeV. Lengthening the antenna by + 9.8 mm will decrease the Q_{ext} value from 2.10^5 down to 1.10^5, the new required value.

These modifications and the re-conditioning of the couplers up to the nominal RF power of 200kW will be performed at CERN.

Dipolar HOM couplers:

The notch filter of the two dipolar HOM couplers can be tuned by adjusting the gap between the loop end and the coupler wall, thanks to a single wave bellow (Fig.1). For the prototype couplers, the bellow wave was fabricated by spinning of the niobium coupler wall. This technique was cheaper but the specified thickness of niobium couldn't be achieved. The obtained wave was too rigid and the tuning of the notch filter was not possible.

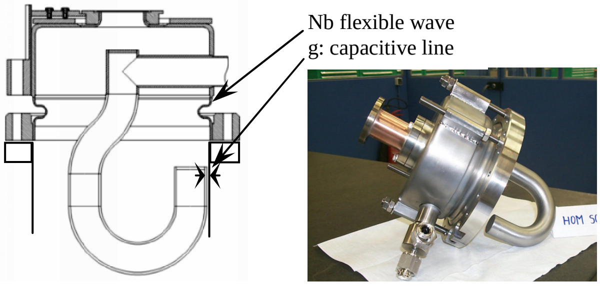

Figure 1: Dipolar HOM coupler with its Nb flexible wave for notch filter tuning.

New dipolar HOM couplers are being fabricated by CERCA with machining of their bellow wave. The flexibility tests, performed on a prototype wave, agreed with the calculations and confirmed that the tuning of the final couplers should be easily achieved. Delivery is scheduled at the end of July 2004.

Cryogenic piping:

Two changes will be brought to the cryogenic circuitry:

1) Copper pieces, cooled by liquid helium, will be placed on the lower part of the circuitry for anchoring thermal straps. These copper straps will help to cool the tuners, the HOM coupler ceramics and the coaxial lines.

2) The upper part of the liquid helium tube, which cools one of the dipolar HOM coupler loops, will be pulled down in order to improve the cooling efficiency. On the prototype, the upper part of this tube was too close from the liquid helium level and the resulting pressure drop was not large enough to activate the thermo-siphon effect inside the loop.

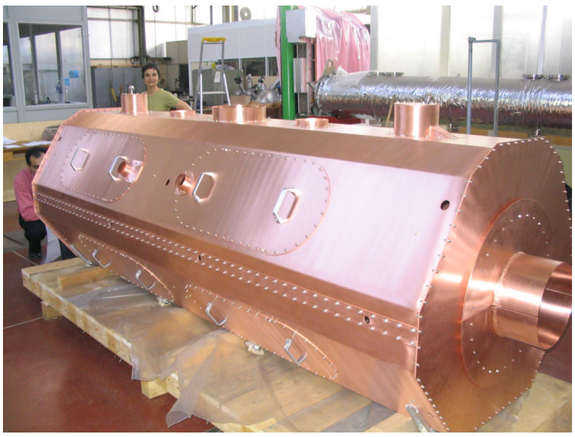

Figure 2: Copper thermal shield with 8 dismountable access doors.

Copper thermal shield:

The cryomodule prototype had no thermal shield and the cold mass was wrapped into 80 super-insulating multi-layers in order to limit the radiative losses. This solution allows an easy access to the cold mass through large dismountable trap doors on the vacuum tank. The possibility of access inside the module was very appreciable during the development period, but the resulting cryogenic static losses of about 117 W [2,3] are not compatible with a daily operation of the cryomodule. A copper shield, cooled with liquid nitrogen, was designed to be inserted into the vacuum tank with dismountable trap doors (see Fig.2). The estimated static losses should be lowered down to 30W with this copper shield.

3D HOM ANALYSIS

The HOM damping of the structure was optimized using 2D codes and assuming that HOM couplers could be considered as a small perturbation [4]. However, very high damping could be achieved with this coupler scheme making invalid the assumption of small perturbation. The RF measurements on the prototype were difficult to interpret in the 400 MHz region, where the first two dipole modes D1 and D2 are lying. The predicted Q_{ext} of these two modes were similar, around 800. They could not be observed with a network analyser on the cavity at 4K, probably because they could not be excited using the available ports. A beam experiment was carried out at ESRF in single bunch mode with the beam horizontally off axis. Two resonances were observed, one at 400 MHz with an estimated Q_{ext} of about 100, and a second one at 403 MHz, with an estimated Q_{ext} between 1000 and 4000. Since such high damping values lead to large frequency shifts and the predicted frequencies for D1 and D2 were 403 and 404 MHz respectively, a mode identification was hazardous. The worst scenario would associate the D2 mode with a computed R/Q of 51.6 Ω/m and a Q_{ext} of 4000, leading to an impedance of 206 kΩ/m, well above the threshold for coupled bunch instability of about 125 kΩ/m with the initial SOLEIL parameters (2.5 GeV). The study of a very similar damping system for the SUPER-3HC project had shed a light on the increased complexity of the damping for these two modes and had led to strengthen the damping of the second dipole mode using two additional HOM dipolar couplers since the damping requirements were more severe [5].

