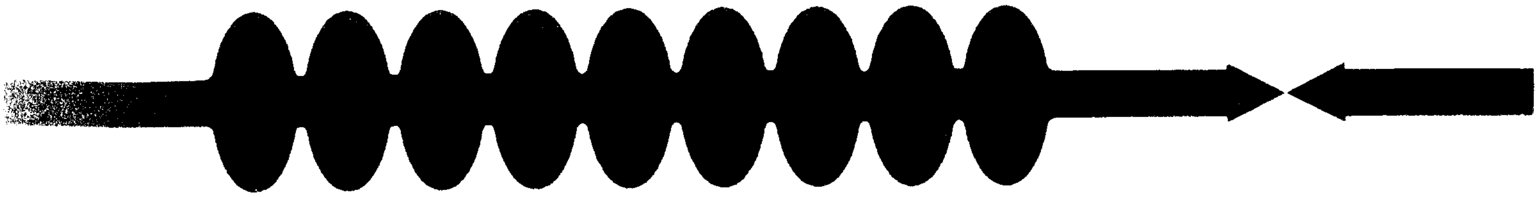

# TESLA - COLLABORATION

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# DESIGN OF POWER AND HOM COUPLERS FOR TESLA

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## ABSTRACT

The basic TESLA accelerating structure is a 1 m long, 9-cell superconducting cavity operating at a frequency of 1.3 GHz and an accelerating gradient of 25 MV/m. Each of these cavities has one fundamental mode power input coupler and two higher order mode (HOM) couplers. The rf requirement of the input coupler is a peak power of 200 kW for 1.3 ms at a 10 Hz repetition rate. 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 rf power present. The HOM couplers must extract from the cavities the beam induced HOM energy that does not propagate to the rf absorbers located at the end of each cryomodule. Two distinct input couplers and two distinct HOM couplers designs have been produced. Their design criteria and performance will be reported.

## INTRODUCTION

TESLA [1] (TeV Energy Superconducting Linear Accelerator) is one of a family of proposed $e^+e^-$ linear colliders[2] with a CM collision energy of 500 GeV. TESLA is unique among these proposed accelerators in that it uses superconducting rf accelerating cavities. The basic TESLA accelerating cavity[3] is shown in Figure 1. It consists of 9 cells that are dimensioned to operate in the standing wave $\pi$ mode of the $TM_{010}$ passband at a frequency

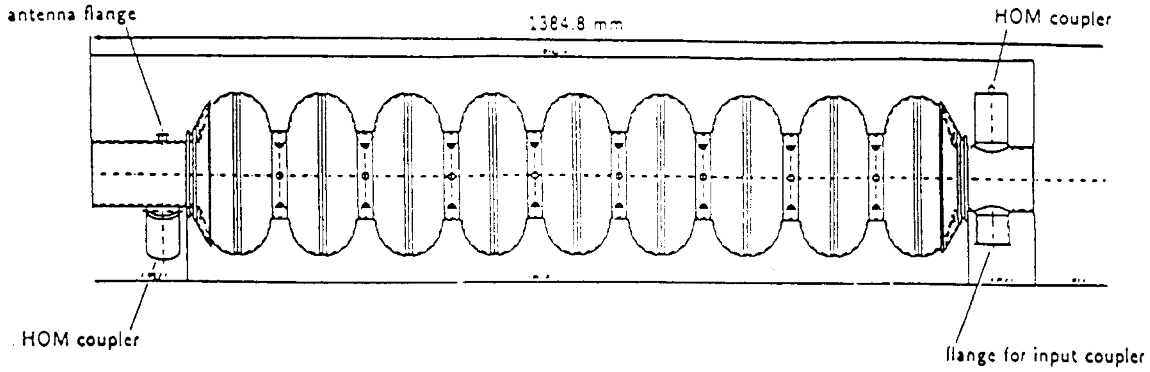

**Figure 1.** TESLA 9-cell superconducting cavity with coupler locations.

of 1.3 GHz. The cells, bore tube and flanges are fabricated out of high purity niobium sheets (RRR=300).

