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HOM/LOM Coupler Study for the ILC Crab Cavity*

L. Xiao, Z. Li, K. Ko, SLAC, Menlo Park, CA94025, U.S.A

Abstract

The FNAL 9-cell 3.9GHz deflecting mode cavity designed for the CKM experiment was chosen as the baseline design for the ILC BDS crab cavity. The full 9-cell CKM cavity including the coupler end-groups was simulated using the parallel eigensolver Omega3P and scattering parameter solver S3P. It was found that both the notch filters for the HOM/LOM couplers are very sensitive to the notch gap, which is about 1.6MHz/micron and is more than 10 times more sensitive than the TTF cavity. It was also found in the simulation that the unwanted vertical π-mode (SOM) is strongly coupled to the horizontal 7π/9 mode which causes x-y coupling and reduces the effectiveness of the SOM damping. To meet the ILC requirements, the HOM/LOM couplers are redesigned to address these issues. With the new designs, the damping of the HOM/LOM modes is improved. The sensitivity of the notch filter for the HOM coupler is reduced by one order of magnitude. The notch filter for the LOM coupler is eliminated in the new design which significantly simplifies the geometry. In this paper, we will present the simulation results of the original CKM cavity and the progresses on the HOM/LOM coupler re-design and optimization.

I. INTRODUCTION

The Beam Delivery System (BDS) for the ILC has adopted the 14mrad crossing angle design for the colliding beams [1]. A transverse deflecting cavity, as known as crab cavity, is required to provide a transverse rotation to the bunch to achieve a "head-on" collision at the Interaction Point (IP) and thus to improve the luminosity. Superconducting RF technology has been chosen for the ILC crab cavity for efficient handling of the long bunch trains. The crab cavity design for the ILC BDS is based on the 3.9GHz deflecting mode cavity originally developed at Fermilab [2] for the CKM (Charged Kaons at the Main Injector) beam line as the RF requirements are quite similar [3]. A 9-cell version is being developed for the ILC. Two 9-cell crab cavities operating at 5MV/m deflecting gradient will be needed for each of the positron and electron beam lines.

The FNAL 9-cell cavity is shown in Fig. 1. The polarization-flats are formed in the vertical orientation of the cells (1.5-mm indentation) to split the degeneracy of the horizontal and vertical TM110 modes by about 9MHz. The lower frequency polarization mode is in the horizontal plane and is chosen to be the operating mode. The bunch is in phase quadrature with the RF so that the head and tail are kicked in the opposite directions by the deflecting mode to realize horizontal rotation (crabbing). To achieve a clean crabbing to the bunches, effective wakefield damping is crucial. In addition to the Higher Order Modes (HOM), the Lower Order TM010 Modes (LOM) and the Same Order vertical TM110 Modes (SOM) also need to be damped. The extraction of these modes is realized through the HOM, LOM, and SOM couplers respectively. At the upstream (left) end of the cavity are the input and HOM couplers. The HOM coupler is 135° azimuthally relative to the input coupler. At the downstream (right) end are the LOM/SOM couplers. The SOM is in the vertical plane and the LOM is 135° relative to the SOM.

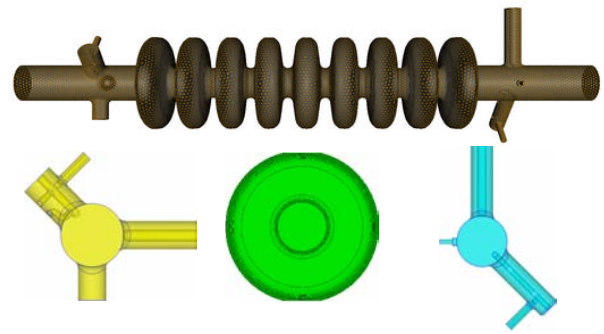


Figure 1: Mesh of the FNAL deflecting mode cavity with input and HOM couplers on left end and SOM and LOM couplers on right end.

The FNAL 3.9GHz deflecting mode cavity was simulated using the parallel eigensolver Omega3P and scattering parameter solver S3P developed at SLAC under the DOE SciDAC program [4]. The damping of the LOM, HOM, and SOM modes were calculated. The sensitivities of the notch filters of the LOM and HOM respect to the notch gap were analyzed and found to be very sensitive. Modifications to the LOM and HOM couplers were performed to improve the damping as well as the notch filter tuning sensitivity.

In this paper, we will first present the numerical studies of the existing FNAL 3.9GHz deflecting mode cavity. And then we will present the modified coupler design to improve the damping and coupler tuning. And finally, we will discuss the future plan on the ILC crab cavity design and optimization.