It was therefore decided to make a detailed study of the first dipole modes of the SOLEIL cavity using the complex eigen-solver of HFSS. The model includes the full cavity and the dipolar couplers terminated by matched loads. The introduction of couplers strongly distorts the electric field distribution of D1 on the cavity axis. It appears to be strongly damped since its computed Q_{ext} is about 75, and its frequency is shifted by -3.3 MHz and -2.8 MHz for its two polarizations, D1a and D1b, respectively. The field distribution is so severely modified with respect to the un-damped case that no polarisation plane can be defined for this mode. Therefore, we computed a R/Q map of the mode by scanning the transverse plane. The difference between the un-damped and damped case is shown in figure 3 for D1a.

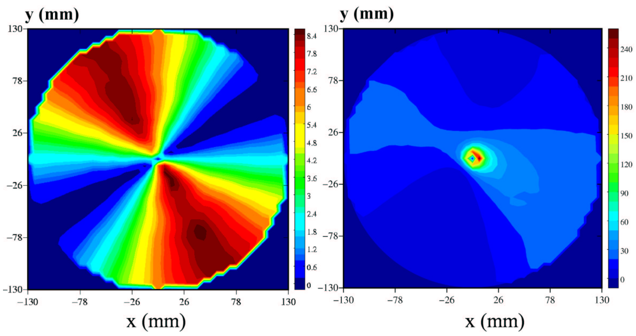

Figure 3: R/Q [Ω/m] map of D1a (left: un-damped, right damped, different colour scales)

The maximum R/Q in the damped case is 25 times higher than the un-damped value. This led us to compute the 5 next dipole modes to verify that their impedance was not exceeding the coupled mode instability threshold of 493 kΩ/m at 2.75 GeV. D2 still appears as the most dangerous mode. The results for D1 and D2 are summarized in table 1.

Mode	f [MHz]	Computed Q_{ext}	Measured Q_{ext}	Z [kΩ/m]
D1a	400.7	74	~ 100	2.1
D1b	401.2	72		0.8
D2a	403.9	1850	1000 - 4000	40
D2b	404.2	1890		64

Table 1: First dipole modes properties from 3D computations

The computed impedance of D2b is below the instability threshold by a factor larger than 7, which is a safe margin. The computed Q_{ext} are in good agreement with estimated values from beam measurements [6].

Fundamental mode rejection

The dipolar HOM coupler includes a notch filter to reject the fundamental mode coupling. Both, low-level measurements and high power tests, pointed out an insufficient rejection. Recently, HFSS calculations have been carried out to analyse the problem with a realistic model of the cavity and coupler. They show that the capacitive line involved in the filter rejection was too long on the prototype and has to be shortened by 30 % in order to reach Q_{ext} values above 10^{10}. Additional simulations including the lower part of the FPC showed that the Q_{ext} corresponding to a tuned notch filter was reduced by a factor which depends on the FPC antenna penetration [7]. To recover a higher Q_{ext} for the HOM coupler, the rejection line length has to be further adjusted by Δl. The relative HOM coupler / FPC orientation is different for each HOM coupler; for the actual antenna penetration (Power coupler Q_{ext} of 10^5), the Δl is +/- 0.8 mm, depending on the HOM coupler. Nevertheless, a single standard of HOM coupler will be fabricated. As a consequence, the Q_{ext} will not be optimal in the central tuning position, but it should be raised to about 5.10^9 with the final adjustment of the capacitive gap.

CONCLUSION

The cryomodule is now totally disassembled and reassembling will start at the end of August 2004, integrating the new thermal shield and dipolar HOM couplers. RF power tests at 4.5K of the complete cryomodule shall be performed at CERN before the end of 2004. It will be installed in the SOLEIL storage ring at the beginning of 2005. The order for the fabrication of the second cryomodule, based on the same design, will be placed in September 2004.

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