A NEW SRF CAVITY SHAPE WITH MINIMIZED SURFACE ELECTRIC
AND MAGNETIC FIELDS FOR THE ILC*

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Abstract

The TESLA TDR cavity has been chosen as the baseline design for the International Linear Collider (ILC) main linacs. There are continuous SRF R&D efforts to develop alternative cavity designs that can produce higher gradient which in turn could lead to significant cost savings in machine construction and operation. It is believed that the maximum gradient achievable in a superconducting cavity is limited by the critical magnetic flux Bc of the niobium, which is approximately 180 mT. Most of the new designs were focused on minimizing the surface magnetic field (Bs) while the requirement on electric field (Es) was relaxed. The Low Loss design was one of the optimized designs with a Bs reduction of more than 10% over the baseline design which could support a gradient as high as 50 MV/m. The Es field in this design is however about 15% higher than the baseline design. Though it is not clear what undesirable effects the high Es field may induce at high gradient, it is advantageous in a design with both Bs and Es surface fields minimized. In this paper, we will present an optimized cavity shape that minimizes both the Bs and Es fields. The design of the HOM couplers for damping the wakefields will also be presented.

INTRODUCTION

The TESLA TDR cavity shape [1], was proposed as the baseline design for the International Linear Collider (ILC) [2]. The cavity shape was optimized mainly with respect to Es/Ea, the ratio of maximum surface electric field to the accelerating gradient, and a ratio less than 2 was achieved. This low surface field ratio was considered advantageous in suppressing electron field emission at high gradients. Remarkable progresses have been made in understanding the limitations of field gradient in a superconducting cavity since the TDR was developed. It is believed that the maximum gradient achievable in a superconducting cavity is limited by the critical magnetic flux Bc of the niobium which is approximately 180 mT [3]. The later works on the ILC cavity optimization were then aimed towards a lower Bs/Ea ratio. The Low Loss (LL) [4,5,6] cavity shape was then developed as an alternative design for the ILC. The geometry of the LL cavity is optimized to have a lower Bs/Ea ratio and a higher shunt R/Q by reducing the size of the iris and increasing the cavity volume in the high magnetic field region. As a comparison to the TDR shape, the iris radius of the LL cell is 30-mm, 5-mm smaller than TDR, and the side wall of the LL cell is more upright. These modifications resulted in more than 10% lower in Bs/Ea and 15% higher in R/Q and geometric factor G which make the cavity more efficient in acceleration and less cryogenics loss. However, the Es/Ea of the LL design is about 15% higher than the TDR cavity. If the B field limitation is the dominant factor for reaching high gradient, the new LL shape could support an ultimate gradient of over 50 MV/m because of low Bs/Ea ratio. There are concerted efforts in various labs to fabricate and test the LL shape cavities [7,8] to realize such a gradient goal. Significant progresses have been made in high gradient testing of the LL 9-cell cavities in the past years. These efforts are on going to explore the gradient reach of such a design. Although it is not clear what undesirable effects the high surface electric field may induce at high gradients, it would be advantageous to have a cavity design that has both the Es/Ea and Bs/Ea minimized to alienate potential side effects of high surface fields. We have recently developed a Low Surface Field (LSF) cavity shape for the ILC. This shape could potentially improve the cavity performance since both the Bs and Es fields are lower. In this paper, we present the optimization results of the LSF shape, and the HOM coupler design to damp the harmful dipole modes.

CELL SHAPE OPTIMIZATION

Choice of Iris Aperture

A small iris opening increases the shunt impedance thus reduces the stored energy in the cell for a given gradient, and in turn lowers the surface fields. It was found however that the cell-cell coupling quickly becomes undesirably small as the iris radius becomes much smaller than 30-mm as shown in Table 1. At a lower cell-cell coupling, the field imbalance becomes more sensitive to cell dimension errors as the figure of merit for the sensitivity is \( N^2/k_{cc} \), where \( N \) is the number of cells and \( k_{cc} \) is the cell-cell coupling. In addition, a smaller iris opening will result in higher wakefields which would tighten the alignment tolerances. So the 30-mm iris radius is chosen for the LSF design.

<table>
<thead>
<tr>
<th>iris radius (mm)</th>
<th>Bandwidth (MHz)</th>
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<tbody>
<tr>
<td>25.0</td>
<td>9.6</td>
</tr>
<tr>
<td>27.5</td>
<td>13.0</td>
</tr>
<tr>
<td>30.0 (LL &amp; LSF)</td>
<td>19.2</td>
</tr>
<tr>
<td>35.0 (TDR)</td>
<td>24.2</td>
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Cell Profile

The new shape profile is similar to the LL shape except that the disk wall is straight up without a tilt angle. The cell contour is composed of an elliptical iris \((an, bn)\) and

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an elliptical top \((at, bt)\) connected by straight lines, as shown in Fig. 1. For a given disk thickness \(T\) \((an=T/2)\), \(bn\) and \(bt\) are optimized to minimize the surface E and B fields while cell radius “\(b\)” is adjusted to obtain a resonant frequency of 1.3-GHz. Fig. 2 shows the results of the surface field \(Bs/Ea\) and \(Es/Ea\) versus disk thickness. The TDR and LL cavity designs are also shown for comparison. The best surface field solution among these designs is the one that with an \(=11.8\)mm, which reduces the \(Bs/Ea\) by \(11\)% and \(Es/Ea\) by \(5\)% as compared with the TDR. However it was found that the dipole modes in this design are more trapped in the cell due to the thicker iris and are difficult to be damped. The next best solution is the design with \(an=10.5\)mm which is chosen as the LSF shape. This design has surface fields \(Bs/Ea\) \(11\)% lower than the TDR and \(Es/Ea\) \(15\)% lower than the LL. The cell profiles and the surface fields along the cell contours of the TDR, the LL, and the LSF designs are shown in Fig. 3 for comparison.

