A 1.3 GHZ WAVEGUIDE TO COAX COUPLER FOR SUPERCONDUCTING CAVITIES WITH A MINIMUM KICK

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Abstract

Transversal forces as a result of asymmetric field generated by the fundamental power couplers have become a concern for low emittance beam in future accelerators. In pushing for smallest emittances, Cornell has finished a physics design for a symmetric coupler for superconducting accelerating cavities. This coupler consists of a rectangular waveguide that transforms into a coaxial line inside the beam pipe, eventually feeding the cavity. We will report on the RF design yielding to the extremely low transversal kick. In addition, heating, heat transfer and thermal stability of this coupler has been evaluated.

BACKGROUND

Many new accelerator designs, especially for light source applications, reply on high quality, low emittance electron beams. This not only results in highly optimized photo guns (DC, RF, or SRF), but also requires a careful control of the emittance growth in the injector linac. This is usually achieved by a highly sophisticated beam dynamics optimization, as in described in [1-3]. It has been realized that transversal kicks introduced by the fundamental power coupler and the higher order mode coupler give a significantly contribution to the emittance growth.

Due to axial asymmetry that usually exist in these couplers, the electromagnetic fields, have transverse components and produce a transverse kick to the electron beam. A way to compensate the dipole kick is using two identical couplers placed symmetrically to feed the RF into the cavity, like done in the Cornell ERL injector [4]. This complicates the cryo-module design significantly while higher than dipole moment kicks still remain.

To explore opportunities to further minimize transversal kicks to the beam of any order we designing a waveguide-to-coaxial type coupler as shown in Fig. 1, resulting in super-symmetric fields. That coupler has a tube inside the beam pipe which forms a coaxial line with the beam pipe while shielding the beam from the asymmetric fields. 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 [5,6]. Later similar couplers were considered at DESY [7] and FNAL [8].

In this paper, we shortly review the RF optimizations of this coupler design while focusing on the mechanical and cryogenic properties.

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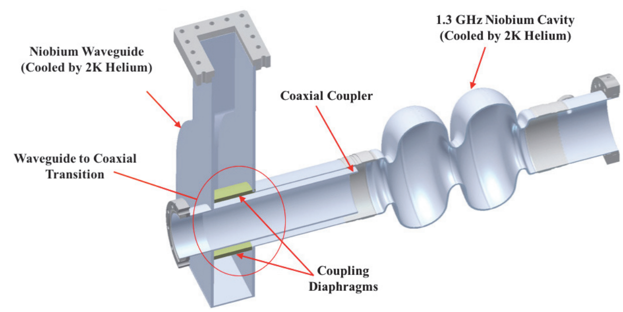

Figure 1: Cornell design of a super-symmetric fundamental power coupler, based on a waveguide-to-coax transition.

RF DESIGN

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 and therefore needs to be minimized.

Our design started from a scaled version of the Darmstadt coupler. For the Cornell injector cavities with a beam pipe diameter of 106 mm, the diameter of the coaxial coupling tube was chosen to be 78 mm. The external quality factor of the coupler can be adjusted by choosing an appropriate length of the tube. Figure 2 describes this behaviour while Fig. 3 reports the transverse associated with this.

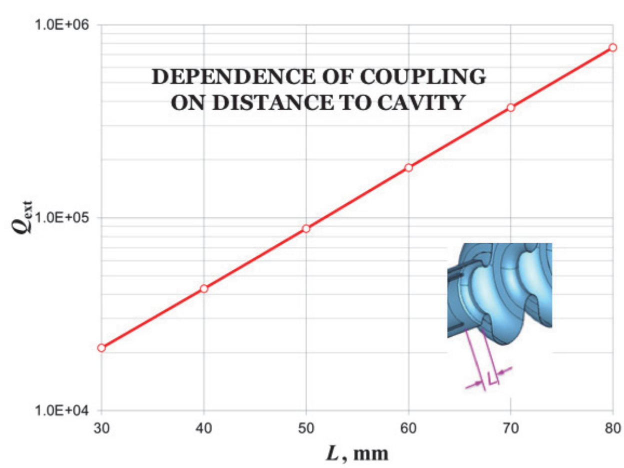

Figure 2: External Q of the coupler as a function of the distance from the coaxial tube to the first iris of the cavity, indicating an ideal cut-off behaviour of the fields.

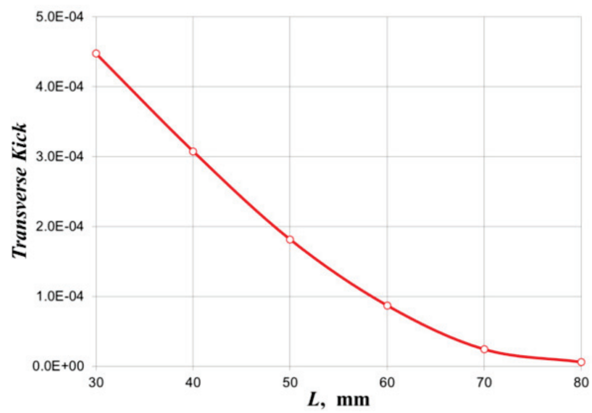

Figure 3: Transversal kick to the beam as a function of the distance of the coaxial line to the cavity. See fig. 2, too.

