COUPLERS AND HOM DAMPERS

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Abstract

A superconducting cavity ready for the installation in a particle accelerator need to be equipped with a quite complex suite of ancillary devices often as complex and challenging as the cavity itself. Fundamental power coupler(s) (used to feed power to the accelerating beam) and HOM couplers (used to extract the idle RF power left from the circulating beam on the cavity modes different from the accelerating one) are examples of that kind of devices. Tuners (used to keep the frequency and phase of the cavity locked to the master oscillator used as a pace maker for the beam bunches) are a further category of ancillaries. All types, if not properly designed and built, will probably degrade the cavity performance beyond any possibility of easy recover. The lecture will introduce the different implementation of couplers and tuners and the related design constraints.

1. INTRODUCTION

A successful S/C cavity meeting the accelerator's specifications is only the glamorous part of the painful task of building a S/C RF accelerating structure.Once defined the cavity electromagnetic design, checked for the best compromise among accelerating field, peak surface fields (electric and magnetic) versus accelerating field ratios, power dissipation at low temperature, mechanical stiffness against atmospheric pressure and radiation pressure (Lorentz force) and so on, you have accomplished about 30% of the task.

Before building an accelerator ready S/C accelerating structure you have to design the cryogenics of your module, deciding, depending on the frequency choice, to use normal or sub-atmospheric normal liquid helium, or to go below the helium lambda point (2.19 K) and go superfluid., either sub-atmospheric @ 50 mbar or pressurized @ 1000 mbar. This part of the design is quite cumbersome, painful and account for roughly another 30% of the design effort. No magic rule exists; You have to start with a design and go dawn drawing all the lines of the Blue Print till You find a really serious road block. At this point, you have to change the design to find a new solution overcoming the roadblock; at some point, a new bock will appear; and the design of the cryogenic system will proceed in an iterative way until to the end, hopefully.

In general the cryogenic design account for roughly another 30% of the total design.

The third broad category of items in the successful design of an accelerating module account for all the ancillaries needed to feed energy to the accelerated beam via RF fields in the cavity. The system must also keep the synchronism between the RF waves and the accelerated bunches. Last we need to avoid any dangerous interaction between the different bunches (through the cavity RF fields) in the accelerator leading to a dramatic loss of beam intensity.

This last part of the design accounts for about the remaining 40% of the design task and accounts for the Main Couplers, the Cavity Tuners and the High Order Mode (HOM) dampers.

Since any flaws of any components connected to the superconducting cavities can, and most likely will, degrade the cavity performance beyond any possibility of easy recover, the attention to the details of the design, fabrication and assembly of the couplers, dampers and tuners is at least as important as that for the cavities themselves. In the past, cavity performance was often degraded between tests in a vertical dewar and the running operation in cryomodules. Components that can contribute to this degradation were improperly designed fundamental power coupler and HOM dampers. Failure of the tuners is one of the most likely failures putting a superconducting cavity out of operation.The design a “good coupler” or a “good HOM damper” (a working one) need a lot of skill in different fields as Cryogenics, Mechanical engineering, material science, vacuum technology and RF electromagnetic field modeling.

Beginning in the early ’80, work on fundamental power couplers and HOM dampers has been at the forefront of technology. Several papers have addressed the issues related to these components before [0],[1], [2], [3], [4], [5], [6], [7],[8].

Since the technical solution for the design and the construction of the couplers have strongly progressed in the past years; to avoid compete with better teachers (my teachers) and compelled by the page limit, I prefer to address in my lecture the technological issues of the coupler design and construction. I suggest the quoted references, and mainly the Lengeler’s lecture [0], as the main reference for the people interested in a deeper insight of the theoretical background lying below the coupler’s subject.

1.1 Coupling power to the beam

The designs of the main coupler are largely imposed by specific requirements associated with the characteristics of the accelerated beam. This discussion will mostly address accelerator applications and the issues related to high-power operation.

Traditionally, one of the attractive features of superconducting RF cavities has been the low losses that enable operation in continuous wave (CW) with relatively high gradients and considerably lower dissipation than for normal-conducting cavities. So much so, in some areas of accelerator physics, CW operation and pulsed operation have often in the past automatically identified one type of technology or the other. Accordingly, the parameters and the design requirements imposed on couplers have also been dictated by the average power levels and the peak power levels that the couplers would have to handle.The RF power dissipation of a superconducting accelerating cavity ranges in the 10 to 200 Watt interval depending upon the operating frequency and temperature.

