Design of a symmetric coupler for superconducting elliptical cavities

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Abstract. As kicks from fundamental power couplers become a concern for low emittance future accelerators, a design for a symmetric coupler for superconducting accelerating cavities has been started. In this coupler, a rectangular waveguide transforms into a coaxial line inside the beam pipe to feed the cavity. So far the RF design revealed an extremely low transversal kick on which we will elaborate. We will also address concerns about cooling and the thermal stability of the coaxial transition line. Therefore, we will calculate the heat, heat transfer and thermal stability of this coupler and evaluate the risk of quenching due to particle losses on the coupler.

1. Background and Introduction

The proposed Cornell Energy Recovery Linac (ERL) [1] and other new ultra high brightness synchrotron light sources have increasingly high demands on high quality, low emittance electron beams. To achieve this, high brightness electron emission on a photo cathode is used providing minimal emittances. However, the low energy section of the linac that accelerates the beam further more can significantly contribute to the emittance increase of the accelerated beam. Usually, the injector produces the strongest effect on the beam due to low beam energy. One component of that can be asymmetric fields coming from the fundamental power coupler.

Due to axial asymmetry, electromagnetic fields in the vicinity of the power couplers feeding RF to the accelerating cavities, have transverse components and produce a transverse kick to the electron beam. That leads to the emittance dilution of the beam. To reduce this effect, the injector cavities of Cornell ERL are equipped with two identical input couplers symmetrically placed on two sides of the beam pipe [2]. That

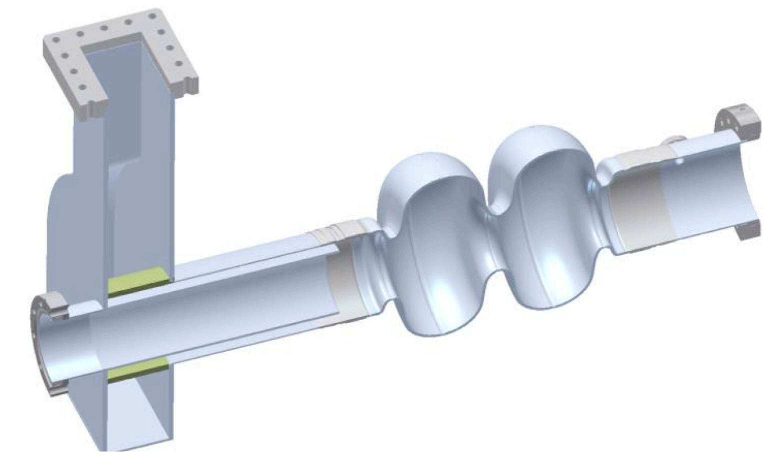

Figure 1. the symmetric coupler, attached to a 2-cell injector cavity

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design eliminates the dipole transverse kick. However, there exist quadrupole field components and this quadrupole focusing distorts the beam [3].

Usually, power couplers are antenna type couplers attached to a side port of the beam pipe near the cavity, usually placed on one side, generating a strong dipole kick. Even though mitigation strategies exist like the symmetric feed from two sides, the lack of rotational symmetry remains. This guided us in designing a waveguide-to-coaxial type coupler resulting in super-symmetric fields. The geometry of the coupler we designed is shown in figure 1.

That coupler has a tube inside the beam pipe which forms a coaxial line with the beam pipe. This coaxial line is coupled to a power transmission line. Couplers of that type were designed, built and used for the 3 GHz superconducting cavities at the S-DALINAC in the early 90s and are operational since then[4]. In that design the coaxial transmission line was coupled to the coaxial line in the beam pipe by movable antenna. Later similar couplers were considered at DESY [5] and FNAL [6]. An analysis showed that there is room for improvements of these designs. For practical sizes of the beam pipe, two modes can propagate in the beam pipe coaxial line: a fully axially symmetric TEM mode and a dipole TE11 mode. The TE11 mode is excited in the coaxial line due to asymmetric coupling to the transmission line. This dipole mode produces a transverse kick to the beam.

In this paper, we will show the RF optimization we did to minimize transversal kicks. We will also report on the investigations on the thermal stability of the coupler under different conditions and describe the mechanical properties and eigenfrequencies of the coupler.