In the framework of the LCLS-II project[9], in which 9-cell ILC-type cavities will be used, we explored the properties of this coupler design with respect to the higher external Q ($1*10^7$) and the smaller beam pipe. Under these conditions the coaxial line can resonate on both TEM and TE11 modes. TEM resonances boost the coupling while resonances of TE11 mode enhance the kick. This situation is depicted in Fig. 4.

We found that the kick to be minimal ($3\times10^{-6} - 3\times10^{-7}i$) 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. Using an angle of 2.8° the kick could be fully compensated.

More details on RF optimizations and results can be found in [10].

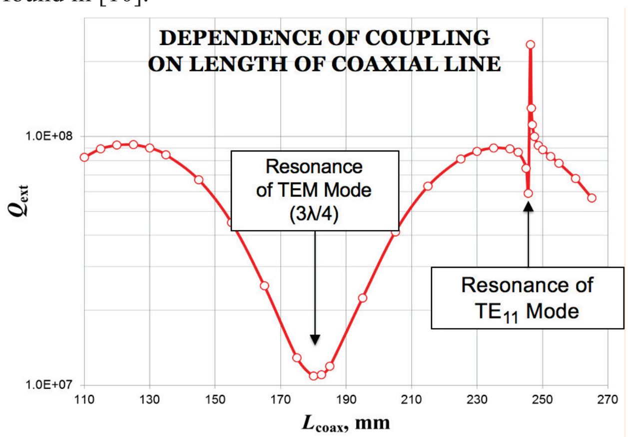

Figure 4: External quality factor for the super-symmetric power coupler in an ILC like geometry.

THERMAL ANALYSIS

Without an active cooling of the cylinder forming the coaxial transition, the coupler as designed may under certain conditions be thermally unstable. Operation experience in Darmstadt suggested that the coupler may become normal conducting in case beam losses occur. To investigate this in more detail, we conducted a careful thermal analysis, as described below.

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 [11]:

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

$K_{e,s}/K_{e,n}(T)$ 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 [12]. The specific heat of the niobium cylinder was assumed to follow the Debye model $Cv = \gamma T + AT^3$. Using experimental data from [13], values for the parameters were calculated as $\gamma = 0.0946$ kgJK^2 and $A = 1.28 \times 10^{-3}$ kgJK^4 (for T > Tc) and $\gamma = 0$ and $A = 5.01 \times 10^{-3}$ JkgK^4 for T < Tc .

Table 1: Parameters of the Theoretical Model for the Thermal Conductivity of Niobium (taken from [12]).

Par.	value	definition
RRR	400	Residual res. ratio
ρ_{295K}	$1.45\bullet10^{-7}$ Ωm	Resistivity at 295 K
L	50 μm	Phonon mfp (Nb)
T_C	9.2 K	Critical temp. (Nb)
L	$2.45\bullet10^{-8}$ WK^{-2}	Parameter of equ. (1)
A	$2.3\bullet10^{-5}$ mW^{-1} K^{-1}	Parameter of equ. (1)
B	$7.0\bullet10^{3}$ Wm^{-2}K^{-4}	Parameter of equ. (1)
1/D	300 mK^{-3}W^{-1}	Parameter of equ. (1)
α	1.76	Parameter of equ. (1)

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, representing the worst place a beam could hit. Due to the RF field, there is additional heating along the cylinder surfaces which follows the equation

$$\frac{dP}{dA} = \frac{1}{2}R_s\,|H|^2$$

where dP/dA is the power dissipated per unit area, Rs is the surface resistance, and H is the local magnetic field.

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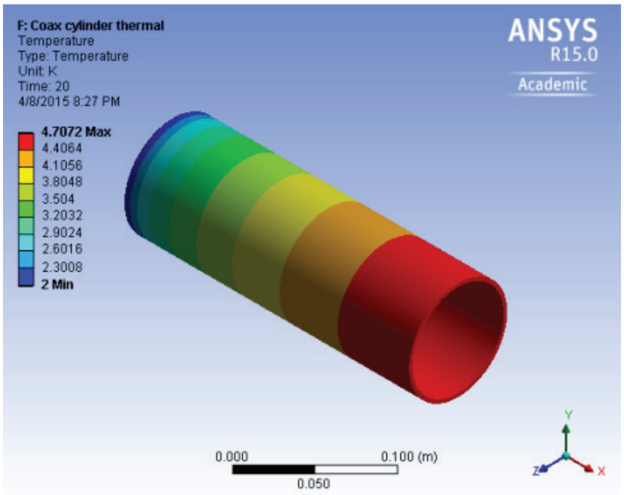

Figure 5: Steady state temperature distribution of the coaxial cylinder, when exposed to RF field and an additional beam loss induced heat load of 0.5 W at the outmost position.