II. RF SIMULATIONS ON THE FNAL DEFLECTING MODE CAVITY

2.1 The LOM coupler

The LOM coupler utilizes a hook-type electric probe to couple to the TM010 modes as shown in Fig. 2. The hook geometry forms a resonance around the TM010 band to enhance the coupling. A notch filter at 3.9GHz is needed to reject the coupling to the operating mode.

*Work supported by DOE contract DE-AC02-76SF00515
#liling@slac.stanford.edu

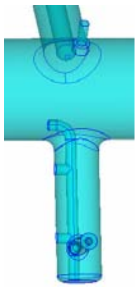


Figure 2: The LOM coupler with hook-type coupling probe.

The results for the first monopole band are shown in Fig. 3. There are three modes around 2.83GHz that are high in R/Q as shown by the red dots. These modes need to be well damped to minimize the beam loading/heating. The blue solid dots are the Qext calculated with the original drawing dimensions for the hook-type probe, which has a resonance that is slightly off the TM010 monopole band as shown in Fig. 4. The hook length was then adjusted to shift the resonance to around 2.83GHz to enhance the coupling. The hollow dots in Fig.3 are the Qext after the adjustment which are dramatically improved.

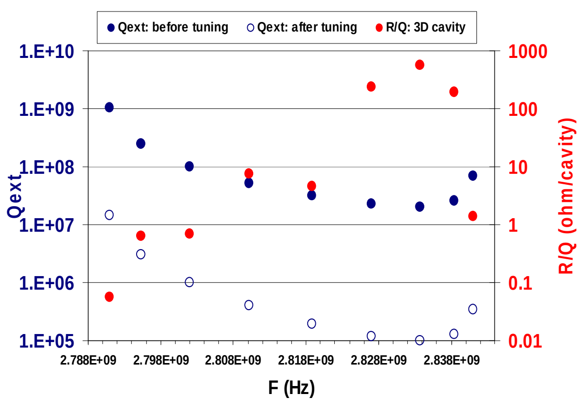


Figure 3: Omega3P results of the LOM TM010 monopole modes.

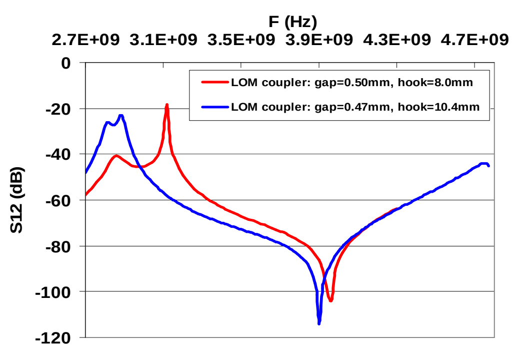


Figure 4: Resonance and notch filter characteristics of the LOM coupler. The red curve is based on the original drawing dimensions and the blue curve is after the adjustment.

The notch filter is tuneable in the actual cavity by deforming the end plate to adjust the notch gap. The Omega3P/S3P simulations showed that the sensitivity of the notch filter tuning for the LOM coupler is about 2.2MHz/micron, which is more than 10 times more sensitive than the TESLA TTF cavity and could be problematic for reaching the needed rejection. We will address this issue in the next section for the new design.

2.2 The HOM and SOM couplers

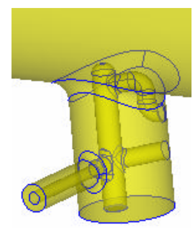


Figure 5: The HOM coupler with loop-type coupling probe.

The HOM coupler for the deflecting cavity is roughly a scaled version of the TESLA HOM coupler [5] to the 3.9GHz frequency as shown in Fig. 5. There is only one HOM coupler for the crab cavity to damp the HOMs of the horizontal polarization. The SOM coupler is the same type of coax coupler as the input coupler except it is placed in the vertical plane to damp the SOM mode and the HOM modes in vertical plane.

HOM Coupler: Fig. 6 shows the simulation results of the Qext for the HOM as well as the SOM modes. The Qext of the operating mode due to the HOM coupler is about 3e+7 with the original dimension thus notch filter is not rejecting well at 3.9GHz. While re-tuning the HOM coupler, it was found that the notch frequency is also very sensitive to the gap width, about 1.6MHz/micron, which is more than 10 times more sensitive than the TTF cavity [6]. Fig. 7 shows the tuning curve and the tuning sensitivity of the notch frequency to the gap width.

