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:

\[ P_{\text{HOM}} = k_{\text{HOM}} I^2 / f_b \]

where \( I \) is beam current, \( f_b \) is the bunch passage frequency and \( k_{\text{HOM}} \), which depends on the bunchlength, is the loss factor of the cavity, from which the fundamental loss factor is subtracted. 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.

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 TBCC 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 accelerating field ratio (\( E_p = 1.8 \) and \( H_p = 40 \) mT/MV/m).

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 \( \lambda_g \) 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.

![Plot of the E-field of the TM110 mode](image)

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

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

Unfortunately, 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.

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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>R/Q (Ohm/cell)</td>
<td>97</td>
</tr>
<tr>
<td>E/Hacc</td>
<td>2.1</td>
</tr>
<tr>
<td>Hp/Eacc (mT/MV/m)</td>
<td>4.45</td>
</tr>
<tr>
<td>kz (V/pC/cell) σ=10 mm</td>
<td>0.20</td>
</tr>
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</table>

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 rises and loop areas of 12 cm².

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.

REFERENCES