NUMERICAL INVESTIGATIONS OF WAVEGUIDE INPUT COUPLERS FOR THE TESLA SUPERSTRUCTURE

M.Dohlus, S.G.Wipf, DESY, Hamburg, Germany

Abstract

A superstructure of cavities has been proposed for the superconducting TESLA Linear Accelerator which will reduce the number of components (Input and HOM couplers) and also improve the average gradient. Thus the input power per input coupler has been drastically increased: 700 kW (T_{hf} =1.4 ms, f_{rep}=5 Hz) for the design operation and 1.4 MW for the possible upgrade version. In this paper two types of waveguide couplers were examined, including windows and bellows, taking the geometrical limitations of the cryomodule into account with respect to: maximum fields, cryogenic losses and the kick experienced by the beam.

1 INTRODUCTION

The parameters for the Tesla Technical Design Report, (TDR)[1], for a superstructure with 28 cells and an active length of 3.23 m, are shown in Table 1.

Table 1: Tesla Technical Design Report Parameters

	500 GeV	**800 GeV**
Average Gradient	22 MV/m	35 MV/m
Q_e	2.4 10^6	2.7 10^6
RF-Pulse Length	1.38 ms	1.38 ms
Beam Pulse Length	0.95 ms	0.86 ms
Bunch Current	9.5 mA	9.3 mA
Power per coupler, incl. regulation reserve	0.7MW	1.4 MW
Repetition rate	5Hz	4Hz

The peak power for which the coupler must be designed is however considerably higher than the power which is transmitted to the beam. This is due to:

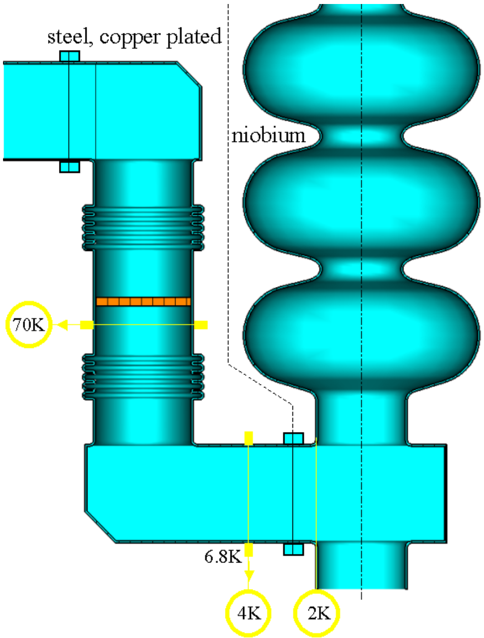
The filling of the resonator: At the beginning of the fill process there will be 100% reflection. This leads to a standing wave pattern where the peak field can reach an amplitude which is double that of the matched field at the maxima of the standing wave pattern.

Reflections during acceleration: The sources of reflection are: Lorentz force detuning and external adjustment of the external Q-factor, Q_e.

High peak power processing: This mode of operation is required for the processing of cavities or sub-cavities of the superstructure. During processing the peak fields in coupler and waveguides are increased by the same factor.

2 GEOMETRY

The geometry of the "L"coupler is shown in Figure 1, so named due to the two L-shaped bends. The beam couples the cavity to the rectangular waveguide, (85∗185mm^2) this connects to an elliptical waveguide (axes 85,170mm), running parallel to the cavity axis. An elliptical cross section is chosen to facilitate the technical construction of the bellows and the ceramic window. The bend protects the window from direct particle bombardment from the beam tube. Finally a further 90° bend connects to a rectangular waveguide (82.5∗165mm^2). The angles at the bends are so arranged that internal reflections at the bellows and window are compensated.



