A Telescopic RF Input Coupler for TESLA

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Abstract

A telescopic-type RF input coupler for the TESLA superconducting cavities is under study. We present the results of numerical computations for waveguide to coaxial line transition designs that could be used to test a prototype of such a coupler.

1 Introduction

The project for a TeV Energy Superconducting Linear Accelerator (TESLA) is being studied by an international collaboration[1]. The main concepts of this approach to a next generation linear collider and the new technologies for superconducting (SC) cavities will be demonstrated and verified on the TESLA Test Facility (TTF), now under construction at DESY [2].

The basic TESLA accelerating structure is a 1 m long, 9-cell SC cavity operating at a frequency of 1.3 GHz and an accelerating gradient of 25 MV/m. Each of these cavities has one input power coupler and two high order mode (HOM) couplers. The RF requirements of the input power coupler is a peak power of 208 kW for 1.3 ms at 10 Hz repetition rate (average power consumption 2.8 kW). For High Peak Power (HPP) processing of the SC cavities in situ the coupler should be capable of withstanding 1 MW pulsed power transmission at reduced pulse length and repetition rate (100 µs at 0.5 Hz). The maximum electric field in the HPP regime will reach 1.4 MV/m on the inner part of the coaxial line near the cavity. The input coupler must also accommodate a 15 mm cavity motion during cryostat cool down and must minimize the cryogenic heat load with and without the presence of RF power. The coupling should be adjustable to change the external Q over the range \(1 \times 10^6\) to \(9 \times 10^6\). The variable coupling is needed to compensate variations in cavities, couplers, the RF distribution system and the beam current. To do this the antenna of the coupler must be movable in range ± 5 mm [3].

The coupler is one of the critical components of the TESLA approach to a linear collider. At the present time two different designs for such a coupler have been developed, one at FNAL and the other at DESY[4,5]. A few prototypes of both couplers have been tested at Fermilab and DESY at high power level. Although the latest results for the FNAL design are quite encouraging, nevertheless, many problems are still unsolved. During a recent workshop on couplers (29-30 May 1996 at DESY) it was confirmed that neither of these couplers satisfy all requirements completely, therefore there is a strong interest in alternative coupler designs with improved or more economic features.

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The main problems with the existing designs have been identified with the following elements of the coupler; the cold and warm windows and the bellows in the coaxial line. To avoid the need for a cold window, to reduce the manufacturing costs of the coupler and to simplify its assembly inside the cryomodule, a telescopic type coupler has been suggested at LAL.

2 Coupler design

The TESLA linac will use ultraclean technology whereby all SC cavities and couplers should be assembled and pumped in a clean room before mounting inside the cryostats. The entire coupler, however, is not mounted inside the cryostat. Therefore both existing coupler designs consist of two parts, one of which is assembled with the cavity in the clean room, while the second part extends out of the cryomodule. In this approach two ceramic windows are necessary. The cold window separates the high vacuum in cavity from the vacuum in the outer part of coupler. The warm window separates the coupler vacuum from the waveguide atmosphere. In the proposed telescopic design, the whole coupler is assembled once in a clean room, hence, the need for a cold window is obviated.

The main idea of the telescopic coupler is illustrated in Fig.1, where the coupler is shown in three states. In the folded state (1) the coupler is mounted with the cavity in a clean room and stays in this state during assembly of all cavities, pumping (or filling with dry nitrogen) and installation inside the cryomodule. The coupler has a common vacuum with the cavity and is isolated from the atmosphere by the cylindrical warm window (as shown on Fig.1) or by a vacuum valve. In the second stage, the coupler is extended (2) like a telescope to be attached to the feeder waveguide system outside the cryomodule. The bellows on the external side of the coaxial line allows the length of the coupler to be almost doubled.

During cool down the SC cavities shrink along the beam line (towards one fixed point at the centre of the cryomodule) with a maximum shift of about 15 mm. The cold end of the coupler follows this shrinkage and therefore, to compensate, the coupler should be mounted before cooling in position (3) so as to be in the correct position (2) after cool down.

