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HOM AND LOM COUPLER OPTIMIZATIONS FOR THE ILC CRAB CAVITY*

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Abstract

The FNAL 9-cell 3.9 GHz deflecting cavity designed for the CKM experiment was chosen as the baseline design for the ILC BDS crab cavity. Effective damping is required for the lower-order TM_{010} modes (LOM), the same-order TM_{110} π-mode (SOM) as well as the higher-order modes (HOM) to minimize the beam loading and beam centroid steering due to wakefields. Simulation results of the original CKM design using the eigensolver Omega3P showed that both the notch filters of the HOM/LOM couplers are too sensitive to the notch gap, and the damping of the SOM is insufficient for the ILC. To meet the ILC requirements, the couplers were redesigned to improve the damping and tuning sensitivity. With the new design, the damping of the LOM/SOM/HOM modes is significantly improved, the sensitivity of the notch filter for the HOM coupler is reduced by one order of magnitude and mechanically feasible, and the LOM coupler is simplified by aligning it on the same plane as the SOM coupler and by eliminating the notch filter. In this paper, we will present the coupler optimization, tolerance studies and multipacting analysis for the crab cavity.

INTRODUCTION

The crab cavity design for the ILC beam delivery system (BDS) is based on the 3.9 GHz deflecting mode cavity originally developed at Fermilab [1] for the CKM (Charged Kaons at the Main Injector) beam line as the RF requirements are quite similar for the two machines. Two 9-cell crab cavities operating at 5 MV/m deflecting gradient will be needed for each of the positron and electron beam lines for the ILC [2].

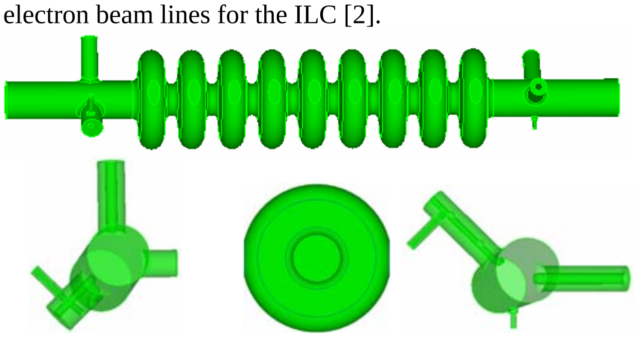

Figure 1: Model of the FNAL deflecting mode cavity with input and HOM couplers at left end and SOM and LOM couplers at right end.

The FNAL 9-cell deflecting mode cavity model is shown in Figure 1. The polarization-flats are formed in the horizontal orientation of the cells (1.5 mm indentation) to split the degeneracy of the horizontal and vertical TM_{110} π-modes by about 9 MHz. The lower frequency polarization mode is in the horizontal plane and 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 TM_{010} modes (LOM) and the same order vertical TM_{110} π-mode (SOM) also need to be damped through the HOM, LOM, and SOM couplers respectively.

While a crab cavity prototype had been fabricated at Fermilab for RF tests, a detailed numerical analysis of its RF properties and wakefield damping was not carried out. In this paper, we use the parallel eigensolver Omega3P and the scattering parameter solver S3P [3] to simulate and analyse the Fermilab design. It is found that the LOM, HOM and SOM couplers provide inadequate damping to some modes, and that the sensitivities of the LOM and HOM notch filter gaps are too high that they impose stringent tolerance requirements for tuning. Because of these limitations of the original design, we propose an improved design that can alleviate the aforementioned problems by modifying the HOM and LOM couplers. We will also present multipacting analysis of the couplers to determine if there are any possible high power processing barriers.

SIMULATIONS OF THE FNAL DEFLECTING MODE CAVITY

In the original Fermilab design, the fundamental and SOM couplers are situated at opposite ends of the cavity and perpendicular to each other, while the LOM and HOM couplers are oriented at certain angles at opposite ends such that all the modes are efficiently damped. To investigate the effectiveness of this configuration for wakefield damping, we use the complex eigensolver in Omega3P to solve for the modes up to the second dipole band, where most of the modes are below the beampipe cutoff frequency of 4.88GHz. Figure 2 shows the R/Q and Qext of the first monopole and the first two dipole bands. For the monopole band, the modes around 2.83GHz have relatively high R/Q. For the first dipole band, the R/Q is small except for the operating mode and the SOM mode which also has a high Qext. The second dipole band modes have low R/Q and Qext, and hence their effects on

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wakefield can be neglected. In general it can be seen that the exiting couplers achieve efficient damping for the LOM's and HOM's. However, it is desirable to improve the damping of other modes such as the SOM.

The critical dangerous mode is the SOM polarized in the vertical plane. Simulations have indicated that the Qext of this mode is not as sensitive to the intrusion of the SOM coupler antenna as expected. This is attributed to the mode coupling between the vertical π–mode (SOM) and the horizontal 7π/9 mode since the frequency spacing between them is small relative to the widths of the two resonances. The mode mixing causes the field distribution to twist and the maximum electric field of the SOM no longer aligns with the SOM coupler as shown in Figure 3, reducing the effectiveness of the damping. In addition, the mode mixing may 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 [4].