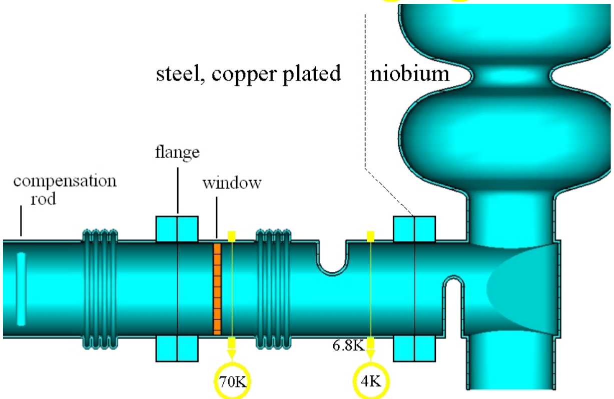


Figure 2. View of the "S" waveguide coupler showing the constrictions, bellows, window and compensation rod.

Figure 2 shows the straight, "S" version. In order to avoid the two bends, a straight elliptical waveguide is used, (axes 85, 170mm) with the window and bellows directly connected to the beam tube. Two constrictions, at the beginning of the waveguide, protect against particle bombardment. These also with the compensation rod provide the matching of the window and the bellows. As the S version needs considerably more transverse space than the L version, the connection flange to the exit side is directly behind the window.

2.1 Coupling and the Coupling Geometry

The coupling between the cavity and the waveguide is mainly determined by the distance between them and the distance to the waveguide termination on the other side of the beam tube. The slanted end of the S waveguide was originally for a designed to minimise the surface area and thus the electrical losses in normal conducting walls. The high gap fields compensate the loss of coupling. The length of the beam tube between the cavity and the beginning of the waveguide is practically the same in both S and L cases in spite of the different lengths of the termination (which is $\lambda/4$ or the L geometry)

3 PEAK FIELDS

Rectangular waveguides have an advantage over coaxial ones in that the same power transfer is possible with lower peak fields, see Table 2.

Increased fields always occur at every change of cross-section and at the connection to the ceramic window. For the S version at the position of the constrictions peak fields of 2.0 MV/m at the first and 2.8 MV/m at the second constriction occur, for an input power of 1MW. The L version is considerably better in this respect; at the connection between the elliptical and rectangular waveguides MAFIA[2] calculations give a maximum field strength of 1MV/m. A standing wave, which occurs in both versions in the area of the window, is necessary for the matching. For 1MW input power, the maximal field strength in that area is 0.8MV/m

4 RF LOSSES and HEAT LOSSES

The RF losses and the heat flow from a lower to a higher temperature level are particularly critical in couplers for superconducting structures, as they must be absorbed at low temperatures where the cryogenic systems have a relatively low efficiency.

Although waveguides have lower rf losses than coaxial lines, see Table 2, their greater cross-section leads to a higher thermal conductivity. In addition only the losses on the outer conductor of the coaxial waveguide count, as the inner conductor is only connected to the relatively non-critical temperature level of 70K. Table 2 lists the damping constants for different waveguide types, with frequency 1.3GHz and $\kappa=10^9 S/m$ for copper at 40K. The coupler is connected to the beam tube at 2K. Connections to 4K and 70K are as shown in Figures 2 and 3.

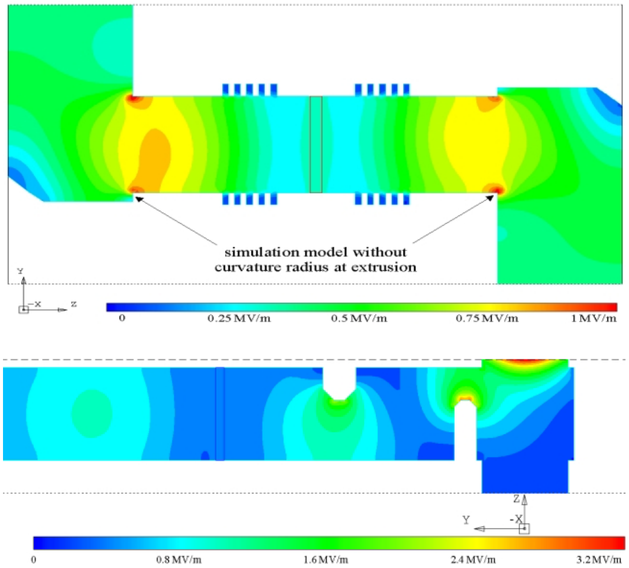


Figure 5. Contour plot of the fields in the L coupler (above) and the S coupler (below), where the field amplitudes at the constrictions can be seen ($P=1MW$).

