Superconducting Cavities Calculations for a B-Factory

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Abstract

The RF superconducting scenario to achieve the high current and short bunch regime in the future high luminosity colliders offers many advantages : it could provide the high required focalisation voltage with a smaller number of cavities and hence a smaller coupling impedance than copper cavities. Furthermore, it saves a large RF installation since only the beam power has to be restored. But several challenges, in particular, the HOM power to extract, the input power to inject and the strong damping of the higher order modes, have to be met to obtain the desired gradient of the order of 10 MV/m with the beam current of a few amperes. As the choice of the cavity shape and the associated HOM damping system is of outstanding importance, different structures are analysed and discussed.

THE REQUIREMENTS

The RF voltage needed for the longitudinal bunch focusing decreases, while the parasitic modes effects increase when the RF frequency is raised. On the other hand, the power handling capability of the main coupler is limited today to a few hundreds of kilowatts. 500 MHz single-cell cavities are then usually chosen. The two main requirements the RF system has to meet are :

1) the power deposited by the beam should be small
2) the damping of the higher order modes should be high

The higher order modes losses per cavity are given by :

$$P_{HOM} = k_{HOM}\, I^2 / f_b$$

where I is beam current, f_b is the bunch passage frequency and k_{HOM} , which depends on the bunchlength, is the loss factor of the cavity, from which the fundamental loss factor is substracted. In case of resonant excitation of a mode, the power deposited into this mode is approximatively given by (for Q not too small) :

$$P = 2\, R/Q\, Q_L\, I^2$$

where R/Q is the geometric impedance and Q_L the loaded Q of the mode. We see that for HOM losses arguments, both loss factor and Q have to be small. On the other hand, for reasons of multibunch instabilities, the damping of the higher order modes has to be very strong. For currents of a few amps, loss factors per cell of a few tenths V/pC and loaded Q of the order of 100 for the highest R/Q modes have to be achieved.

THE DIFFERENT APPROACHES

The closed structure

The classical SC cavity shape, with the antimultipacting round shape in the equator region and a beam hole diameter over wavelength ratio of about 0.35, several couplers have to be mounted directly on the wall of the cavity (figure 1) for meeting the damping requirement. When this configuration can give very low Q of the HOMs with judiciously located electric or magnetic couplers, the surface field enhancement and the risk of multipactor associated with the coupler holes could spoil the gradient performance of the cavity. Cold tests on a niobium cavity with couplers attached to the RF surface could answer this question. We can note however that, with this scheme, several cells can be housed in a single cryostat leading to a compact module, and that the couplers give negligible beam perturbation.

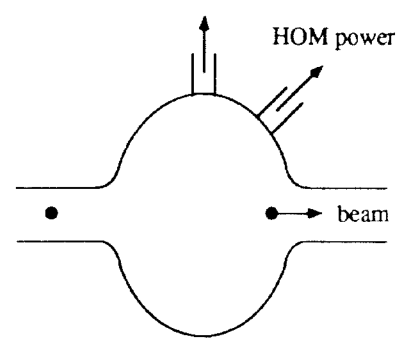

Figure 1 : the closed structure.

The opened structure

Sitting the couplers on the beam tubes, as usual in SC cavity designs, these tubes need to be enlarged to ensure the required damping. If the iris aperture is large enough, we can hope that all the HOMs have their frequencies beyond the cut-off frequency of the beam pipe and propagate out of the cavity. The propagating modes are then easily damped with coupling devices placed between cavities, outside the cryostat. For example, with a beam tube diameter of 12 cm, the cut off frequencies are 957 MHz and 732 MHz for the TM and TE modes respectively. Unfortunatly, the first two dipole modes remain always confined inside the cavity, since their resonance frequency is decreasing as the iris diameter is increased. This approach is prospected in [1] where the two troublesome modes are extracted with help of a fluted beam pipe. In the same way, these both transverse modes plus one longitudinal mode are found to be trapped inside the cavity in [2], where two couplers must be mounted close to the cavity, in order to damp them adequately.

From the beam power deposition point of view, the loss k_{HOM} factor of the cavity itself is very good, lower than 0.2 V/pC for an iris aperture of 24 cm and a bunchlength of 10 mm. The SC cavities must however be joined to the vacuum chamber of the machine by means of very long tapers, which will be finally the dominating part of the overall loss factor. For instance, using 20° tapers, to join the cavity exit tube of 24 cm diameter to a vacuum chamber of 10 cm diameter, we find, with TBCI calculations [3], 0.8 V/pC for the taper-out and - 0.3 V/pC for the taper-in, leading to a final extra loss factor of 0.5 V/pC.