The Quality Factor Q_o of a cavity is proportional to the ratio between the stored energy U and the power dissipation P:

$$Q = \frac{\omega U}{P} \qquad (1)$$

From equation (1), a rough estimation of the dissipation can be obtained remembering

$$Q = \omega \frac{\int_V \frac{B^2}{\mu} \, dV}{R_S \int_S H_{//}^2 \, dS} \qquad (2)$$

$$P = \omega \frac{\int_V H^2 dV}{Q} \leq \frac{\omega H^2 V}{Q} \qquad (3)$$

For a LepII cavity, operating at 350Mhz at an accelerating field of 7 MV/m the Q_o value is $3x10^{9,}$ the a volume is 0.8 m^3, the peak magnetic field B 28mT.Assuming the magnetic field constant on all the volume V(excess approximation) we get from (3) a dissipated power of ~30 Watt.

The primary task of a coupler is an efficient transfer of power from a generator to a "load" (cavity and beam). From this perspective, a coupler can be considered as a properly designed transition in an otherwise perfectly matched transmission line, by which a properly determined energy admission rate can be delivered to the beam.

The power transferred to the beam can span a very broad range depending on the accelerator's application. The beam power can be as low as few watts (heavy ion linacs as Atlas or RIA in USA, ALPI in Italy). Or reach the hundred of Kilowatt range in High Luminosity storage rings as B-factories (~100 KW for a LEPII cavity up to 300KW for KEK-B): even higher beam power is foreseen in the next generation of Synchrotron Radiation sources and High Intensity linacs for Neutron Spallation, Neutrino Factories and Muon Colliders.

For the above reasons the couplers will be designed for a broad range of coupling coefficients, usually with a strong over coupling factor (ratio between the power delivered to the beam and the power dissipated in the cavity walls) ranging from 100 to 10000. Superconducting cavity couplers must work reliably on a wide range of coupling coefficients depending on the different operating conditions of the accelerator. During the operation the coupler have to sustain strong variations of standing wave ratios (VSWR), high peak voltages and high peak currents

1.2 The coupler as a Vacuum barrier and a low losses Cryogenic transition.

Because of their proximity to superconducting cavities, most couplers must play also other roles, which substantially complicate their design and possibly limit their performance. Two of these "derived" or "secondary" functions are

Vacuum barriers; between atmospheric pressure at room temperature, and low-temperature vacuum at extremely low pressures.

Thermal transitions between room temperature RF transmission systems and the low-temperature superconducting cryogenic environment, with or without dynamic heat loading generated by the RF.

The first function is played by radiofrequency windows (usually low loss tangent ceramics but also in some case [9] thin foils of high mechanical strength organic polymers as Polymide) Great deal of care needs to be used in setting the position and the operating temperature of the windows to avoid condensation of the residual gases. The condensed gas can dramatically change the RF properties of the window leading to enhanced dissipations or change in the electron secondary coefficient of the material. The occurrence of such events can very easily induce the failure of the window either by local heating and burnout (due to the increased the RF dissipation in some spot of the window), or by electron resonant discharges (multipacting) sustained by a secondary emission coefficient greater than unity. The enhanced secondary yield can produces a strong electron multiplication avalanche leading to puncturing of the window.

The thermal insulation task is accomplished trough a quite complex and sophisticated combination of low thermal conductivity low RF losses materials, counter-flow refrigeration of the coupling loop or antenna, choice of intermediate temperature intercept point.

2. MAIN COUPLERS: COAXIAL OR WAVEGUIDE?

Of all the possible geometries for coupling to superconducting cavities, two main choices have been adopted: coaxial and waveguide coupling.

Not being limited by a cutoff frequency coaxial couplers are in general more compact, especially for low frequency systems, and a variety of geometry and window arrangements are available to adapt to the specific need of the system; only power density considerations and suppression of multipacting levels play a role in determining the size of coaxial coupling systems. The design (both mechanical and electromagnetic) and the construction are somewhat complex and tricky due to the large number of components and the sudden changes in the electric impedance.