Table 2: Damping constants and peak fields

Wave-guide	**Dimensions,** mm	**Damping constant,** dB/m	**Peak E-Field,** MV/m
coaxial	70Ω, ∅=80	$2.36\cdot10^{-3}$ (1)	1.1
rectangular	82.55·185	$1.09\cdot 10^{-3}$	0.35
rectangular	82.55·165	$1.32\cdot10^{-3}$	0.39
elliptical	85·175	$1.82\cdot10^{-3}$	0.45

Both the waveguide and the bellows are copper-plated steel, 2mm and 0.2mm thick respectively, with 10µ plating (RRR=10). The effective length of the bellows is 3 times the geometrical length. S version: 32mm, L version: 40mm. The bellows is very important to achieve a high thermal resistance in spite of the compact length. The window is ceramic (AlO), 8mm thick, $\varepsilon_r=9.5$, $\tan\delta=3\cdot10^{-4}$. In order to absorb the dielectric losses at the 70K level, the thermal line is placed just before the window.

As input quantities for the calculation of the thermal and rf losses for the matched coupler, the normalised losses, (with respect to input power and conductivity), were determined by means of field calculations. In the case of the L version, the bellows was actually taken into account while for the S version the calculation was made without the bellows and the losses were appropriately scaled afterwards. The solution of the coupled thermal problem $\kappa=\kappa(\tau)$, $\lambda=\lambda(\tau)$) was achieved with the help of a one dimensional model. The normalised 1-D losses (κ=const.) were determined per unit length of the waveguide (including discontinuities and constrictions) from 3-D calculations for the matched coupler. The resulting cryogenic loads are shown in Table 3.

---

(1) only 23.7% losses are on the outer line, i.e. $0.66\cdot10^{-3}$ dB/m are applicable

Table 3: Thermal and rf losses for the matched couplers

f_{rep} = 5*Hz*, *rf pulse length*=1.4*ms*		
Klystron Operation	L Version $\boldsymbol{P_{2K}}$ **/** $\boldsymbol{P_{4K}}$ **/** $\boldsymbol{P_{70K}}$(W)	S Version $\boldsymbol{P_{2K}}$ **/** $\boldsymbol{P_{4K}}$ **/** $\boldsymbol{P_{70K}}$(W)
static losses (Power, P=0)	0.039 / 0.83 / 2.79	0.013 / 0.086 / 2.89
P=0.8 MW	0.127 / 1.81 / 4.04+2.96 (2)	0.165 / 1.79 / 4.73+2.96 (2)
P=1.4 MW	0.153 / 2.67 / 5.08+5.20 (2)	0.209 / 2.53 / 6.26+5.20 (2)

5 COUPLER KICK

The integrated transverse field strength, $V_t = \int (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \mathbf{e}_t dz$ can be written as

$$V_t = M_1 \cdot a + M_2 \cdot b \tag{1}$$

where M_1, M_2 are coupling constants, for the incoming and outgoing waves, *a* and *b*.

The reference plane for the wave parameters is at the entrance to the coupler. The coupling constants can be determined by calculating the fields of the matched coupler ($a=a_1, b_1=0 \Rightarrow \mathbf{E_1}, \mathbf{B_1}$), thus $M_1=V_t/a_1$.