For T < Tc , the surface resistance follows the well-known BCS equation. In our calculation we assumed a residual resistance of 5 nΩ. The magnetic field values were used to model RF heating as a temperature dependent, position-dependent heat flux into the cylinder. 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 1×10^{-5} W in the superconducting state. As we found that RF heating is not a factor in the thermal stability, we continued our calculation using an 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.

Figure 6 shows the steady state temperature distribution of the cylinder subject to RF losses and a 0.5 W deposition from an electron beam halo. The maximum equilibrium temperature along the cylinder under these conditions is about 4.7 K. Simulations with greater beam deposition showed that the power necessary to drive the

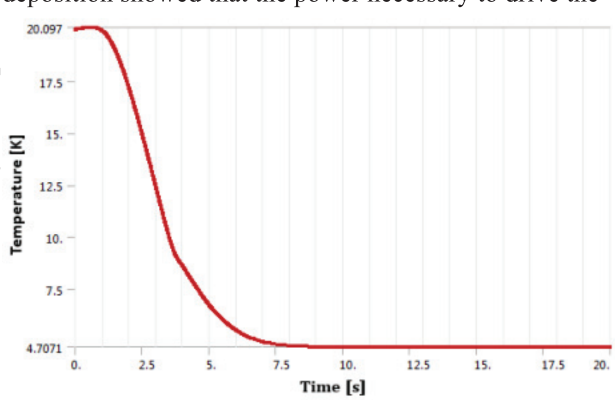

Figure 6: Recovery from a quench, as described in the text.

cylinder above Tc at steady state would have to be greater than 5.5 W.

Furthermore, we calculated how the coupler would recover from a quench once it occurs. Details of the quench process and its recovery depend on operational parameters of the cavity, energy levels and on quench detection and RF tripping 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 the 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, which confirms operational experience, too.

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 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 [14].

The five lowest frequency modes were calculated for each component. The frequencies of these modes are given in tab. 2. Results for the lowest frequency mode of the waveguide and the coax cylinder are given in fig. 8 and Fig. 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.

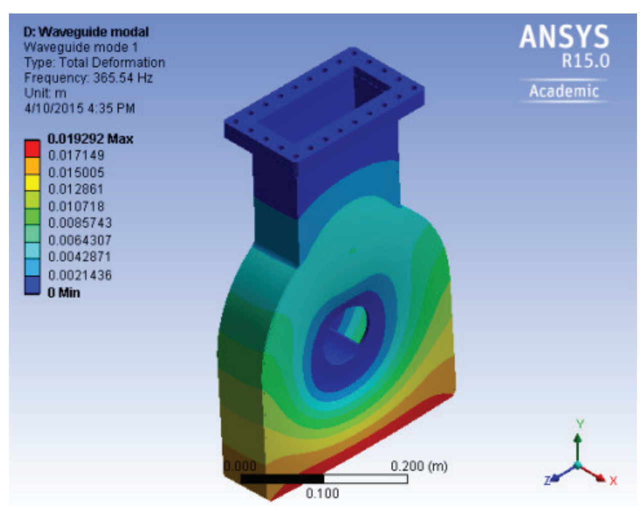

Figure 7: Lowest natural frequency mode of the waveguide at 365.5 Hz.

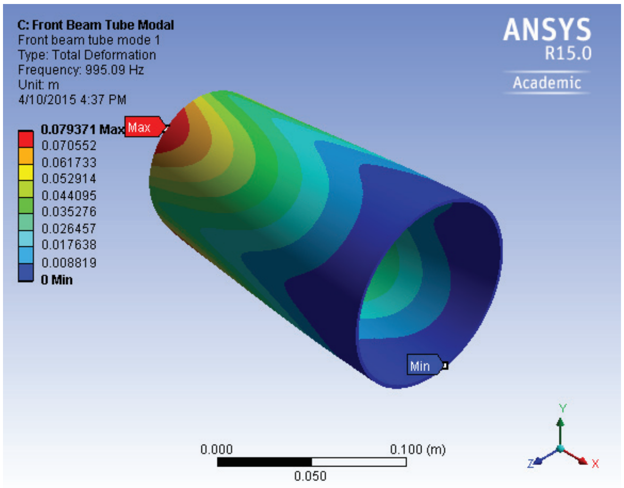

Figure 9: Lowest mechanical eigenmode frequency of the coaxial line, found at 995.2 Hz.

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

Wave-guide	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

POTENTIAL APPLICATION

RF fields as calculated during the design process have been used to investigate the effect of the time dependent coupler kick on the emittance growth, using beam parameters of the LCLS-II machine. As of now, a slightly smaller emittance growth, compared to a conventional coupler has been calculated [15]. However, the difference has been found too small to justify pursuing this new design, given the time line of the project.

This does not preclude that for other beam parameters the reduced coupler kick of this coupler may lead to a more significant reduction of the emittance growth.

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 very small transverse kick to the beam, which 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 quenches, 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 to exclude strong mechanical excitation.

The symmetric coupler can be integrated into the design of the superconducting cavity. Even so 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.

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