DESIGN OF A HEAVILY DAMPED SUPERCONDUCTING CAVITY FOR SOLEIL

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Abstract

To provide the necessary beam power and RF voltage, while coping with coupled bunch instabilities, a superconducting RF system is under study for the Synchrotron Light Source SOLEIL. A special arrangement combining a pair of single-cell cavities, strongly coupled through a large beam pipe, but ended with much smaller ones, and equipped with "classical" HOM dampers is investigated. Results of simulations, after optimization of the cavity shape, beam pipe opening and length, as well as the HOM-couplers design, are presented. Lastly, as beam power deposition and contribution to the overall ring impedance are of main concern, the short range wakefields of the overall cavity assembly have been also carefully studied.

1 INTRODUCTION

An R&D program, involving collaboration with other european laboratories, in particular CERN and ESRF, on a superconducting RF system for the 2.5 GeV storage ring of SOLEIL light source [1] has been set up. The relevant parameters are the total RF voltage of about 4 MV for an rf acceptance of ±6%, and the RF power of 400 kW, including the magnet and insertion losses, to transfer to the beam. The LEP cavity frequency, or more rigorously 353 Mhz, has been chosen. Two single-cell cavities can then be used, with a very moderate gradient (below 4 MV/m) and a power of 200 kW per coupler, which lies in the capability range of the existing LEP couplers. Coupled bunch instabilities is of major concern, because of the high design beam current of 500 mA, (with the total rf buckets filling by 396 bunches), needed for the high brilliance multibunch mode. The order of magnitude of the required damping of the longitudinal and transverse Higher Order Modes of the cavities is given by the well-known approximate formula (assuming short bunches and coincidence of HOM frequency with one single excitation spectral line)

$$f_r R_S < \frac{2E/eQ_S}{\alpha \tau_S I_o} , \quad f_o R_\perp < \frac{2E/e}{\beta_\perp \tau_\perp I_o}$$

with I_o the beam current, E the energy, Q_s the synchrotron tune, α the momentum compaction, $\beta_\perp$ the beta function at the cavity location, τ_s and $\tau_\perp$ the longitudinal and transverse radiation damping times, f_r and f_o the HOM resonance and revolution frequencies.

The harmful HOM impedances are of the order of 10 Ω for monopole and 100 Ω/m for dipole modes per cavity Taking the SOLEIL parameters and assuming that the cavities are installed in the short straight sections, where $\beta_\perp \leq 5$m, one obtains HOM damping requirements better than 2500 for longitudinal and 1250 for transverse planes.

2 CAVITY CALCULATIONS

For SC cavities, we refrain from mounting couplers along the cavity wall and two strategies can be prospected :

- either wide-open beam tubes, covered in rf lossy materials on the inner surface, form themselves coupling devices [2,3]; efficient damping can then be achieved but at the expense of large openings, risk of cavity pollution due to the proximity of the ferrite, and large overall lengths (one single cavity per cryostat).
- or a string of cavities, linked with large beam pipes in-between, but terminated on smaller outer pipes, form then resonant multi-cell structures, with strong coupling for the HOMs and very weak coupling for the accelerating mode [4]; "classical" HOM dampers can hence be mounted on the large pipes, where the standing wave HOM fields have large amplitude; several cavities can be housed in one cryostat and the end beam pipes have moderate opening.

Since first estimations look very promising, this latter solution has been chosen for the Soleil project. Intensive calculations have been carried out with the help of a self-acting code, which has been specially developed for the optimization of a 2-cavity system. The expected external Qs are computed, assuming magnetic or electric coupling (the maximal penetration depth of the coupler has been fixed to one quarter of the pipe radius. All geometric parameters have been varied, like the equator and iris radii of the cell, and in particular the beam tube diameters and the cavity spacing. At each step, after an automatic re-adjustment of the equator radius to get the right accelerating mode frequency (350 Mhz), the optimal location of the coupler, which minimizes the impedances, is sought by a scan all along the inner beam tube. At each location, the product $R/Q_n * Qex_n$ is computed for all the n modes below the cut-off frequency of the smaller end tubes and the maximal value $R_{max} = \mathrm{Max}\{R/Q_n * Qex_n\}$ of these n products is retained. The optimal coupler

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location is of course the one which gives the minimal value of R_{max}. Fig.1 shows for example the maximal impedance - at optimal coupler location - for dipole (top) and monopole (bottom) modes, as a function of the inner tube length and for different tube radii, from 140 to 220 mm. The end pipes aperture has been fixed to R=130mm. The impedances decrease regularly when the inner pipe increases, but above a certain radius (about 20 cm), the situation reverses.