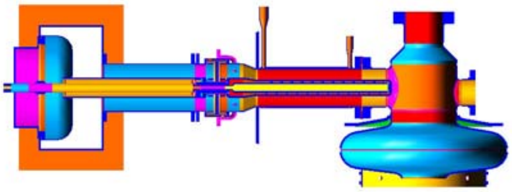


Fig. 1 The SNS coupler is based on a modification of the LEPII [15] coupler. The window matching design has been applied in the past to room-temperature systems. The SNS coupler developments has greatly benefited from the experience and the collaborations of several laboratories and industries around the world and has reached 2 MW peak in high-power tests

Waveguide coupling is conceptually simpler, since it does not require a transition between the waveguide, usually carrying the power from the RF sources, and the cavity interface. This solution, dating back to early stages of superconducting RF designs [10], was adopted in two accelerators now in operation (Cornell (CESR)/CEBAF, CESR-B, Figure 2. Due to the existence of a cutoff frequency in waveguides, the size of the coupler is generally larger at a given operating frequency than for the coaxial case. Because of the larger cross section of the coupling line, the contribution to the infrared heat transfer to the cryogenic environment is usually larger [11].

Fig. 2 The CESR-B single cell cavity makes use of a waveguide coupler. This is the highest power waveguide coupler in operation, having reached close to 300 kW CW in operation with beam. [12]

The CEBAF upgrade project [13] will use waveguide coupling, and new design options for TESLA have been considered which involve waveguide coupling as well [14]..

2.1 Coaxial Couplers

The ancestor of the Coaxial Coupler used to feed RF power to the beam in superconducting accelerator is the Doris coupler developed in Kernforschungszentrum Karlsruhe (KFK) in the early ’80, figure 3.[1]

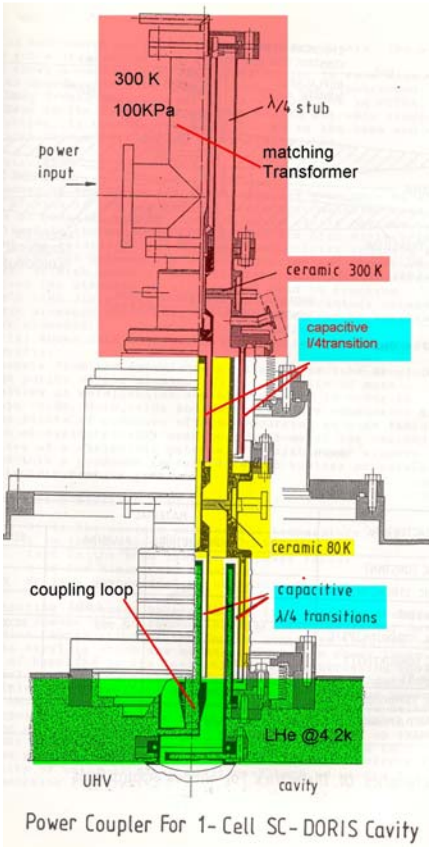


Fig. 3 Doris S/C cavity Coupler (1980 circa) 50KW @ 500 MHz rated powerThe coupler was developed in the Joint effort CERN-KFK for the proof of feasibility of a Superconducting RF Accelerating System to be used to boost the energy of LEP up to 100 GeV per beam.

Despite the early stage of the application of superconductivity to accelerating structures, the design tackle and solves all the key problems in such a device. The Doris coupler was used in 1980 at Desy in the first successful test run of a superconducting cavity used in an e^+e^- storage ring

Proceeding inside to outside the cryostat, we first find the Low Temperature (4.2K) section of the coupler. In this coupler, (as in all the early coax-couplers of the time) the coupling is obtained through the Magnetic Field. For this reason the coaxial line ends with a superconducting loop and a rather complex field transformer (Helium cooled) used to obtain a pure magnetic field coupling. The loop field transformer section was (together the windows) the trickiest part of the design. Due to dimensional constraints, the design team was forced to insert a demountable flange between the Loop and the field transformer. The RF current in the joint was quite large and produced some heating despite the use of a clever all-Niobium superconducting joint. This “Crocodile Joint” was able to scratch the thin oxide layer (10-15 nm) growing on the fresh niobium surface.

The low temperature (4.2K) section was thermally insulated by the intermediate section of the coupler working at 80K.