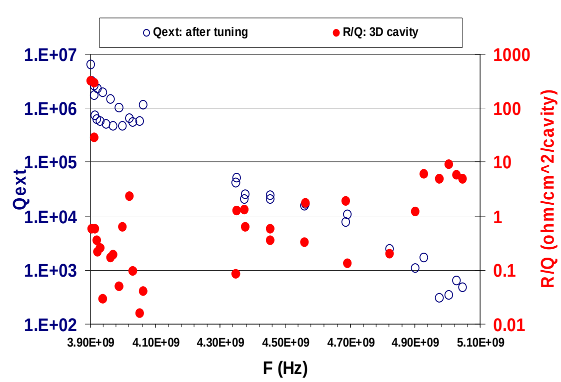


Figure 6: Omega3P results of the HOM TM110 and TE111 dipole modes.

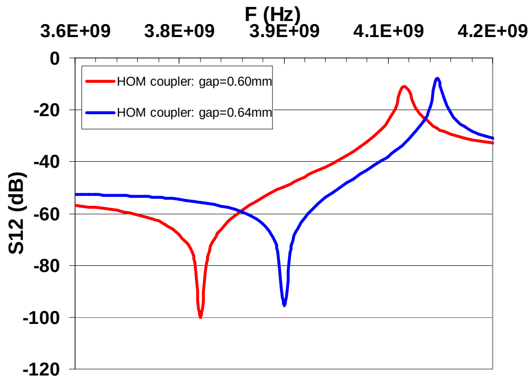


Figure 7: HOM notch filter tuning curves which show the sensitivity of the notch frequency to the notch gap.

Because of the notch rejection at 3.9GHz for the HOM coupler, the wakefield due to the operating mode at 3.9GHz will not be damped by the HOM coupler. The beam excited wakefield is in phase quadrature with the operating crabbing field, which will cause beam induced phase jitter or beam centroid kick in the horizontal plane. This issue need to be addressed in the input coupler design.

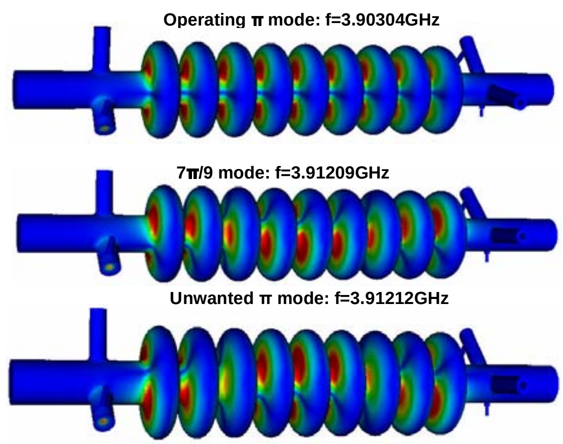


Figure 8: Mode patterns on the pair of TM110-π modes and one TM110-7π/9 mode.

SOM coupler: The SOM coupler simulated is with a centre conductor intrusion of 5-mm into the beam pipe. The Qext for the high R/Q SOM mode was obtained to be around 4.5e+6. Simulations indicated that the Qext of this mode is not as sensitive to the intrusion as expected. The reason was found to be related to the mode coupling between the vertical π–mode and the 7π/9 mode in the horizontal plane. The mode mixing causes the field distribution to be twisted and the maximum electric field in the SOM coupler region is no longer lined up with the coupler as shown in Fig. 8. This twisting reduced the effectiveness of the coupling. In addition, the mode mixing may also cause x-y wakefield coupling which is presently being investigated. This problem however can be resolved by modifying the cell shape to decouple these modes [7].

The numerical simulations show promising damping achieved with the existing couplers. However there are areas, e.g. notch filter sensitivity and mode mixing that are identified to require further improvements. In the next section, we present some modified designs to address some of these issues.

III. LOM/HOM COUPLER DESIGN FOR THE ILC CRAB CAVITY

3.1. The LOM Coupler

The existing LOM coupler is at a 135° angle as respect to the input coupler. With this angle the LOM coupler would couple to both the operating TM110 mode and TM010 monopole modes. So a notch filter is required to reject the operating mode.

Figure 9: LOM coupler for the ILC crab cavity.