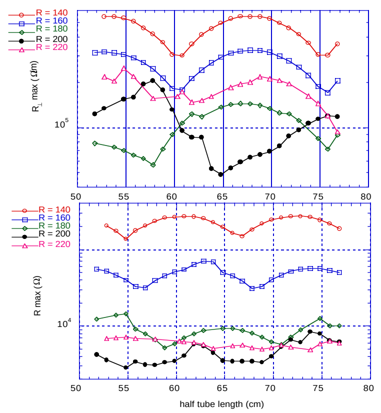

Figure 1: maximal impedances for dipole (top) and monopole (bottom) modes, as a function of the inner tube length & for different tube radii.

We conclude that a tube radius of 20 cm, with a cavity spacing of about 3 half wavelengths, is optimal for both transverse and longitudinal modes. Besides, the optimal locations of the dipole and monopole couplers are found very far from the iris of the cavities (21 and 53 cm), relaxing the power constraints on the fundamental mode rejection filter. The twenty dipole and monopole modes are listed on Table 1. Assuming magnetic coupling with a loop area of 20 cm^2, the predicted external Q is also given. Furthermore, we checked that the modes above cut-off, of much lower R/Q, can be easily damped by simple room-temperature couplers outside the cryostat, close to the conic transitions.

Freq (MHz)	R/Q (Ω/m)	Qex (10^3)	Freq (MHz)	R/Q (Ω)	Qex (10^3)
403	4.8	0.80	579	0.2	0.15
404	51.6	0.90	594	2.7	1.27
454	0.01	0.50	611	11.6	0.30
482	61.6	0.27	632	0.1	0.48
493	6.7	5.01	663	6.3	0.30
504	100.0	0.49	699	8.35	0.25
540	2.5	0.21	723	1.9	1.49
587	2.4	1.53	746	0.3	0.23
636	14.6	0.96	788	0.9	2.61
674	3.4	1.11	844	0.5	0.11

Table 1: Frequency, R/Q and predicted Qex for dipole (left) and monopole (right) modes below cut-off.

Electric field lines, calculated by URMEL, are plotted for example on Fig.2 for the fundamental mode (very weak cavity coupling) and the highest R/Q monopole HOM (strong cavity coupling). The main fundamental mode parameters are R/Q of 45 Ω per cavity, peak electric and magnetic surface fields of 2 and 4.5 mT/MV/m.

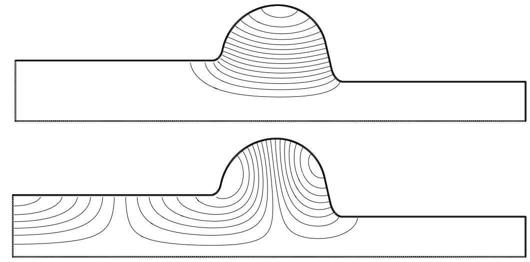

Figure 2: Electric field lines for the fundamental mode (top) and the highest R/Q monopole HOM (bottom)

3 HOM DAMPERS DEVELOPMENT

The specifications on the mode damping levels will be carefully checked in the near future through measurements on copper cavities and adjustable HOM couplers prototypes. Meanwhile, the performance of the couplers have been evaluated with the help of the “High Frequency Structure Simulator” (HFSS) code. These calculations intended first to insure the validity of the above Q predictions, but will also serve as a guide to the rf optimization of the couplers. Concerning the dipole mode damping, we adopted the SC loop coupler with the loop perpendicular to the beam axis, already used on Saclay, LEP or TESLA cavities (see [5] or [6] for example), which proved itself, but with a much higher coupling factor. Concerning the longitudinal mode damping, magnetic coupling with the loop parallel to the beam axis, much more efficient than electric coupling, has also been chosen, but with an additional sheet notch filter. The outer diameter (160 mm) of the HOM devices has been set to 40% of the bam pipe diameter, leading to a loop mean radius of almost 50 mm, whereas the inner conductor is between 20 and 30 mm. Once the coupling parameters are known, the rf elements, which are usually added to improve further the response of the coupler, especially in the vicinity of the HOM frequencies, can be determined by means of equivalent circuits. Though very similar to the longitudinal coupler, we present here only the method we folllowed for designing the dipole coupler.
The first step consists in evaluating the parameters related to the necessary notch filter centered on the fundamental mode. For the dipole coupler (loop perpendicular to the beam axis for Hz coupling), the filter is made of the loop inductance, in series with the capacitance formed by the loop end, facing the outer wall. We build HFSS models composed of a cylindrical waveguide (the beam pipe of diameter 400 mm), connected to the HOM port. Three modes are launched from the WG (the mode of interest, TM01, being the third one), and the notch frequency corresponds to a zero transmission. By varying the length of the capacitive line at the end of the loop, the parameters of the notch filter can be accurately determined from a linear fit (L=32 nH and C=6.4 pF).