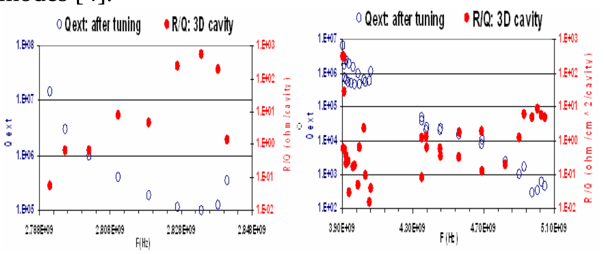

Figure 2: Omega3P damping results – LOM (left) and HOM (right), respectively.

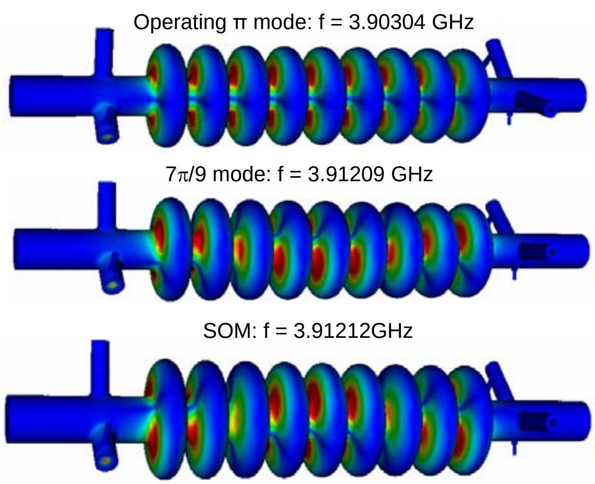

Figure 3: Mode patterns of the TM_{110}-π dipole pair and the horizontal TM_{110}-7π/9 mode.

In practice, the notch filters in the LOM and HOM couplers need to be tuned to the fundamental mode frequency for the rejection of input power from the fundamental coupler. Using the S-parameter code S3P to determine the transmission coefficients for different notch gaps, the tuning characteristics of the LOM and HOM notch filters are plotted in Figure 4. The sensitivities of the LOM and HOM notch filters are found to be 2.2 MHz/μm and 1.6 MHz/μm, respectively, an order of magnitude higher than that of the TESLA TTF cavity. This may affect the rejection of the fundamental mode power and cause damage to the LOM and HOM couplers.

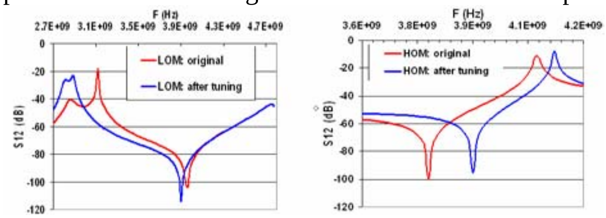

Figure 4: S3P results on tuning characteristics of the notch filters in the LOM coupler (left) and in the HOM coupler (right). The red curve is for the original design and the blue curve is after adjustment of the notch gaps of the LOM/HOM couplers and the hook length of LOM coupler.

NEW DESIGN FOR THE ILC CRAB CAVITY

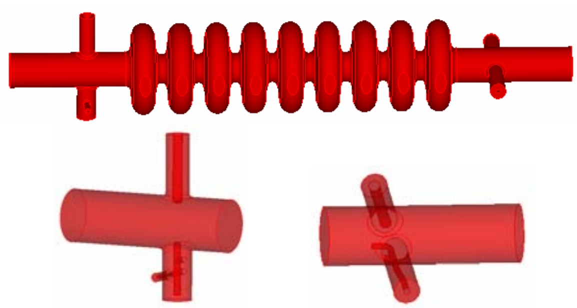

Figure 5: Model of the new crab cavity.

The existing LOM coupler is oriented 135^{o} in the azimuthal direction from the input coupler. It will couple out both the operating TM_{110} π-mode and the TM_{010} monopole modes, and hence the notch filter is required to reject the operating mode. By placing the LOM coupler to the opposite side of the SOM coupler in the vertical plane, the coupling of the operating mode will vanish while those of the monopole modes will not be affected because of their azimuthal field symmetry. This arrangement allows for the elimination of the notch filter and the pickup coax, and hence simplifies the design. The coupler can be adapted to a larger output coax at the end which is advantageous for power handling.

Without a notch filter in rejecting the fundamental mode, both the LOM and SOM coupler adjustment for misalignment need to be investigated. Simulation showed that when the central conductor of the new LOM coupler shifts by 1 mm, the operating mode's Qext can still reach the order of 10^9.