The basic rf power source[4] for TESLA is a 1.3 GHz klystron capable of producing a peak power up to 5 MW (100 kW average) at the TESLA duty cycle. The klystron rf output passes thru a circulator and is then split approximately equally by directional couplers into 16 WR650 waveguide channels to power 16 cavities. The input couplers transmit the rf power from the waveguide at room temperature to the cavity at 1.8 K. The circulator protects the klystron from the rf power that is reflected due to mismatches in the rf circuit, primarily from the cavity, but also due to imperfections in the waveguides and input couplers.

Each 9-cell cavity is energized by a single power input coupler to which 1.3 ms long rf pulses with a peak power of 200 kW are applied at a 10 Hz rate. The accelerating gradient of 25 MV/m is reached 0.5 ms after the rf pulse is applied. At this time, 800 beam bunches, spaced 1 μs apart, are injected into the cavities and accelerated. Each beam bunch contains 5 $10^{10}$ particles. The input coupler must also tolerate a 1 MW peak power pulse at reduced pulse length and repetition rate for in situ peak power reprocessing of 9-cell cavities after installation in the cryostat or after a vacuum failure.

As the beam bunches traverse the cavities, they excite higher order mode (HOM) resonances in the cavities. The electromagnetic fields of this induced HOM energy interact with the beam, causing beam instabilities, emittance growth and energy spread. The HOM energy is also an unacceptable 1.8 K heat load and in extreme cases can cause thermal breakdown of the superconducting cavities (quench) unless the HOM energy is extracted from the cavities. Approximately 70 % of the HOM energy in the TESLA cavities is expected to be above the beam tube cutoff frequency and will be absorbed by broad band rf absorbers located at the end of each cryomodule. The remaining HOM energy and some HOM energy above cutoff but trapped between the cavities will be extracted by the HOM couplers. Each 9-cell cavity has 2 HOM couplers for this purpose.

The basic TESLA cryogenic unit is the 12 m long cryomodule[5]. Each cryomodule contains eight 9-cell cavities plus beam focusing and steering magnets. Each 9-cell cavity within the cryomodule is contained within its own 1.8 K vessel. These vessels are filled by gravity with 1.8 K liquid He from the 1.8 K liquid He supply pipe located above the cavities. The cryomodule also contains 4.5 K and 70 K radiation shields. The He supply lines for these shields also serve as heat intercepts for devices that penetrate to the 1.8 K region, e.g., supports, input couplers, etc. The input coupler and 2 HOM couplers of each cavity are attached to the bore tube of the cavity outside of its 1.8 K vessel. This results in a simplified mechanical structure and eliminates a source of He leaks as all the coupler joints within the cryomodule have vacuum on both sides. However, the large number of cells per cavity makes it more difficult to obtain a uniform accelerating field in time for the next accelerated beam bunch and to couple adequately to all the HOM excited within the cells.

An international collaboration has assembled a TESLA Test Facility (TTF) at DESY, Hamburg, Germany, to demonstrate the technical viability of TESLA. TTF already has the infrastructure to clean, assemble and test superconducting cavities. The present effort is to produce 4 complete cryomodules that will be part of a 500 MeV test linac. As part of this effort, DESY[6] and Fermilab[7] have each developed an input coupler, and DESY[8] and Saclay [9] have each developed a HOM coupler.

## INPUT COUPLERS

The two TESLA input coupler versions are shown in Figure 2 and Figure 3. Although they differ in detail, they both satisfy the same electrical , mechanical and cryogenic requirements.

### Waveguide-Coax Transition

This component transforms the $TE_{10}$ mode transmitted by the WR650 waveguide into the TEM mode transmitted by the coaxial line of the coupler. This transformation needs to be achieved with minimum reflections (matched at 1.3 GHz) for rf efficiency and diagnostic reasons. The magnitude and phase of the reflected power are an important indicator of coupler and cavity performance. The Fermilab input coupler utilizes a