The semi-closed structure

Observing the frequency of the first transverse modes is decreasing when the beam hole is increasing, we tried to maintain the iris small, but connected to the beam pipe with a large diameter (figure 2). We checked that, with a iris diameter of 15 cm and a beam tube diameter of 27 cm, all the longitudinal and dipole higher order modes are propagating out. The performances of the accelerating mode are preserved, like the shunt impedance (134 Ohms), the peak surface electric and magnetic fields over acceleratin field ratio (Ep=1.8 and Hp=40 mT/MV/m).

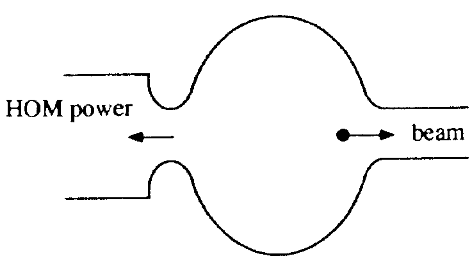

Figure 2 : the semi-closed structure

If the cell is oriented in such a way the beam enters by the large tube and exits by the small tube, seeing only the step-in (see figure 2), the loss factor is only 0.16 V/pC. However, a taper must connect the vacuum chamber and the large beam pipe of the cavity.

As all the modes, except the fundamental one, are propagating, we estimated the minimal Qs we can hope, assuming the large beam tube terminated by a perfectly matched load. As standard cavity codes like Urmel [4] don't allow dissipative boundary conditions, we used the wellknown pulling effect by reactive loading [5]. Reliable computation methods, even in case of very low Q, using this effect have been described, see for example [6]. We insert a pure reactive load, a short-circuited tube, instead of the resistive load and compute the resonance frequencies with different waveguide lengths. Figure 3 shows for example the plot of the electric field of the high R/Q TM110 dipole mode, normally trapped when both the iris aperture and the beam pipe are large. Using the formulation of [6], figure 4 shows the phase variable (given by $2\pi L/\lambda_g$, where λ_g is the guide wavelength and L is the tube length) as a function of the resonance frequency, from which a Q of 525 can be deduced.

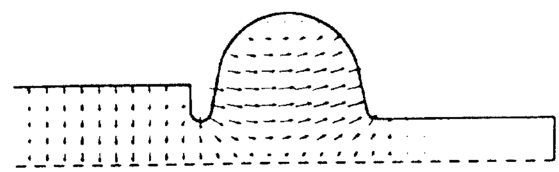

Figure 3 : Plot of the E-field of the TM110 mode

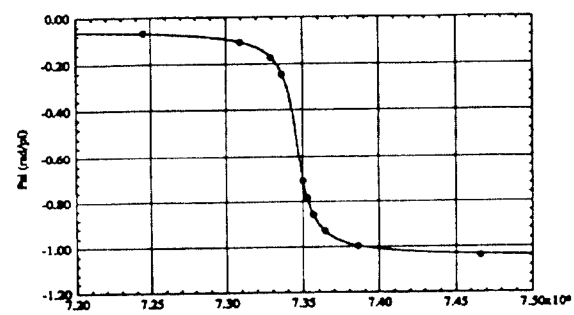

Figure 4 : Phase variable vs. resonance frequency

Table 1 gives frequency and the Q of the HOMs up to 1500 MHz (the dipole R/Q.is calculated at 34 mm from the beam axis).

Mode type	Freq.(MHz)	R/Q	Q
TE111	674.72	1.1	388
TM110	734.64	3.7	525
TM011	896.92	8.7	512
TM111	1031.95	5.2	40
TM020	1059.34	1.2	570
TE112	1066.94	2.1	28
TE121	1169.98	0.1	163
TM021	1357.91	0.3	501
TM012	1417.37	4.4	2445

Table 1 : Calculated Q for the semi-closed structure.

Unfortunatly, even though all HOMs propagate, the calculated damping, although close to the design value, is a bit too weak, in particular for the TM012 longitudinal mode.