The coupler has a tapered coaxial line (from $\Phi 40$ mm at the cavity end to $\Phi 60$ mm at the waveguide end) which consists of three-parts for the outer line and two-parts for the inner line. An initial gap (at room temperature) of 0.05 mm between adjacent parts seems enough for easy sliding. The coupling can be changed by moving the antenna (the inner electrode) with the help of the bellows from outside the cryomodule. A spring inside the inner electrode of the coaxial line will try to maintain the coupler in its unfolded state.

An obvious problem which one could encounter with this type of coupler is the RF contact between unbrazed parts of the coaxial line. However, several solutions exist which could provide a good mechanical contact between sliding parts after cooling down to 70°K.

The first is the well known sliding finger contact, which has been reported to have been successfully used in a high power coupler during a long operating period [6]. This kind of solution is simple enough and could be applied to the telescopic coupler after further study.

Another possible solution is the coaxial choke cavity, frequently used in moving joints [7]. This type of contact has been also tested for the LEP coupler. The calculations made for the telescopic coupler geometry show that the fields inside the choke are small enough and that the rf current in a sliding contact can be reduced considerably. However the manufacture of a coupler using a choke cavity in place of contacts would appear to be complicated because of the small dimensions of the coaxial line.

The third option to achieve a good RF contact would be to use materials with different thermal expansions coefficients, that result in a strong contact after cooling to liquid nitrogen temperature (the working temperature at the location of the contact). The properties of the proposed metals for the working tem-
perature are presented in the table below:

<table>
<thead>
<tr>
<th>Material</th>
<th>α/10⁻⁶</th>
<th>300°K</th>
<th>200°K</th>
<th>100°K</th>
<th>75°K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel</td>
<td>16.8</td>
<td>15.2</td>
<td>10.2</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>17.0</td>
<td>15.1</td>
<td>10.5</td>
<td>7.6</td>
<td></td>
</tr>
<tr>
<td>Titanium</td>
<td>8.9</td>
<td>7.2</td>
<td>4.4</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>Tungsten</td>
<td>4.5</td>
<td>4.1</td>
<td>2.7</td>
<td>1.8</td>
<td></td>
</tr>
</tbody>
</table>

In our proposed telescopic coupler design the middle part of the outer electrode is made from the copper and connected with the flange, held at the temperature of liquid nitrogen, 70°K. The remaining parts are made from the stainless steel to reduce heat losses which should be less, than 6 W, 0.6 W and 0.06 W for 70°K, 4°K and 1.8°K respectively. To reduce RF losses all internal parts of the coupler should be plated with 10 μm of copper. The tip of the copper tube will be brazed with titanium (or tungsten). The initial 0.05 mm gap between sliding tubes Ø60mm will decreases to 0.01 mm after cool down. This is enough to compensate the initial gap and to ensure a good RF contact. In this case the deformation is still plastic. The other contacts are obtained in the same way, as is shown schematically in the figure below.

Therefore we have chosen the third option for the telescopic coupler and this type of contact is now under study.

3 Test of rf contact

To study the quality of the rf contact at high power level, a test setup, the general view of which is shown in Fig.2, was designed. The two RF contacts are arranged between the three parts of the coaxial line’s outer conductor. All of them are made from stainless steel, coated with 10 μm of copper. To have the same contact as in a real design the diameters of contacting tubes differ, therefore they can be assembled in only one way: one should be heated while the other is cooled to LN temperature. While testing at room temperature the contacts will be much stronger. The single piece inner conductor is tapered to maintain 50 Ω impedance everywhere in the coaxial line. To transmit the RF power from the klystron to the load through the coaxial line, two different waveguide/co-axial transitions are used. One of them with a Ø 60 mm coaxial line has been developed for the coupler design itself, while the other, with Ø 40 mm (the diameter of that part of the coupler welded to the SC cavity beam tube) is necessary for tests of the coupler.
For these tests a few diagnostics are foreseen; vacuum and RF (forward and reflected waves) measurements, e− pick-up electrodes, RF antennas outside the coaxial line, viewports for checking for sparking and, of course, visual observation after the high power tests. The coaxial line is pumped via the waveguide. The area around the contacts is under vacuum and will be pumped independently.

This setup is now under manufacture. The waveguide to Ø 40 mm coaxial line transition is ready and has been tested at low power level. The geometry of this transition, matched using four stubs, is shown in Fig.3. The measured and simulated (by HFSS) reflection coefficients (S11) vs. frequency for two different positions of the short circuit are in good agreement (see Fig.4). Frequency tolerance to the short circuit position is about 12 MHz/mm. The high power tests of the contacts will be done on a test stand at Saclay (CEA) with a 1.6 MW klystron (1.3 GHz, 1.3 ms pulse length, 0.1 Hz repetition rate) [8].