The re-design for the HOM coupler is focused on improving the notch filter sensitivity with respect to the gap adjustment. The goal is to reduce the sensitivity from 1.6 MHz/μm to the same level of the TTF cavity, which is 0.1 MHz/μm. The notch frequency of such a coupler is determined by the inductance of the central conductor and the capacitance of the notch gap. The capacitance changes more drastically when the notch gap is small, and therefore it is preferable to have a large gap to reduce the sensitivity. With an increased notch gap, the length of the central conductor needs to be adjusted correspondingly to maintain the notch filter frequency at 3.9 GHz. The filter sensitivity as a function of the gap width is shown in Figure 6. At a gap width of 3.1 mm, the sensitivity is about 0.1 MHz/μm, which is acceptable.

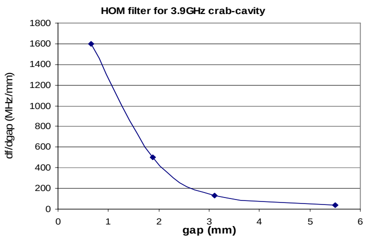

Figure 6: Notch sensitivity vs. gap.

The new HOM coupler uses a two-stub antenna instead of the coupling loop as shown in Figure 5. This modification removes the narrow gap between the loop and the outer cylinder and reduces the possibility of multipacting. All the dipole HOM's are well polarized either in the horizontal or vertical plane for the deflecting mode cavity. Thus, the HOM coupler can be placed opposite to the input coupler in the horizontal plane to couple out one polarization, and the other polarization can be damped effectively by the LOM and SOM couplers at the other end.

The present SOM coupler is a coax-type coupler similar to the input coupler. Due to the x-y mode mixing, the SOM's Qext is about $2.5\text{x}10^6$ for a reasonable central conductor intrusion, and higher than the required $2.6\text{x}10^4$ from preliminary beam studies [5]. In order to provide sufficient damping for the SOM, the cell indentation is increased (from 1.5 mm to 1.9 mm) to avoid x-y coupling between the SOM and the nearby mode by way of enlarging their mode separation.

Taking into account of the above considerations, the damping of the first monopole and dipole bands calculated using Omega3P are shown in Figure 7. Significant improvement over the original design can clearly be seen. The SOM's Qext is reduced to an value of $7\text{x}10^5$, and its mode pattern shown in Figure 8 shows a pure polarization orthogonal to the operating mode (see top picture in Figure 3). By shaping the tip of the centre conductor of the SOM coupler, the SOM can be damped more effectively. Furthermore, the Qext of the operating mode at the HOM coupler port is found to be $1.4\text{x}10^{10}$, indicating that it is well rejected by the HOM coupler.

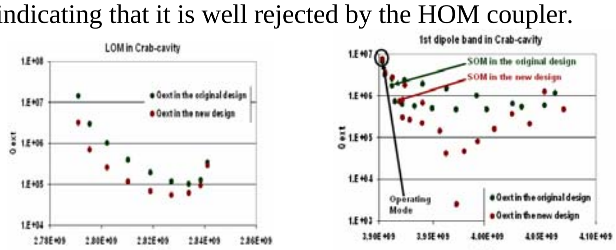

Figure 7: Omega3P damping results for the cavity with new LOM and HOM coupler designs.

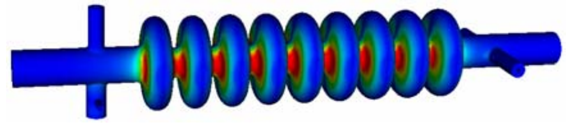

Figure 8: Field pattern of the SOM in the new design.

MULTIPACTING ANALYSIS

Multipacting in the cell and LOM/HOM couplers are simulated using Track3P. No multipacting activities have been found in the cell and LOM coupler up to a peak transverse field gradient of 5MV/m. We do find resonant particle trajectories in the HOM pickup region (see Figure 9). The impact energies of the electrons are between 85 eV and 240 eV, and this energy range is too low to cause multipacting for the copper pickup probe. Preliminary studies show that by rounding the pickup shape with curved surface, the occurrences of resonant trajectories can be reduced.

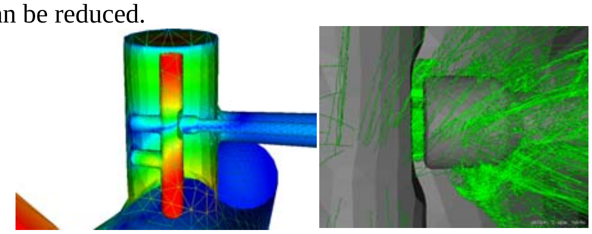

Figure 9: Resonant particle trajectories in the HOM coupler using Track3P.

FUTURE PLAN

The modified designs for the LOM and HOM couplers presented in this paper are preliminary. We are presently working on beam dynamics studies to determine the beam loading and wakefield damping requirements for the ILC BDS. Further coupler optimizations will be carried out to meet such requirements.

Without the need for a notch filter in the LOM coupler in the new design, it allows the possibility of combining the LOM and SOM couplers into a single coupler, which will further simplify the end-group design. The optimization of such a design is underway.

In addition, possible trapped modes 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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