The RF transmission was guaranteed by a capacitive coupling (λ/4 at the operation frequency) among the inner and outer coaxial parts. The resonant length of the line gives a first order cancellation of the reflected power at the electrical discontinuity, forcing an electric short at the conductor gaps. The capacitive coupling allows thermal conduction between the two temperatures only by radiation, ruled by the Stefan Boltzman law.

$$Q = \sigma(T_1^{\$} - T_2^4) \quad (4)$$

σ=6x10[8] [watt]/[Kelvin]/[m[2]]

The use of quite small surfaces and the intermediate temperature of 80 K, kept at a reasonable the heat flow from 80 to 4.2 Kelvin. Reasonable means, in this context, lower than the static heat load @ 4.2K coming from: the helium tank suspensions, the radiation from the helium tank and the 80K radiation shield, plus the dynamic load from the RF dissipation on the cavity surface. The 80K section is symmetric through the center plane, where the low temperature window is placed.

The window is a flat low loss ceramic brazed to the inner and outer conductors of the coaxial line. The outer conductor is in thermal contact with the 80K intermediate shield of the cryostat: the inner conductor is conduction cooled through the ceramic.

The 80K ceramic play in this case a triple role of:

Mechanical fastener of the inner conductor,

Thermal link: between the 80K thermostat and the inner conductor of the intermediate temperature section.

Vacuum Barrier between the UHV region in the coupler and the Cryogenic vacuum inside the cavity.

The 300 K section is electrically coupled to the 80k section in the same non-contacting way using the resonant capacitive coupling (λ/4 at the operation Frequency) used at the 4.2k side of the coupler. A room temperature coax ceramic window, similar to the 80k one, is used as a separation between the standard RF air coaxial line at atmospheric pressure, and the UHV room temperature line coupled to the 80K section. The λ/4 stub at room temperature is used to compensate the residual impedance mismatch introduced on the line by the window and the discontinuities produced by the capacitive coupling and the 90 Degrees bend.

Due to the rather modest (50-60KW) power level of operation, the KFK-CERN Doris Coupler was fully coaxial, connected to the RF Amplifier via a 3 1/8” standard EIA air coaxial line at room temperature. At higher power (greater than 100 KW), exceeding the air coax line rated power, as in Lep II and TRISTAN, the RF power distribution system at room temperature must use wave-guides.

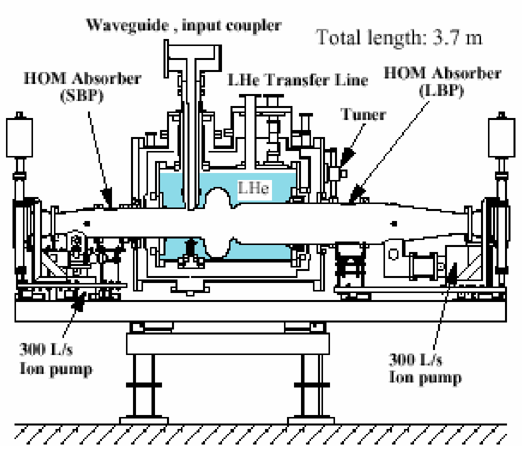


Fig. 4 The KEK-B coupler is the coaxial counterpart of the CESR-B coupler. The design makes use of a single planar coaxial ceramic window at room temperature. Operation close to 400 kW has been achieved. [16], [17]

The design for the main couplers for TRISTAN, LEPII [15] and HERA was mainly the evolution of the coaxial coupler used in the copper cavities of LEPI. The only relevant difference was the coupling to the accelerating cavity trough E-field at the beam tube. This feature is peculiar for the superconducting cavities; due to the high quality factor (Q0~10^9-10^{10}), the field strength of the evanescent wave in the beam tube is high enough to allow a coupling strength giving a loaded quality factor Q_L in the 10^{5}-10^7 range, and a optimum power transfer (critical coupling) at full beam. Modifications of this kind of coax coupler are currently used in KEK-B, up to 400KW continuous wave, and up to 2MW peak in the SNS cavities.

Coaxial couplers offer one more advantage: the impedance of the coaxial line can be chosen to be different from the standard 50 Ω, without modifying the coupler's outer dimensions in order to modify the power levels at which multipacting can occur [18].

The coupling strength depends on the longitudinal location and the size of the coupling port, but in the case of electric coupling, a large range of coupling values can be achieved by proper insertion of the center conductor into the line. Therefore, proper matching can be easily obtained by changing only one parameter and variable coupling can be achieved with proper (if not simple) adjustment of the inner conductor. This last feature can be achieved in accelerators having a too large (to be dealt just by RF controls) variation of beam loading during operation.