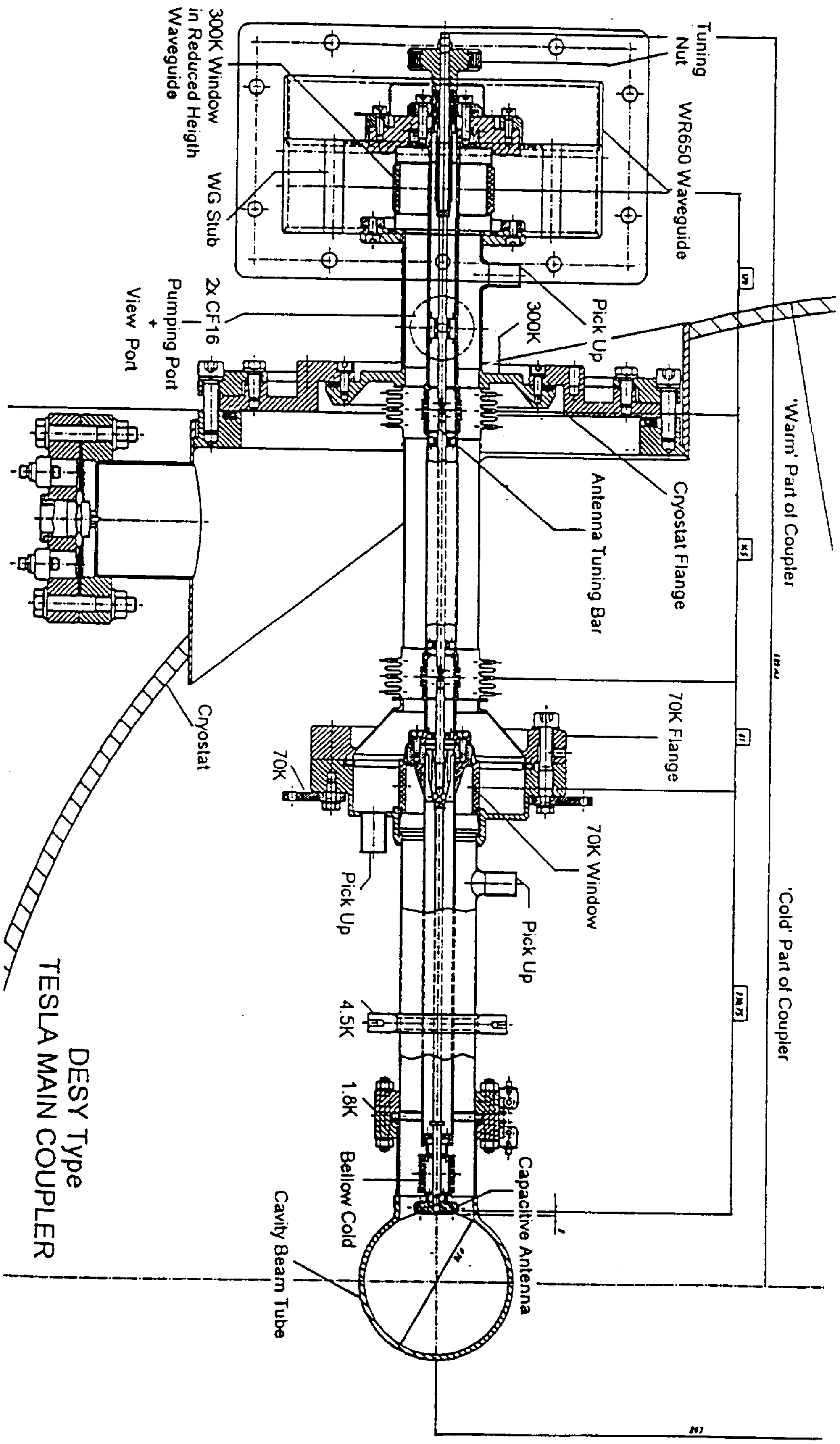

**Figure 2.** DESY designed TESLA power input coupler.

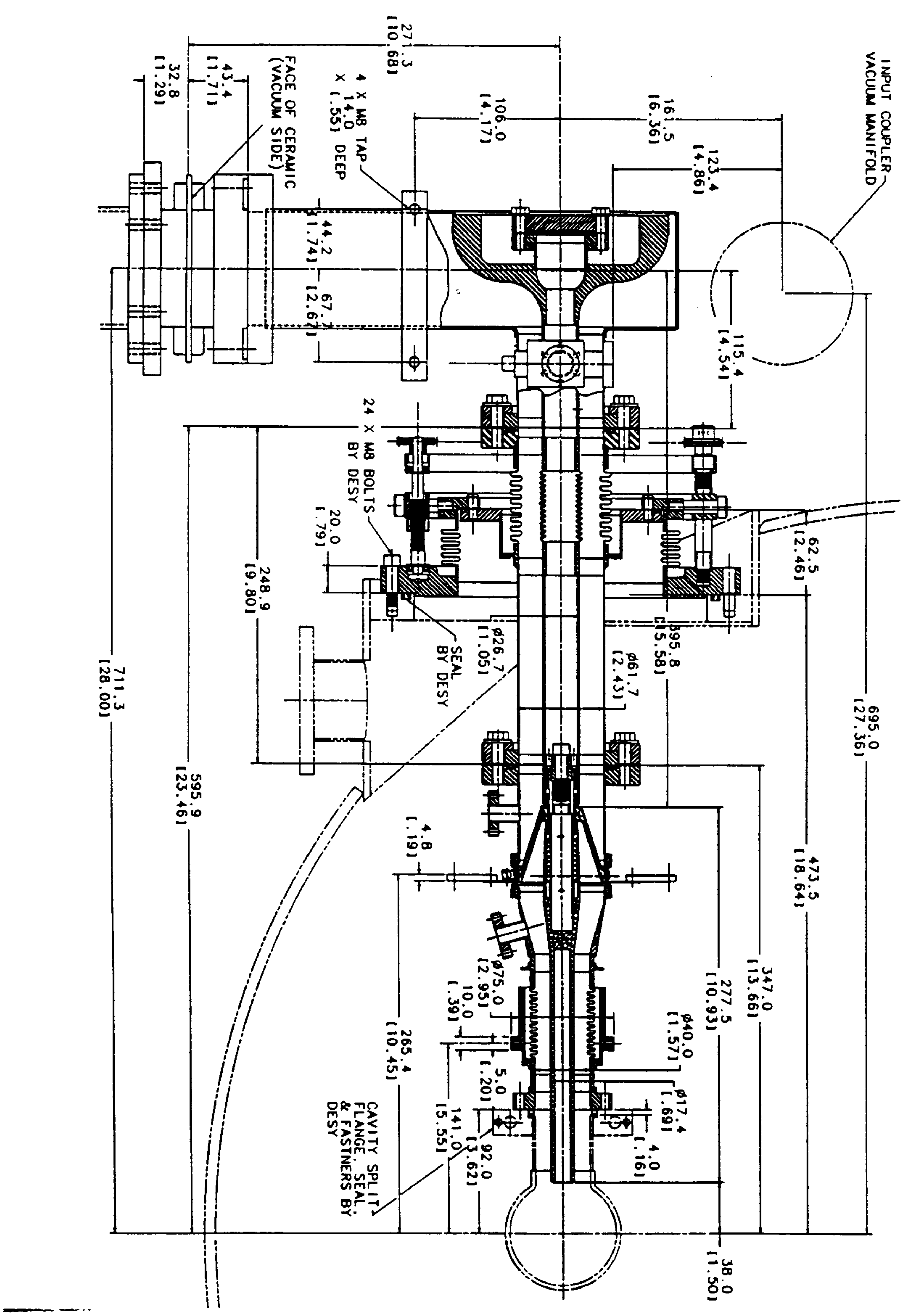

**Figure 3.** Fermilab designed TESLA power input coupler.

"doorknob" transition. The Hewlett Packard code, HFSS (High Frequency Structure Simulation), has been used to calculate the shape of the "doorknob" to assure a match at 1.3 GHz. The DESY transition uses a "flattened doorknob"; the WR650 waveguide tapers to a reduced height WR650 section. It is matched by two posts located in the reduced height waveguide upstream of the warm rf window.

### Warm Window

This component isolates the atmosphere in the waveguide from the upstream vacuum of the coupler. The Fermilab warm window is a commercial "pillbox" type, located immediately upstream of the "doorknob" transition and matched by two posts upstream of the window. The DESY warm window is cylindrical and mounted within the waveguide transition and concentric with the inner coax conductor. Both windows are fabricated out of high purity $Al_2O_3$ (>99%) and are "thin" to minimize rf losses.