Recent calculations have shown that the same transition (coax Ø 40 mm) could be made more simply by using a doorknob type geometry and matching with a capacitive diaphragm in the waveguide (Fig.5). HFSS (High Frequency Structure Simulator) simulations indicate that this transition has a very broad bandwidth, of the order of 320 MHz (see Fig.6).

4  Waveguide to coaxial line transitions.

This component of each coaxial coupler transforms the TE01 mode transmitted by WR650 waveguide into the TEM mode transmitted by the coaxial line. To achieve the minimum reflection coefficient at 1.3 GHz, which is necessary for good RF efficiency, the Hewlett-Packard HFSS code has been used. For the telescopic coupler two different designs of the transition have been studied:

- The DESY-type transition with the cylindrical warm window.
- The Fermilab-type doorknob transition without window.

We adopt the latter option with the vacuum valve and the planar warm window mounted in the waveguide.

In all cases we have used WR650 waveguide tapers to reduce the guide height to 45 mm. It is important for the telescopic coupler to reduce the weight and dimensions of the transition, which forms part of the coupler. The diameter of the coaxial line was chosen to be 60 mm to reduce multipactor problems. The main goal of our simulation was to obtain a low reflection coefficient and a broad passband, providing a low sensitivity of the transmission coefficient from geometry variations due to manufacturing tolerances, heating etc.

The construction of the first design is similar to the DESY design, but with increased window and coaxial line diameters. A general view of the half-geometry of the WG-coax transition is shown in Fig.7. The ceramic (Al2O3) window, Ø 76 mm and width 4 mm, is supported by two copper collars, Ø 80 mm and 1 mm thickness, to prevent it from mechanical loads and shocks. The waveguide is assembled with the coaxial part of the coupler outside the cryostat and so, to provide a good RF contact between them, two metallic rings are applied around the window (above and below). Two stubs Ø 10 mm on the air side allow this transition to be matched. The calculated passband for this design is approximately 40 MHz (see Fig.8).

The electric field map on the mid-plane (plane of symmetry) is shown in Fig.9. The maximum field is concentrated inside the ceramic window close to the tips of the collars. Electric fields were calculated for 1 W of forward RF power. High fields on the ceramic, (about 1 MV/m for 200 kW forward power) can produce sparks, first of all from the air side. These fields are higher than the maximum electric field
in the coaxial line for the travelling wave regime, given by:

\[ E(V/m) = \frac{\sqrt{2}P[W] Z[\Omega]}{r_0 \times ln(r_1/r_0)}, \]

where \( r_0, r_1 \) are the inner and outer radii of the coaxial line. This gives \( E_{\text{max}} = 0.9 \) and \( 1.4 \) kV/m for \( \Phi 62 \) mm and \( \Phi 40 \) mm diameters respectively, and \( 1 \) W of travelling wave power (\( Z = 50 \Omega \)).

The geometry of the doorknob transition, is shown in Fig.10. The calculated passband, about 140 MHz (see Fig.11), is broader than for the DESY type transition. The advantages of this type of transition are the simplicity of the design, less sensitivity to manufacturing errors and sufficiently low electric fields on the surface of the doorknob (Fig.10). The electric field map in the plane where it achieves its maximum value is shown in Fig.12. The vacuum isolation for this transition is provided by the waveguide window, available from industry (TH 20141A). One of these windows has been successfully tested at Saclay up to 1.6 MW [8]. During assembly, a telescopic coupler with a doorknob transition could be isolated from air by a vacuum valve. This possibility is under study.

5 DC bias.

From experience obtained at CERN the major problem for the power handling capability of couplers for SC cavities arises from multipactor (MP) in the coaxial line [9]. The power scaling for one point multipactor (taking place on the outer electrode), which appears to be the more dangerous, was found [10] to be:

\[ P_{\text{mp}} \sim f^4d^4Z, \]

where \( f \) is the RF frequency, \( d \) - the diameter and \( Z \) - the impedance. For example, the calculated MP threshold starts from tens of kW travelling wave power for a \( \Phi 40 \) mm coaxial line. The first cure to suppress MP is to increase the diameter and/or the impedance of the coaxial line. However, the more successful method to suppress MP is to apply a DC bias between the outer and inner coaxial lines. A voltage of a few kV allows one to completely avoid MP. Other well known procedures such as titanium (or titanium compounds) coating or surface treatments should be applied also but used alone they cannot ensure success [11].