2. RF design

2.1. Coupler for the Cornell 2-cell injector cavity

Figure 1 shows the model of the ERL injector cavity with the Darmstadt type of symmetric coupler. The geometry of the 3 GHz coupler has been scaled and adjusted for 1.3 GHz injector cavity. The coupler is attached to the 106 mm beam pipe; the inner diameter of the inner tube is 78 mm. For optimizing the parameters of the field transformer one can play with the sizes of two diaphragms, the width of the wide waveguide section and the distance to the short. Due to exponential decay of the fields in the beam pipe, the logarithm of the coupler Qext is a linear function of the distance to the cavity (see figure 2). By this means, the coupler can be designed to serve different RF requirements based on the operational need. Figure 3 shows the transverse kick of the coupler which decreases with increasing external Q.

These calculations were performed using parameters of our injector. To demonstrate the features of the coupler design we demonstrate parameter on an ILC type cavity in the next subsection.

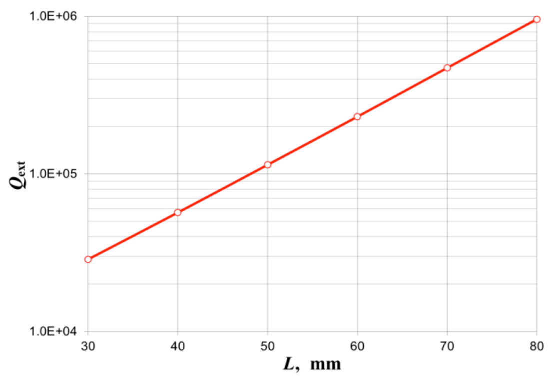

Figure 2. External Q as a function of the distance between the coaxial line and the first cavity iris

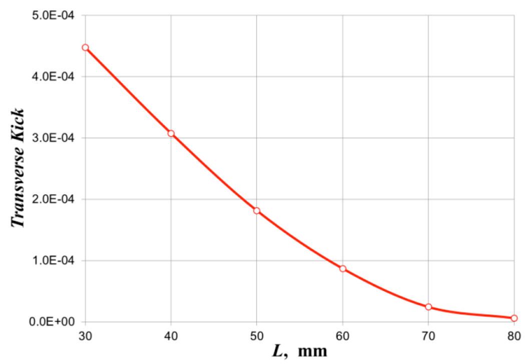

Figure 3. Transverse kick as a function of the distance of the coaxial cylinder to the cavity.

2.2. Coupler for an ILC type cavity

The influence of the transverse kick of input coupler might be significant for other linacs, especially for injectors. One of those machines is LCLS-II, in which 9-cell ILC cavities will be used [7]. Part of the optimization process of the coupler was to choose an appropriate length of the coaxial line inside the beam pipe. This coaxial line formed by this tube and the beam pipe is open on the cavity end and shorted on the wave-guide end. It can resonate on both TEM and TE11 modes. TEM resonances boost the coupling while resonances of TE11 mode enhance the kick and have to be avoided.

For a fixed external quality factor of 1×10^{7} we found that the kick has the lowest value (3×10^{-6} – 3×10^{-7}i) in the vicinity of the resonant length for the TEM mode. This kick may be significantly reduced if the cavity end of the coaxial line is cut with a small angle to the square plane, as indicated in figure 4. As one can see, the kick is fully compensated at the angle of 2.8°.

We also found that for a larger diameter of the beam pipe and a thicker coaxial tube one can get better suppression of the TE11 mode. Figure 5 shows the result of this parameter study for a beam pipe diameter of 126 mm and a coaxial tube thickness of 8 mm. Comparing the results to the finding of the LCLS-II/ ILC geometry the S21 parameter for the dipole TE11 mode is smaller by 24 dB-leading to a stronger suppressed kick. The size of the coaxial tube can be achieved by having a hollow cylinder, cooled by helium from the inside, which would also avoid thermal runaway in case the beam hits.