We look now for 'universal' parameters, which characterize completely the coupling system, allowing to predict the damping for any mode and any resonator, assuming of course the same beam pipe stand. From an equivalent circuit [7], composed by a RLC circuit for the cavity mode, a transformer for the coupling factor, and a L_bC_b serie circuit for the loop, we deduce that 3 parameters, L_b, C_b and an equivalent coupling area S_b of the loop, are enough for the dipole coupler. These relevant parameters were determined with a HFSS model composed of a lossy cylindrical cavity (diameter 400 mm, the length fixing the resonance frequency) connected to the HOM coupler. Because of the strong coupling, the conductivity of the cavity has to be very low (around 10 $\Omega^{-1}m^{-1}$), in such a way that the reflection coefficient is closer to 0 rather than unity. The TEM mode is launched from the coupler end at frequencies around the resonance frequency of the TE_{113} mode, where the Hz component is maximum at the coupler location. Fig.3 shows for example the density plot of the magnetic field (Hϕ component maximal at the coupler location) for the TM_{012} mode, used for the design of the longitudinal coupler. From the S_{11} curves obtained for various cavity lengths, and with a least squares method, the values of the relevant 3 parameters are determined. For the dipole coupler, we find L_b=42 nH, C_b=4.9 pF and Qex=45 at 650 Mhz, corresponding to an equivalent loop area of 40 cm^2. The S_{11} curves, calculated from the above parameters and provided by HFSS for the TE_{113} mode of the pillbox cavity (the first resonance peak corresponds to the polarization with the electric field in the loop plane) are plotted on Fig.4. These coupler parameters should meet easily the damping requirements of the Soleil cavities.

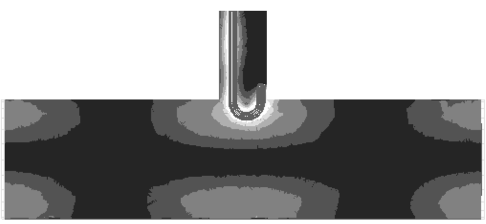

Figure 3: density plot of the magnetic field (Hϕ maximal at the coupler location) for the TM_{012} mode.

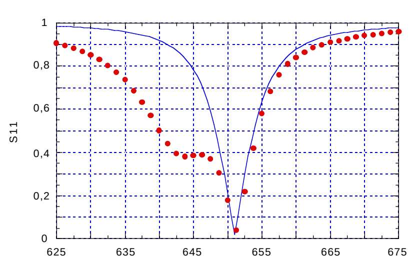

Figure 4: S_{11} curves, calculated from the equivalent circuit (solid line) and calculated by HFSS (circles) for the TE_{113} mode of the pillbox cavity

4 BUNCH WAKE AND HOM POWER

For the design short bunches (around 5 mm), the beam power deposition is of major importance, and must be, as much as possible, avoided at cryogenic temperature. If the loss factor coming from the cavities alone is rather small (about 0.75 V/pC for both cavities), the main contribution come from the two transition tapers between the cavity beam pipe and the tiny ring vacuum chamber of half height 12.5 mm, amounting to almost 3 V/pC in total, assuming conic 0.5 m long tapers. The bunch wake potentials (σ_z=5mm), computed by the code NOVO [8], are plotted on Fig.5, which shows also the individual contributions of the cavities and the tapers. The HOM power amounts to about 2 kW and 3 kW for the high flux (396 $\times$ 1.26 mA) and temporal structure (9 $\times$ 10 mA) modes, respectively. If it turns out that this HOM power gives too much trouble, the taper could be lengthened or the vacuum chamber could be enlarged in this region. Lastly, the wakefield has been computed for very short bunches (σ_z=1mm), is reproduced on Fig. 6 up to 150 mm behind the bunch center, will be very useful for bunch lengthening calculations. It exhibits resistive behaviour at low frequency , but also sharp resonances at higher frequency (around 10 GHz)

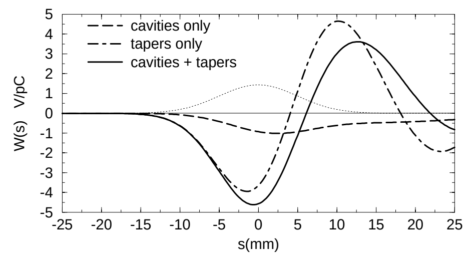

Figure 5: Bunch wake potentials (σ_z=5mm) for the 2-cavity assembly

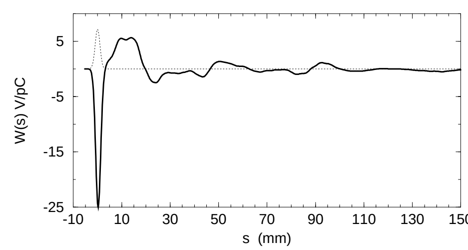

Figure 6: Long range wakefield induced by short bunch (σ_z=1mm) for the 2-cavity assembly.

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