We could apply these same remedies to both transition designs discussed above for the telescopic coupler with the increased diameter of coaxial line, \( \Phi 60 \) mm. The first design with a cylindrical window can be adapted easily for DC bias on the air side by using a thin kapton foil (50 \( \mu \)m) as was done for the CERN coupler.

For the second design, which uses the doorknob transition, the DC voltage should be on the vacuum side, so only materials suitable for vacuum isolation are allowable. To prevent RF radiation through the radial slit (used for DC bias) a choke cavity is proposed. The geometry of the choke is shown in Fig.13. The cavity consists of two quarter-wavelength lines. The insulating ceramic is installed in the gap between these two parts, i.e. in an open circuit location. The electric and magnetic fields along the first and second quarter-wavelength parts of the choke cavity are shown in Figs.14 and 15 respectively. The maximum voltage in the choke, calculated using HFSS, is about 70 V (for 200 kW TW power), which is under the MP threshold (the impact energy of the electrons is of the order of 10 V).

Similar, but more compact, designs with modified geometries for the choke cavity are shown in Fig.16. HFSS simulations of the doorknob transition with the modified choke cavities show that RF radiation through the choke can be negligible. This kind of DC insulation could be applied to any coupler design. A transition with DC bias is now under study and might hopefully be tested this year.
6 SUMMARY.

We have studied and optimized a few types of waveguide to coaxial line transitions for the telescopic coupler: A doorknob transition without a window, a DESY type transition with a cylindrical warm window and designs for Ø 40 mm coaxial line. As the problem of MP in the coaxial line of the coupler appears to be very serious, the application of a DC bias seems to be necessary in order to suppress it. We propose a choke cavity to isolate the inner and outer conductors without power radiating through the coaxial slit.

There remains the problem of the sliding contacts between un-brazed parts of the telescopic coupler. It was decided to use metals with different thermal expansion coefficients to ensure a strong contact at LN temperature. A setup for a high power test of this type of contact was designed and ordered. Low power tests of a WG-coax transition for Ø 40 mm coax were performed and show good agreement between HFSS simulations and the measurements. High power tests will be performed at Saclay this year.

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References

Figure 1: A telescopic coupler in three states: (1)-folded, (2)-extended (working state), and (3)-assembled before cool down.
Figure 2: A design for testing of the rf contacts in the telescopic coupler.
Figure 3: Half-geometry of the waveguide to coaxial line (Ø 40 mm) transition, matched by four stubs.

Figure 4: $S_{11}$ - reflection coefficient vs. frequency for WG-coax transition matched by stubs. (1) - HFSS calculation, (2) - measurements.
Figure 5: A broadband doorknob transition (Ø 40 mm coaxial line), matched by a diaphragm inside the waveguide.

Figure 6: Reflection coefficient \( S_{11} \) for doorknob transition.
Figure 7: A general view of the DESY-type WG-coax (Ø65mm) transition with cylindrical window.

Figure 8: $S_{11}$ coefficient vs. frequency for DESY-type transition.
Figure 9: Electric field map on the transition mid-plane. (forward rf power = 1 W).

Figure 10: The geometry and electric field map inside the doorknob transition (coaxial line Ø 62 mm).
Figure 11: $S_{11}$ coefficient calculated for the doorknob transition ($\Theta$ 62 mm), shown in Fig.10.

Figure 12: Electric field map in the plane $z = 25$mm, where it has its maximum value on the doorknob surface.
Figure 13: Geometry and field map for the doorknob transition with a choke cavity for DC bias.

Figure 14: Electric fields inside the choke cavity. 1. - first (narrow) quarter-wavelength line part, 2.- second part.
Figure 15: Magnetic field along the second (wider) part of the choke cavity.
Figure 16: Two different designs of the WG-coax doorknob transitions with DC bias. A choke cavity is used to suppress radiation.