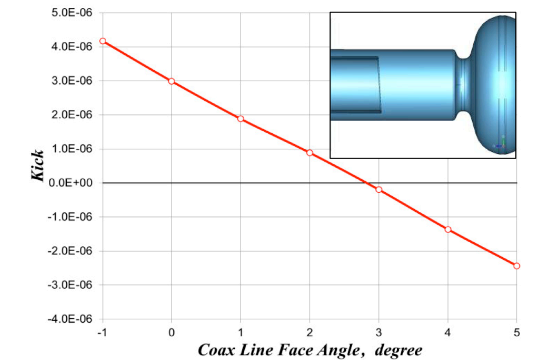

Figure 4. Transversial kick as a function of the face angle of the coaxial tube.

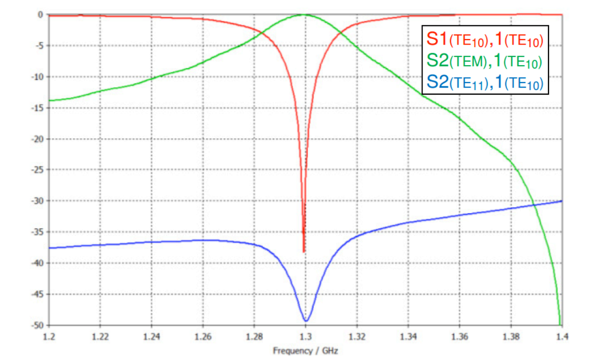

Figure 5. Calculated S-parameters of the waveguide to coax field transformer using the optimized geometry.

3. Thermal Analysis

Without the hollow cylinder forming the coaxial transition, the coupler as designed may under certain conditions be thermally instable. To investigate this in more detail, we conducted a careful thermal analysis, as described below

3.1. Niobium Parameters

The thermal conductivity values that we used in our simulations were taken from a combination of theoretical models and experimental data. The theoretical model that we used was the thermal conductivity equation given by [8]

$$K_s(T)=\frac{K_{e,s}}{K_{e,n}}\left(\frac{\rho_{295K}}{L\cdot RRR\cdot T}+aT^2\right)^{-1}+\left(\frac{1}{D\cdot e^{\alpha T/T_c}\cdot T^2}+\frac{1}{B\cdot l\cdot T^3}\right)^{-1}. \qquad (1)$$

$K_{e,s}/K_{e,n}(T)$ is the ratio of superconducting to normal conducting electron contributions to thermal conductivity. Values and description of parameters are given in table 1. This model is valid for T < 5.8 K. For temperatures above 5.8 K, an experimental data set was used [9]. The specific heat of the niobium cylinder was assumed to follow the Debye model $Cv = \gamma T + AT^3$. Using experimental data from [10], values for the parameters were calculated as $\gamma = 0.0946$ J/(kg*K^2) and $A = 1.28 \times 10^{-3}$ J/(kg*K^4) (for T > Tc) and $\gamma = 0$ and $A = 5.01 \times 10^{-3}$ J/(kg*K^4) for T < Tc .

Table 1. Parameters of the theoretical model for the thermal conductivity of Niobium,(taken from [8])

Parameter	value	definition
RRR	400	Residual Resistivity Ratio
ρ_{295K}	$1.45 \bullet 10^{-7}$ Ω∗m	Resistivity at 295 K
l	50 µm	Phonon mean free path (Nb)
T_C	9.2 K	Critical temperature (Nb)
L	$2.45 \bullet 10^{-8}$ V^2*K^{-2}	Parameter of equation (1)
a	$2.3 \bullet 10^{-5}$ m*W^{-1}*K^{-1}	Parameter of equation (1)
B	$7.0 \bullet 10^{3}$ W*m^{-2}*K^{-4}	Parameter of equation (1)
1/D	300 m*K^3*W^{-1}	Parameter of equation (1)
α	1.76	Parameter of equation (1)

