POWER COUPLER FOR THE ILC CRAB CAVITY

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Abstract

The ILC crab cavity will require the design of an appropriate power coupler. The beam-loading in dipole-mode cavities is considerably more variable than accelerating cavities, hence simulations have been performed to establish the required external Q. Simulations of a suitable coupler were then performed and were verified using a normal conducting prototype with variable coupler tips.

INTRODUCTION

The proposed design for the International Linear Collider (ILC) includes a 14 mrad crossing angle in order to aid the extraction of spent beams [1]. Such a crossing angle will reduce the luminosity of collisions unless a crab cavity system is employed to align the bunches prior to collision [2]. The phase stability required for such a system is very tight due to the small sizes of the bunches at the interaction point (IP) and hence a phase control model was developed to understand the requirements of the crab cavity system [3]. The phase control model simulates the cavity and klystron, including the effects of beam loading, microphonics, and measurement errors, and uses a PI controller to vary the power signal in order to keep the cavity phase and amplitude constant. The results from this model suggest that the crab system requires a power coupler with an external quality (Q) factor, Q_e, of between $1x10^6$ and $8x10^6$, dependant on the beam loading and microphonics. The current power coupler, created for the FNAL deflecting mode cavity, has an external Q factor of $3x10^7$ in order to reduce the required average power required from the klystron, hence a new power coupler must be designed. In this paper we will present simulations of the proposed power coupler and measurements of a variable prototype test model used to validate the simulations.

SIMULATIONS OF THE POWER COUPLER

The ILC crab cavity is a nine cell superconducting RF cavity operating in the fundamental dipole mode at a resonant frequency of 3.9 GHz. The new power coupler is required to reach a minimum external Q factor of $1x10^6$ while maintaining a 30 – 40 mm gap between the coupler and the cavity for ease of manufacture. In order to reach this Q requirement it was necessary to increase the area of the coupler tip and the outer conductor diameter. The beam-pipe has a diameter of 36 mm and hence to allow a pull-out from this pipe to attach the coupler the outer conductor diameter of the coupler was limited to 27 mm. It was decided that a characteristic impedance of 50 Ω would be used for ease of obtaining parts for the prototype coupler, such as the vacuum feed-through.

In order to check that this design wouldn't give rise to multipactor in the straight co-axial sections, we compared the multipactor charts given in [4]. It can be shown that for these couplers multipactor activity starts at about 100kW in these transmission lines.

A simple round tip has been chosen for the coupler, shown in Figure 1. This coupler has been simulated for different penetration depths and different gaps between the coupler and the cavity.

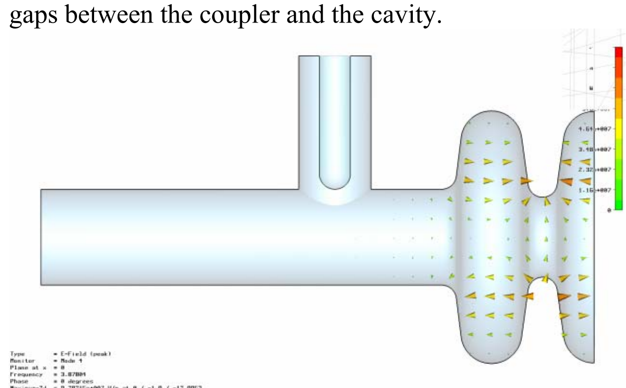

Figure 1: Microwave Studio simulations of a 3-cell cavity.

The couplers were simulated in Microwave Studio [5] and a study of the how the Q factor calculated depends on the mesh density was undertaken before final simulations were made. It was shown that a mesh density of at least 32 lines per wavelength (3,000,000 mesh cells) are required to keep the variation in the calculated Q factor with varying mesh below 3.6 % for a 9 cell cavity.

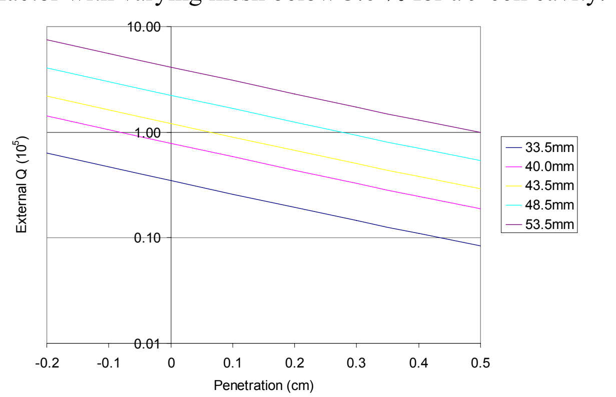

Figure 2: External Q for a 3-cell cavity against tip penetration for a number of different gaps between the coupler and the cavity. Simulated in Microwave Studio.