By symmetry, the coupling to the TM010 modes does not depend on the azimuthal orientation of the LOM coupler while coupling to the TM110 operating mode does. The new LOM coupler design takes the advantage of the symmetry properties of the TM010 and TM110 modes. In the new design, the LOM coupler is placed to the opposite side of the SOM coupler in the vertical plane as shown in Fig. 9. This arrangement allows to eliminate the notch filter and the pickup coax and simplifies the coupler geometry. The coupler can be adapted to a larger output coax at the end which is advantageous for power handling. The Qext for the LOM TM010 modes with the new design are shown in Fig. 10 and are noticeably improved as compared with the original design.

Without needing a notch filter for the LOM coupler in the new design, it opens the possibility to combine the LOM and SOM couplers into a single coupler design which further simplifies the end-group geometry. The Optimization of such a design is under way. The centre conductor of the new LOM coupler needs to be aligned to the electric node of the operating mode to minimize the coupling to this mode. Simulation has shown that the tolerance on this alignment is quite loose [7].

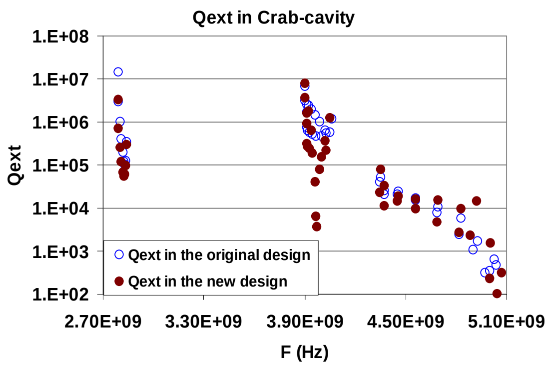
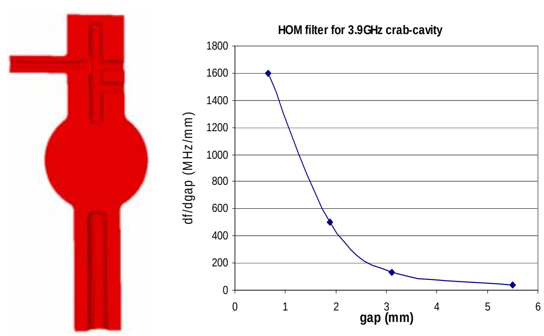


Figure 10: Damping results with the new LOM/HOM couplers.

3.2. The HOM Coupler

The re-design for the HOM coupler is focused on improving the notch filter sensitivity to the gap adjustment. The goal is to reduce the sensitivity from 1.6MH/micron to the same level as the TTF cavity, which is 0.1MHz/micron. The notch frequency of such a coupler is determined by the inductance of centre conductor and the capacitance of the notch gap. The notch sensitivity is then determined by the sensitivity of the capacitance to the notch gap, with the larger the gap the less the sensitivity. In the new design, the notch gap is increased and the length of the centre conductor is adjusted correspondingly to maintain the notch filter frequency at 3.9GHz. The filter sensitivity as a function of the gap width is shown in Fig. 11(b). At a gap width of 3.1mm, the sensitivity is about 0.1MHz/micron which is considered more practical.



(a) HOM coupler (b) HOM notch sensitivity

Figure 11: New HOM coupler for the ILC crab cavity

In addition to the improvement to the notch filter sensitivity, the new design uses a two-stub antenna instead of the coupling loop as shown in Fig. 11 (a). This modification removes the narrow gap between the loop and the outer cylinder which is prone to multipacting. The multipacting characteristics of the new design are yet to be studied. The new coupler couples electrically to the HOMs. The optimal placement for the HOM coupler is in the horizontal plane just opposite to the input coupler. The new HOM damping results are shown in Figure 10 and are improved over the original design.

3.3. The SOM Coupler

The present SOM coupler is a coax type coupler similar to the input coupler. Due to the x/y mode mixing, the SOM damping can reach to the order of $5*10^6$ with a reasonable centre conductor intrusion, whilst lower than 10^6 Qext is required from the preliminary beam studies. By eliminating the x/y coupling and by shaping the tip of the centre conductor, a Qext of $4.5*10^5$ could be achieved, see Ref. [8]. Optimization of the SOM coupler and the design of the combined LOM/SOM coupler are in the future plan.

IV. FUTURE PLAN

The modified designs for the LOM and HOM couplers presented in this paper are quite preliminary. We are presently working with the collaborators in UK and FNAL on beam and wakefield studies to understand the beam loading and wakefield damping requirements for the ILC BDS. Further coupler optimizations will be carried out to meet such requirements. In addition, multipacting in the cell and couplers will be simulated using Track3P, the possible trapped modes at high frequencies in the two-cavity cryostat will be studied, and the effects of cavity imperfection on x-y coupling and wakefield damping will be analyzed.

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