### Cold Window

Both coupler versions have a cold rf window located close to the cavity. This window isolates the coupler vacuum from the ultraclean vacuum of the cavity. The cold window is attached to the cavity in the clean room and prevents contamination of the cavity by micron sized particles during subsequent handling and installation into the cryostat. The windows are "thin" and constructed out of high purity $Al_2O_3$. Both the Fermilab and DESY cold windows are matched to the coaxial line at 1.3 GHz. The Fermilab window is conical in shape. The DESY window is cylindrical.

### Coaxial Lines

Both coupler versions utilize a 50 Ω coaxial line to transmit the rf from the waveguide transition through the vacuum vessel of the cryostat. The coaxial line terminates on the bore tube at a point outside of the 1.8 K vessel that surrounds the cavity. The cold end of the outer coaxial conductor is cooled to 1.8 K by conduction through the niobium bore tube, connection tube, and flange. The static heat load and rf heat loads to the 1.8 K volume are minimized by 4.5 K and 70 K heat intercepts located slightly upstream of the 1.8 K flange and at the cold window respectively. The Fermilab coaxial line upstream of the cold window has an outer diameter of 6 cm and is fabricated out of thin walled stainless steel for mechanical rigidity and minimum heat conduction. The inner surfaces in contact with rf are plated with approximately 10 µm of copper. The coaxial line tapers to 4 cm after the cold window. The inner conductor of the 4 cm coaxial section is thick walled copper to keep the temperature at the inner conductor tip approximately equal to the 70 K temperature at the cold window. The DESY coaxial line diameter is 4 cm over its whole length. It is also constructed out of copper plated stainless steel with a copper inner conductor tip at its end.

### Bellows

Depending on their position in the cryomodule relative to the centrally located fixed suppport, the 9-cell cavities move up to 15 mm during cool down. Both coupler versions have bellows on the inner and outer coaxial parts of the coupler to allow this motion. When warm, the coupler is kinked. When cold, the coupler straightens to its nominal operating position. The bellows are hydroformed stainless steel and copper plated where necessary to reduce the rf surface resistance.

### Coupling Adjustment

Coupling to the 9-cell cavity needs to be adjustable to compensate for cavity performance variations. The nominally required external Q is $3\ 10^6$. The external Q of both coupler versions is adjustable approximately a factor of 10 around this value by adjusting the position of the coupler's inner conductor relative to the bore tube center. The Fermilab coupler achieves this by varying the length of the outer conductor bellow nearest to the bore tube. The DESY coupler adjusts the inner conductor bellow nearest to the bore tube. As the impedance of the 9-cell cavity changes as a function of accelerating field and accelerated beam current, the coupler is matched for the nominal accelerating voltage and beam current. During the rise time of the accelerating voltage in the 9-cell cavity and for beam currents other than the nominal beam current, a fraction of the rf power applied to the input coupler is reflected at the cavity-coupler interface and is absorbed by the rf load attached to the circulator. When the input coupler is matched to the cavity, the rf power going into the coupler is completely absorbed by the accelerated beam.

### Heat Load

The heat loads into the 1.8 K, 4.5 K and 70 K heat sinks have been estimated by a one dimensional program that divides the coaxial conductors into segments and then performs an energy balance on each segment. The program uses temperature dependent tables for the thermal conductivity and electrical resistivity of stainless steel and copper to calculate heat conduction and rf heating. At cryogenic temperature, the 10 μm copper plating dominates not only the rf loss but also the heat conduction. The thickness of the copper plating, the RRR value of the copper, and the copper surface quality are therefore critical. The rf skin depth must also be adjusted for the anomalous skin effect. The calculated heat load[10] during full rf duty cycle operation is essentially identical for the two input coupler designs; approximately .06 W, .6W, and 6.0 W to the 1.8 K, 4.5 K, and 70 K heat intercept points.

### Standing Wave

The input couplers are overcoupled until beam is injected into the cavity. At the beginning of the rf pulse, all of the rf is reflected back from the tip of the inner conductor. The resulting standing wave pattern has a voltage maximum equal to twice the voltage of the traveling wave. The maximum repeats every half wave length with the first occurring approximately at the tip of the inner conductor. The voltage amplitude modulation of the standing wave decreases as the cavity accelerating field rises, reaches zero, and then rises again with a quarter wave phase shift. Beam is injected at the time when the standing wave modulation amplitude is zero and the beam maintains the coupler matched for the remaining duration of the rf pulse. The rf windows of the Fermilab coupler have been placed at voltage minimum locations. The DESY coupler has its cold window at a voltage maximum, the warm window at a voltage minimum. All of the rf windows have been coated with a few nanometers of TiN to reduce multipactoring. The TiN reduces the secondary electron coefficient of the surface. The Fermilab couplers will also have the copper plated surfaces coated with TiN.