3.2. Calculation
Thermal calculations were performed using the transient thermal analysis system in ANSYS®. The rear face of the cylinder (where it is attached to the wave guide) was fixed at 2 K, assumed being perfectly cooled by the helium. To model the power deposition from the electron beam halo hitting the niobium surface, a heat flux of 0.5 W was applied to the front face of the cylinder, which would be the worst case scenario. Due to the RF field, there is additional heating along the cylinder surfaces which follows the equation

$$\frac{dP}{dA} = \frac{1}{2} R_s \mid H \mid^2 \tag{2}$$

where dP/dA is the power dissipated per unit area, Rs is the surface resistance, and H is the local magnetic field [11]. For T < Tc , the surface resistance follows the equation

$$R_s(T) = 2.25 \cdot 10^{-4} \frac{1}{T} e^{-\frac{17.67}{T}} + 5 \cdot 10^{-9} \Omega \, , \tag{3}$$

where the first term denotes the BCS contribution at 1.3 GHz while the second the 5 nΩ term is our assumption about the residual resistance. The magnetic field values were used to model RF heating as a temperature dependent, position-dependent heat flux into the cylinder. As we found that RF heating is not a factor in the thermal stability, in worst case simulations of the normal-conducting behaviour of the cylinder we assumed a uniform magnetic field along the surface of 107 A/m which corresponds to the maximum field yielded by the RF simulation. Further on, we assumed a normal-conducting surface resistance of 10 mΩ.

3.3. Results
In calculations where the magnetic field values along the cylinder were not approximated, the steady state temperature distribution of the cylinder was found to not differ substantially from the case where there are no RF losses. This is because heating due to RF losses in the cylinder is on the order of

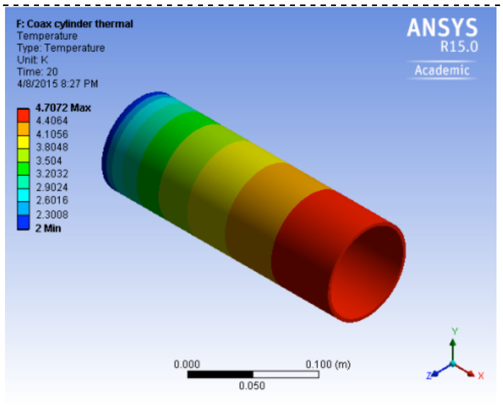

Figure 6. Steady state temperature of the coaxial line, assuming RF heating and a 5 W power deposition due to halo beam

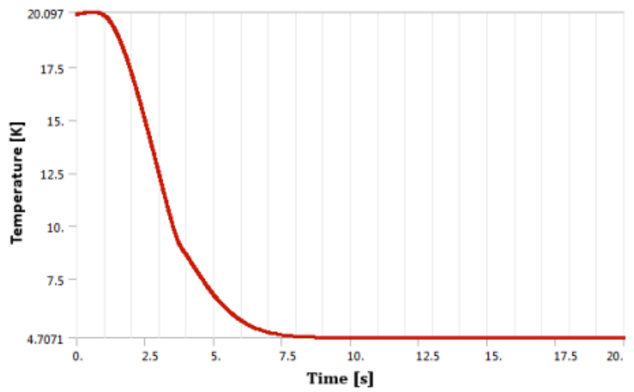

Figure 7. Recovery profile from a quench, assuming the pole tips of the coaxial line has been heated to 20 K.

1 × 10−5 W in the superconducting temperature range, so heating due to the electron beam halo dominates. Figure 6 shows the steady state temperature distribution of the cylinder subject to RF losses and 0.5 W deposition from the electron beam halo. The maximum temperature along the cylinder at steady state is about 4.7 K. Rs increases substantially at Tc so heating from surface currents is much greater when the cylinder has a normal-conducting region. However, these calculations showed that regardless of the initial temperature distribution of the cylinder, the same steady state temperature distribution is reached, at least within the temperature range tested. Simulations with greater power deposition from the electron beam halo showed that the power necessary to drive the cylinder above Tc at steady state would have to be greater than 5.5 W.

We also calculated how the coupler would recover from a quench once it occurs. Details of quench process and its recovery depend on operational parameters of the cavity, energy levels and on quench detection and RF-cut-off techniques. To not limit our-self to a certain scenario we assumed an uniform temperature distribution as a result of the quench at an arbitrary temperature and calculated the cool-down dynamics of the recovery. Figure 7 shows how the maximum temperature along the cylinder drops from 20 K to its steady state value of 4.7 K over time, with the coupler being fully superconducting again after less than 5 seconds.

Nevertheless, the obvious should be noted: if the coupler temperature rises higher than the assumed 20 K, recovery may take longer. In any case our estimates suggest that a catastrophic heat up cannot occur, even if RF is not switched off immediately.