The fields for the second coupling constant can be calculated using $\mathbf{E}_2=\mathbf{E}_1^*$, $\mathbf{B}_2=\mathbf{B}_1^*$, $a_2=0$, $b_2=b_1^*$, which fulfils all the boundary conditions. The operation mode of the cavity can be excited by the beam within a few periods. After this excitation is turned off, the decay of the fields ($a=0$, $b \propto exp(-t\omega/2Q)$) is very close to the conditions for calculating M_2 ($a=0$, $b=const$), due to the high external Q-factor (in our case $>10^6$). The first coupling constant can then be determined from the second.

In the stationary case, when the cavities are filled, the forward and backward waves are fully determined by the running conditions (beam current I_b, accelerating voltage V_{acc}, operation frequency ω) and the cavity parameters (external Q-factor Q_e ,longitudinal loss parameter $k_{||}$, and the ratio of detuning to operational frequency $\delta\omega/\omega$) .

$$a = I_b \sqrt{\frac{2Q_e k_{||}}{\omega}} + V_{acc} \sqrt{\frac{\omega}{2Q_e k_{||}}} \left(\frac{1}{2} - j \frac{\delta\omega Q_e}{\omega} \right), \tag{2}$$

$$b = -I_b \sqrt{\frac{2Q_e k_{||}}{\omega}} + V_{acc} \sqrt{\frac{\omega}{2Q_e k_{||}}} \left(\frac{1}{2} + j \frac{\delta\omega Q_e}{\omega} \right).$$

This assumes that the reference plane is so chosen that the wave parameters are in phase with the the cavity. For reflection free operation ($b=0$), it is necessary that $\delta\omega=0$ and $I_b=V_{acc}\omega/4Q_e k_{||}$. When this relation between I_b and V_{acc} is fulfilled, but $\delta\omega \neq 0$, the forward and backward waves can be determined. An important parameter which characterises the coupler kick is the quotient given by

$$\frac{V_t}{V_{acc}} = \sqrt{\frac{\omega}{2Q_e k_{||}}} \left(M_1 + (M_2 - M_1) j \frac{\delta\omega Q_e}{\omega} \right). \tag{3}$$

The real part acts on a bunch in phase with V_{acc}. The kick for the S version is considerably higher than for the L version. This is determined by the coupler geometry: as the beam pipe is situated practically at the end of the waveguide, transverse magnetic fields are excited, which, for the L version with the λ/4 termination, are much smaller. It would of course be possible to use the same termination for the S version.

6 LORENZ FORCE DETUNING AND KICK

Due to the high external Q with which the superconducting cavities are operated, they are also sensitive to very slight detuning of the order of ω/Q_e or greater. One cause is the the Lorenz forces which react with the cavity walls and cause a time dependent detuning, $\delta\omega$, and deformation during an rf pulse. This influences the coupling fields and thus also the beam, see equation (3). Although the stationary part of the coupler kick can be compensated by static corrections, the "detuning" dependent part varies during one bunch train (0.95 msec).

This effect could be avoided by using couplers on the same side but alternately "upstream" and "downstream" of the super-structure. The coupling parameters, M_1 and M_2, are then connected by

$$M_1^{(down)} = -\overline{M}_2^{(up)} \ , \ M_2^{(down)} = -\overline{M}_1^{(up)} \tag{4}$$

The normalised transverse voltage of both couplers together, V_1/V_{acc} can be obtained from (3)

The detuning dependent term is purely imaginary and does not effect the bunches which are in phase with the accelerating field.

7 SUMMARY

The geometrical and thermal boundary conditions in the TESLA cryostat can be fulfilled for both the waveguide coupler versions. The coupler kick of the L version is comparable to that of the coupler used in the TESLA Test Facility, while the detuning independent part is even better. The peak fields are lower than those in an *ideal* coaxial coupler (∅=80cm and no changes in cross-section). The main disadvantage of the geometrically more attractive S version are the peak field strengths at the constrictions.

REFERENCES

[1] Basic Assumptions for the TESLA Technical Design Report. R. Brinkmann ,April 2000, private communication.

[2] The MAFIA Collaboration, CST GmbH, Buedinger Str. 2a, D-64289 Darmstadt, Germany.

---

(2) dielectric losses in ceramic