## HOM COUPLERS

Two types of HOM couplers have been developed for testing at TTF, one with a flange to allow demounting of the HOM coupler from the bore tube, the other welded to the bore tube. The demountable HOM coupler was developed by CE Saclay and is similar to the HOM coupler used on the LEP cavities but scaled to the 1.3 GHz TESLA fundamental frequency. A sketch of the demountable HOM coupler is shown in Figure 4. The welded HOM coupler (Figure 5) was developed at DESY. It is based on the HOM coupler used on the 4-cell HERA cavities.

Unlike the fundamental mode input coupler that needs to be matched at 1.3 GHz to maximize the power available for beam acceleration, the HOM couplers contain a rejection filter at this frequency to prevent loading of the cavity's accelerating gradient and to prevent an excessive heat load in the HOM cable that connects the HOM coupler to the load external to the cryostat. This filter must have sufficient bandwidth to permit pretuning at room temperature without impairing damping of adjacent HOM frequencies.

The mode families identified as possible sources of beam blowup are: $TE_{111}$ (1622 MHz - 1789 MHz, $TM_{110}$ (1800 MHz - 1889 MHz), $TE_{121}$ (3076 MHz - 3114 MHz), $TM_{011}$ (2380 MHz - 2454 MHz), and $TM_{012}$ (3720 MHz - 3857 MHz). The HOM couplers can provide damping over the frequency range, 1.8 GHz to 10 GHz, as their transfer functions are essentially flat over this range. The external Q for a particular HOM passband frequency depends on the HOM field amplitude at the location of the HOM coupler and the orientation of the HOM coupler. Depending on the HOM passband, coupling can be

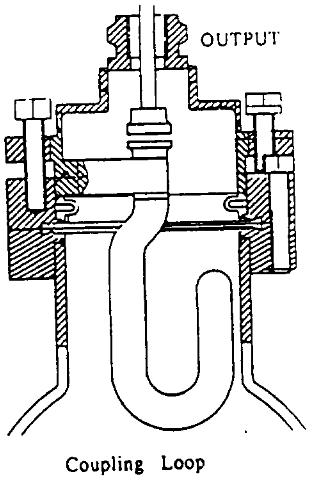

**Figure 4.** Demountable HOM coupler.

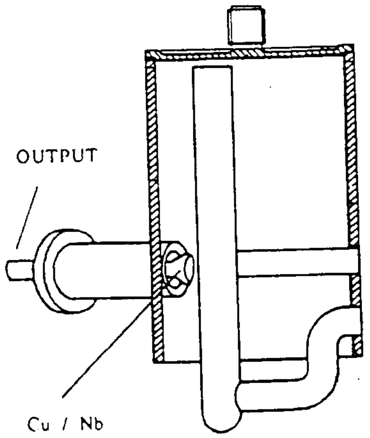

**Figure 5.** Welded HOM coupler.

predominantly to the electric or magnetic HOM fields. To assure proper coupling to the above HOM families, two HOM couplers per 9-cell cavity are placed on the bore tube outside of the cavity helium vessel. The demountable HOM couplers are separated by an azimuthal angle of 115°, the welded HOM coupler at an angle of 150°. These angles are the optimal position for these couplers relative to the summed impedances of the eight highest (R/Q) HOM dipole passbands.

The fundamental frequency rejection filter of the demountable HOM coupler is formed by the inductance of the loop and the capacitance of the loop end to the outer conductor. Final tuning of the rejection frequency is accomplished with a single convolution bellow located above the demounting flange joint. A capacitive probe extracts the HOM power at the top of the coupler. The fundamental frequency rejection filter for the welded HOM coupler is formed by the inductance of the inner conductor pin and the capacitance of the pin gap to the top surface of the coupler. This rejection filter is tuned by an inelastic deformation of the coupler's top. A capacitive probe extracts the HOM power at the side of the coupler. Both HOM couplers can adjust Qext at 1.3 GHz to larger than $10^{11}$.