The 9 cell cavity has a 2.2 MHz separation between the π mode and the 8π/9 mode of the 1st dipole pass-band. As the cavity has a low Q these modes will interfere perturbing the measurement. In order to reduce this errors the coupler was measured when coupled to a 3 cell cavity. The 3-cell cavity has a much better field flatness than the 9-cell cavity and the separation between the π mode and the $2\pi/3$ mode is 22 MHz. The external Q factor can then be scaled to a 9 cell by comparing simulations of 3 cells to 9 cell cavities. A number of 3-cell cavities were also simulated, shown in Figure 2, to investigate the validity of scaling the results from a 3 cell cavity to a 9 cell cavity. For a variety of different couplers the external Q was found to scale by a factor of 3.45, between a 9-cell and 3-cell cavity. It was expected that the external Q to scale with the number of cells, and hence have a ratio of 3 however the calculated Q was higher than expected due to low field flatness in the 9-cell cavity simulation.

MANUFACTURE OF A PROTOTYPE COUPLER.

The coupler simulations were validated using a normal conducting prototype coupler, made from Copper and Aluminium, attached to an Aluminium prototype cavity. The prototype coupler for the ILC crab cavity, shown in Figure 3, has an interchangeable tip, a variable penetration depth and a variable gap between the coupler and the cavity.

Power will be fed from the VNA to the coupler via the Kyocera N-R connector GMM-87157A feed-through. The advantage of this particular feed-through is it has a large 50 Ω inner conductor supported by a ceramic, capable of supporting the heavy coupler inner conductor. Beam-pipe spacers will be used to vary the separation between the coupler and the cavity.

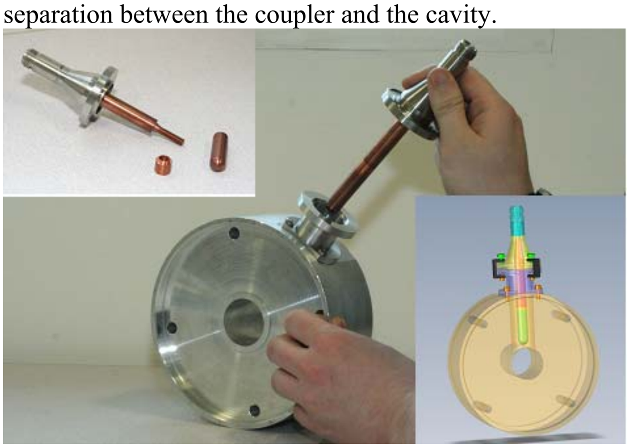

Figure 3: Prototype coupler.

MEASUREMENTS OF THE VARIABLE PROTOTYPE COUPLER

The simplest way to measure the external Q of a coupler is to perform a reflection measurement. The ohmic Q of the cavity has been measured to be Q_0~6,000 and the external Q desired can be as high as $Q_e \sim 10^7$. This results in a S_{11} measurement of 0.9988. This would be difficult to measure accurately using a standard S_{11} measurement of cavity coupling, hence another method is advised.

If we instead use two couplers, one for test and one as a probe, we can measure S_{21} instead which can give more accurate measurements of the external Q factor. First we calibrate the probe coupler. This coupler is simply a piece of semi-rigid coaxial waveguide, RG405, placed penetrating slightly into the opposite beam-pipe. This probe coupler should be chosen so that its refection can be accurately measured but not coupled so strongly that it perturbs the cavity fields. Then the probe coupler is fixed in place and the 3 dB bandwidth, Δf, is measured to find loaded Q of the system. From S_{11} we can calculate external Q from the coupling parameters. First we must calculate the coupling parameter of the probe coupler, β_{probe}

$$\beta_{probe} = \frac{1}{\frac{d_{2,port1}}{d} - 1} = \frac{\frac{1}{Q_0} + \frac{1}{Q_e}}{\frac{1}{Q_{probe}}} \quad (1)$$

where d_2 is the diameter of the circle due to the total reflections of non-resonant signals and the losses in the coupler, shown in Figure 4, and d is the diameter of the Q circle, displayed in a polar measurement of S_{11}.

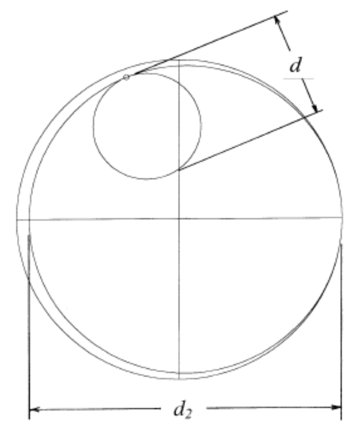

Figure 4: Sketch of an S_{11} measurement of a cavity resonance, showing the circles d and d_2.