The resonant two-cell structure

We consider now a pair of cells, joined by a large beam pipe in between, but with small beam holes outside (figure 5). In this manner, the higher order modes are totally coupled, while the fundamental mode is very weakly coupled. The central tube is the ideal place for the damping devices : it looks like a resonator for the HOMs and its dimensions are chosen to maximize the field levels at the couplers locations. Figures 6 and 7 show the electric field lines for the accelerating mode and one higher order mode (TM021). The expected damping is hence as strong as when the couplers were mounted directly inside the cells without suffering of a too large accelerating mode coupling and without spoiling the cavity gradient performance.

The HOM power can be extracted directly by means of couplers outside the cryostat and several two-cell structures can be housed in a single cryostat (modular structure). The filling factor is therefore very high. Since the outer beam pipe apertures can be chosen close to the vacuum chamber aperture, the problem of tapers is eliminated.

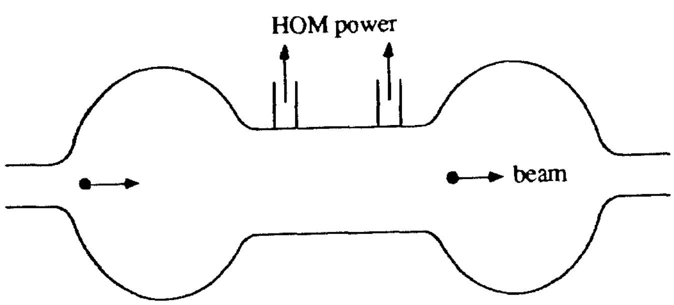

Figure 5 : the resonant two-cell structure.

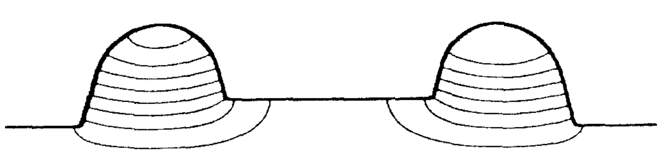

Figure 6 : Plot of electric field (fundamental mode)

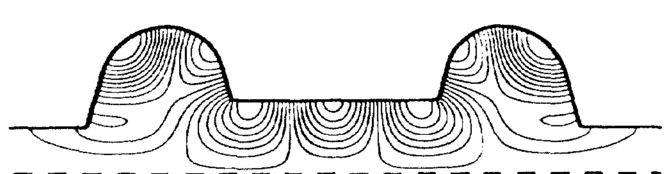

Figure 7 : Plot of the electric field (TM021 mode)

Table 2 shows the fundamental mode parameters and the loss factor for a cell of the structure. The distance between the two centers of the cells was fixed to one wavelength while the diameters of the inner-tube and of the outer-tubes were 27 cm and 17 cm respectively.

R/Q (Ohm/cell)	97
Ep/Eacc	2.1
Hp/Eacc (mT/MV/m)	4.45
kz (V/pC/cell) σ=10 mm	0.20

Table 2 : Main parameters of the resonant two-cell structure.

The Q values are difficult to predict, because of the high fiel levels. However, just to give an idea of the damping, the Qs of the HOMs were estimated, assuming only a magnetic coupling, according the formula :

$$Q_{ex} = \frac{\omega W}{P_{ex}} = \frac{2 R W}{\omega \mu^2 S^2 H}$$

where W is the mode stored energy, R is the load impedance (50 Ω), S is the loop area and H is the magnetic field at the coupler location, calculated by Urmel [4]. Figure 8 gives the calculated Qs for monopole (full circles) and dipole (empty circles) modes with couplers placed at 8 cm from the irises and loop areas of 12 cm^2.

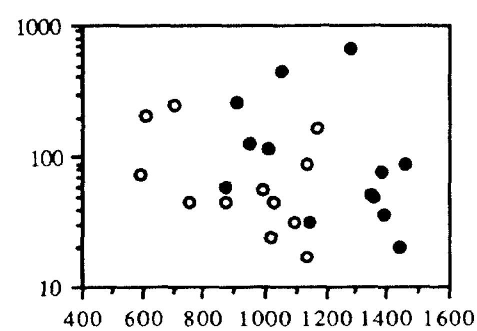

Figure 8 : Calculated Qs vs. mode frequencies (MHz)

CONCLUSIONS

The resonant two-cell structure exhibits at the same time, a high HOM damping capability, along with attractive fundamental mode parameters, low loss factor and a high filling factor capability. However, damping measurements on copper models have to be performed to confirm these results.

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