**SENSITIVITY TO CELL ERROR**

Because of the thicker disk in the new LSF design, the monopole bandwidth is about \(18\)% narrower than the LL cavity. The field flatness in the 9-cell cavity becomes more sensitive to the cell errors as the cell-cell coupling is reduced. The field amplitude deviation in cell “\(i\)” due to a frequency error \(\Delta f_i\) in cell “\(i\)” can be estimated as

\[
\frac{\Delta E_i}{E_i} = \frac{N^2}{k_{ce}} \frac{\Delta f_i}{f_i}
\]

The cell frequency error \(\Delta f_i\) and the coupled mode frequency errors of the 9-cell cavity due to an geometry error in cell “\(i\)” has little differences between the LL and LSF designs. The field imbalance due to the cell error is then inversely proportional to the cell-cell coupling \(k_{ce}\). Fig. 4 compares the maximum field imbalance between the three designs for a 10-micron single cell error, which corresponds to a \(\Delta f_i\) of 150kHz, as functions of cell number. The LSF design is about \(20\)% more sensitive than the LL design.

**HOM COUPLER OPTIMIZATION**

The mode spectrum and the R/Q values of the LSF design are shown in Fig. 5 up to the 3\(^{rd}\) dipole band. The most important dipole mode is the \(1\pi/9\) mode in the third band which has the highest R/Q. The \(6\pi/9\) mode in the 1\(^{st}\) band and the \(5\pi/9\) mode in the 2\(^{nd}\) band are also high in R/Q. The goal of the HOM coupler optimization is to damp the 3\(^{rd}\) band high R/Q to a Q\(_{ext}\) bellow \(10^5\), which is the ILC design requirement.

**End Beampipe**

The end beampipe geometry of the LSF design is similar to the LL cavity. The beampipe radius is 38-mm in the HOM coupler region, and is tapered down to a smaller beampipe radius of 30-mm. The modes up to the 3\(^{rd}\) band are cut off by the 30-mm beampipe \((F_c=2.9\) GHz). Thus the highest R/Q modes are damped “locally” by its own HOM couplers, not affected by adjacent cavities.

**HOM Coupler**

The HOM coupler has the same basic design as the TDR and LL. However, the thicker disk in the new design shifted the frequency of the 3\(^{rd}\) band high R/Q mode about
50-MHz higher. The fields of this mode are more concentrated in the cavity than that in the LL design, as compared in Fig. 7. The HOM damper needs to be modified in order to obtain effective damping.

The loop shape: The width of the loop was reduced to improve the match at the third band frequency. A nose-tip on the loop is included to enhance the electric coupling. The loop angle: The loop angle is optimized to couple effectively to the high R/Q modes. This angle is 45 degrees with respect to the x-y plane with the hook side pointing to the cavity as shown in Fig. 8.

The azimuthal location of HOM couplers: The natural polarizations of the highest R/Q dipole modes in the LSF cavity are rotated about the z-axis, as shown in Fig. 9, if the HOM couplers are placed at the same azimuthal positions as in the LL design. These azimuthal positions were re-optimized for the LSF cavity such that the dominant modes, e.g. the 1pi/9 mode in the 3rd band, are polarized in the x or y directions. The new azimuthal positions of the HOM couplers are quite different from the LL design: the downstream HOM coupler is on the opposite side of the FPC coupler and the upstream HOM coupler is in the vertical plane as shown in Fig. 8. These new coupler orientations result in dipole modes naturally polarized in the x and y planes. An additional advantage of the new orientation is that the RF and short-range wakefield kicks due to the HOM and the FPC couplers at the downstream end partially cancel. The upstream HOM coupler has a 180 degree azimuthal rotational symmetry in terms of the coupling to the dipole modes. One can alternate this orientation among the cavities in a cryomodule to minimize the wakefield and RF kicks in the y-plane.

Damping Results

The Qext of the dipole modes were calculated using Omega3P [9] on the NERSC supercomputers. Optimized Qext for the first three dipole bands are shown in Fig 10. There are a few modes that have higher Qext, but the R/Q of these modes are low. The most important dipole mode to be damped is the 1pi/9 mode in the 3rd band. The Qext of this mode is bellow 10^5 and satisfies the ILC requirement.

Figure 7: Field of the highest R/Q 3rd band mode.

Figure 8: HOM coupler: loop shape and orientation.

Figure 9: Mode polarization versus coupler orientations. Left) mode rotated with original LL coupler orientations; right) mode y-polarized with the new coupler orientations.

Figure 10: The damping results calculated using Omega3P: left) Qext; right) shunt impedance (R/Q)*Qext.

SUMMARY

A Low Surface Field cavity shape was optimized based on the LL cavity design. The LSF shape provides a surface magnetic field 11% lower than the TDR design and the peak electric surface field 15% lower than the original LL design. This design could potentially support 10% higher gradient than the TDR and improve the cavity performance since both the electric and magnetic surface fields are low. The HOM coupler was re-optimized for the new LSF design to damp the dipole wakefields. The Qext of the highest R/Q mode in the 3rd band is bellow 10^5 and satisfies the ILC requirement.

The simulation results presented in this paper was obtained using Omega3P running on NERSC computers.

REFERENCES