The external Q of the probe coupler can then be found from,

$$Q_{probe} = Q_L \left(1 + \frac{1}{\beta_{probe}} \right) \quad (2)$$

In order to find the external Q of the prototype coupler we must measure S_{21}. For a lossless coupler with calibrated cables we find,

$$\frac{1}{S_{21}{}^2} = \frac{P_{in}}{P_t} = \frac{P_c + P_r + P_t}{P_t} \quad (3)$$

where P_c is the power dissipated in the cavity, P_t is the power transmitted through the prototype coupler and P_r is the power reflected in the probe. This can be rearranged to show

$$\frac{1}{S_{21}{}^2} = 1 + \frac{S_{11}{}^2}{S_{21}{}^2} + \frac{P_c}{P_t} \quad (4)$$

applying $P_c/P_t = Q_{e,lossless}/Q_0$ we find,

$$\frac{1-S_{11}^{2}}{Q_{e,lossless}S_{21}^{2}}=\frac{1}{Q_0}+\frac{1}{Q_{e,lossless}} \quad (5)$$

applying this to equations 1 and 2 we find,

$$Q_{e,lossless}=\frac{4Q_L^{2}}{S_{21}^{2}}\frac{1}{Q_{probe}} \quad (6)$$

finally we account for the ohmic losses in the coupler.

$$Q_e=\frac{d_{2,port1}d_{2,port2}4Q_L^{2}}{Q_{probe}S_{21}^{2}} \quad (7)$$

The largest source of error in the measurement is the VSWR of the feed-through, which is not accounted for in this calculation.

COMPARISON BETWEEN MEASUREMENTS AND SIMULATION

The S-parameters of the 3-cell system were measured and used to measure the external Q of the coupler, shown in Figure 5.

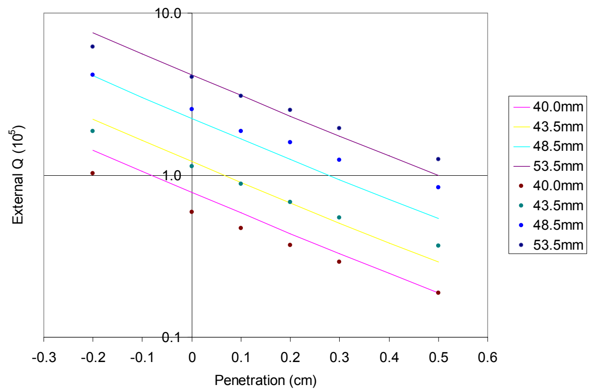

Figure 5: Measurements of the 3 cell cavity compared to the simulations. Lines are simulation results and circles are measurement results.

The measurements were found to agree with the simulations when the coupler penetrated 5mm into the beam-pipe and they were found to disagree for other penetrations. The disagreement was found to vary almost linearly with penetration. A measurement of S_{22} shows that away from the cavities resonance the return loss has a sinusoidal variation with frequency, with a frequency of ~1 GHz, this is consistent with significant reflections at the feed-thru to N-type transition.

If we consider the beam-pipe, coupler, and the feed-thru as transmission line with two impedance steps then the reflections should be equal to

$$\Gamma=\frac{\Gamma_1+\Gamma_3e^{-i2kL}}{1+\Gamma_1\Gamma_3e^{-i2kL}} \quad (8)$$

where Γ_1 is the reflection between the beam-pipe and coupler, Γ_3 is the reflection at the feed-thru, L is the separation between the coupler tip and the feed-thru and k is the wave-number of the signal [6]. This can be used to calculate a correction to the measured Q, using,

$$Q_e=Q_{e,measured}\left(\frac{1-\Gamma^2}{1-\Gamma_1^{2}}\right) \quad (9)$$

setting L such that there is no correction at a penetration of 5mm we find that if the Γ_1 is close to 1, the measured and simulated results agree if the reflections at the feed-thru is set to 0.18, shown in Figure 6.

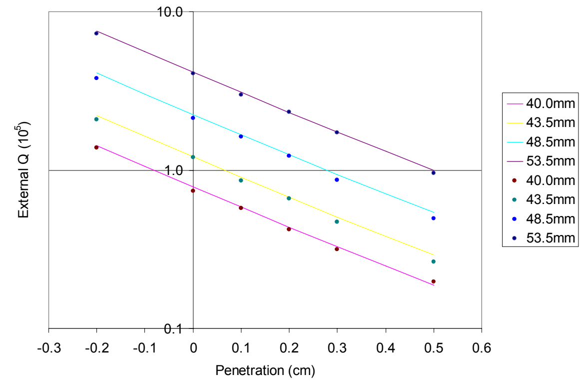

Figure 6: External Q measurements after corrections due to reflection as at the interface. Lines are simulation results and circles are measurement results.

CONCLUSION

The measurements are clearly perturbed by additional reflections between the feed-thru and the N-type connector. It is clear that in order to accurately verify the simulation results it is paramount that the source of reflections in the coupler is identified and removed from further experiments.

In future work we will use the prototype coupler to measure various other coupler tips, including the coupler required for one of the cavities wakefield dampers, known as a same-order-mode (SOM coupler) [2]. This coupler is required to couple to the other polarisation of the operating dipole mode without coupling to the operating mode and hence will be very similar to the power coupler, however this mode is required to have heavy damping hence an optimised tip is required.

ACKNOWLEDGEMENTS

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