4. Mechanical Analysis

The mechanical modal analysis system in ANSYS® was used to find the natural frequencies at which the different components of the coupler resonate. In order to minimize the computational size of the

Table 2. Results from the natural frequency calculation, values are given in Hz

Waveguide	Coaxial Cylinder	Beam tube to cavity	Beam tube to waveguide
365.6	868.2	995.1	2051.2
514.9	868.2	995.1	2052
627.9	966.9	1111.7	2920.3
649.0	967.1	1111.7	3582.7
730.0	1928.2	1914.9	3585.8

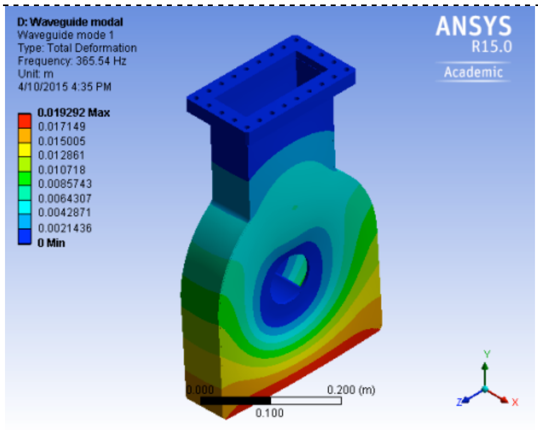

Figure 8. Lowest mechanical eigenmode of the waveguide portion at 365.54 Hz

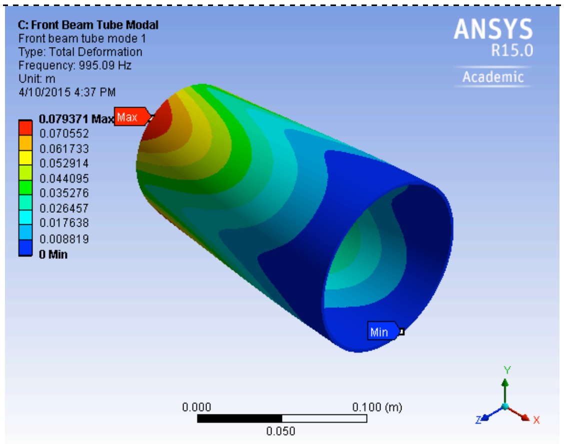

Figure 9. Deformation of the coaxial cylinder at the 868.18 Hz mode.

problem, the waveguide, coaxial cylinder, front beam tube, and rear beam tube were all considered separately. The coupler was assumed to be made from niobium of RRR > 250 and its Young's modulus was taken to be 125 GPa [12].

The five lowest frequency modes were calculated for each component. The frequencies of these modes are given in table 2. Results for the lowest frequency mode of the waveguide and the coax cylinder are given in figure 8 and figure 9, respectively. The lowest frequency mode was calculated to be the 365 Hz mode of the waveguide. This frequency is high enough that resonance should not be dangerous.

5. Summary

A symmetric input coupler developed earlier for 3 GHz S-DALINAC cavities was adapted for Cornell ERL injector cavities and for ILC cavities. The coupler produces a small transverse kick to the beam. The kick can be reduced even more after appropriate optimization of the coupler shape and the size of the cavity beam pipe. A first design has been made and is mature for fabrication.

The thermal calculations showed that the coaxial cylinder extending from the waveguide into the beam tube is expected to remain in a superconducting state, even when hit by particles depositing up to 5.5 W. If the cylinder fluctuates into a normal-conducting temperature range for any reason, it should return to a superconducting temperature range within a few seconds. The mechanical calculations showed that the lowest frequency resonant mode of the coupler should be about 365 Hz. This frequency is high enough that the coupler is not expected to be strongly mechanically excited when in use. This oscillation would not noticeably influence the RF properties. In conclusion, the coupler should not need any further cooling and is unlikely to be vulnerable to mechanical excitation.

The symmetric coupler can be integrated in the design of the superconducting cavity. Even though this complicates the cavity design it reduces the risk of contaminating the cavity during the coupler mounting procedure. If the coupler is made out of niobium (with portions being reactor grade niobium, only) it could undergo the same cleaning techniques as the cavity, including high pressure rinsing.

6. References

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