The HOM couplers are cooled by conduction to the bore tube. The demountable HOM coupler has an additional thermal shunt to 1.8 K at the coupling loop support post location as the thermal conduction through the demounting flange joint proved to be inadequate. To minimize rf heating, caused primarily by currents at the fundamental mode frequency, the inner and outer conductors of the HOM couplers are fabricated out of niobium. The coupler temperature must therefore be maintained below 9 K to avoid a quench and thermal runaway.

## PERFORMANCE

Two prototypes of the Fermilab input coupler have been tested up to a peak power of 70 kW, the highest 1.3 GHz power currently available at Fermilab. The tests were performed without a cavity. The cold windows of the couplers were cooled by immersing the couplers in an open dewar containing LN up to the 70 K intercept point and the coupler ends were terminated with a 4 cm diameter closed pipe. The first coupler was tested with a 50 kW standing wave and two inner conductor tip lengths; the first placed the cold window at a voltage maximum of the standing wave pattern, the second at a minimum. This exposed every part of the coupler to the voltage equivalent of a 200 kW traveling wave. The second prototype input coupler was tested up to 70 kW with the cold window placed at a standing wave minimum. The vacuum trip level during conditioning was set at 2 $10^{-6}$ Torr. Photomultipliers and electron probes detected light and electrons early in the conditioning period. This activity was conditioned away after 2 weeks of operation. These couplers are presently at DESY where they are scheduled to be tested at full power.

The cold rf window of the DESY input coupler has been tested in a three half wavelength long coax resonator. The window was placed at the standing wave voltage maximum at the resonator's center and tested with a 100 kW peak power standing wave.

This is equivalent to the voltage of a 400 kW peak power traveling wave. The observed vacuum, light, and electron activity was removed by conditioning.

Both HOM couplers have been tested at DESY and CE Saclay with copper models of the 9-cell TESLA cavity. The copper cavity tests confirmed that both HOM couplers have sufficient damping of the HOM passbands that were considered as possible emittance growth sources. 1.5 GHz models of the HOM couplers were also tested on a single cell 1.5 GHz superconducting cavity at CE Saclay. Both couplers worked properly up to 12.5 MV/m in cw mode. This represents a significant safety margin for 25 MV/m operation at the 1.3 % TESLA duty cycle.

## SUMMARY

Twelve Fermilab designed input couplers are presently being assembled at Fermilab. Three DESY designed input couplers have been ordered from industry. These input couplers are expected to start arriving at DESY within a few weeks. They will be conditioned in a fixture that tests two couplers in series, and after successful testing, will be assembled to 9-cell cavities that have been preconditioned in a vertical dewar. Testing of the HOM couplers is already in progress at full rf power during conditioning of 9-cell cavities in a vertical dewar.

## ACKNOWLEDGMENTS

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## REFERENCES

1. H. Edwards, Proc. 6th Workshop on RF Superconductivity, CEBAF, Vol.1, p.361 (1993).
2. J. Rossbach, Proc. 1992 Linear Acc. Conf., Ottowa, Vol.1, pg. 25.
3. D. Proch, Proc. 6th Workshop on RF Superconductivity, CEBAF, Vol.1, p.382 (1993).
4. A. Gamp, Proc. 6th Workshop on RF Superconductivity, CEBAF, Vol.1, p.492 (1993)
5. A. Tazzari, F. Alessandria, F. Castagna, L. Catani, M. Ferrario, M. Minestrini, T. Nicol, Proc. 6th Workshop on RF Superconductivity, CEBAF, Vol.1,p.440 (1993).
6. B. Dwersteg, G. Weichert, N. Adelt, Proc. 6th Workshop on Superconductivity, CEBAF, Vol.2, p.1144 (1993).
7. M. Champion, Proc. 6th Workshop on RF Superconductivity, CEBAF, Vol.1, p.406 (1993).
8. J. Sekutowicz, Proc. 6th Workshop on RF Superconductivity, CEBAF, Vol.1, p.426 (1993).
9. S. Chel, A. Mosnier, M. Fouaidy, T. Junquera, contributed to 4th European Particle Accelerator Conference, London, June 1994.
10. T. Peterson, TESLA Report 93-37, available from DESY.