When the beam loading variation exceeds over an order of magnitude the coupling factor (and Q_L), variable coupling become mandatory, as in the LHC cavity coupler.

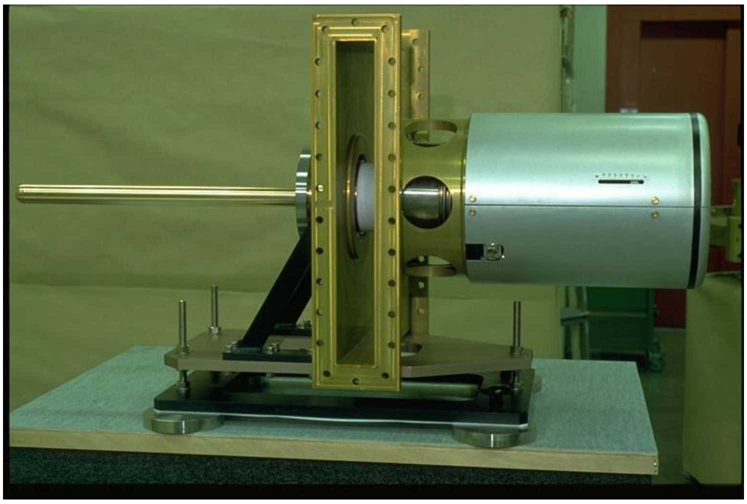


Fig. 5 Variable coaxial coupler for the LHC. The variable insertion mechanism allows a change in coupling factor by over an order of magnitude. This coupler has a cylindrical window in the waveguide. [19]

2.2 Waveguide couplers

A few important features of the waveguide coupling systems deserve some mention here. A good review of some of these issues is found in [9]. Because of the waveguide geometry,(a large hollow tube) windows for waveguide couplers are generally more difficult to manufacture and more prone to break. Multiple windows within the waveguide's cross-section have been used [19]. The coupling strength can be adjusted in three basic ways: 1) by the size of the coupling iris, 2) by the longitudinal location of the waveguide with respect to the cavity's end cell, and 3) by the location of the terminating short of the waveguide itself, as in the case of CEBAF's cavities.

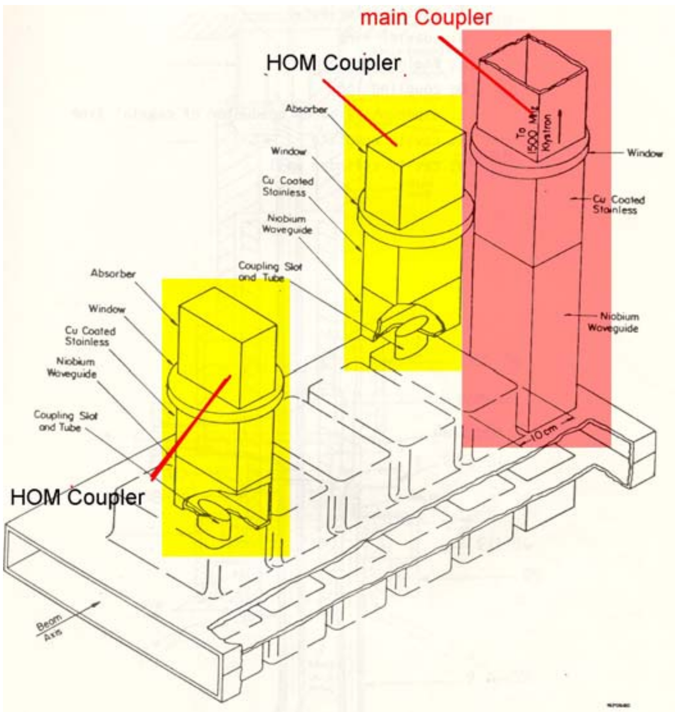


Fig. 6 Muffin Tin Cavity Waveguide coupler. Developed in CORNELL for use in a L-band cavity for e^+e^- Storage rinfg, in the late '70, early 80, contains all the features of the Waveguide couplers used in CEBAF and CESR.

The first example of waveguide coupler was the coupler for the muffin thin cavity (figure 6) developed in CORNELL in the late ’70 early ’80. [23] The coupling system was designed to handle 60 KW at 1500 MHz: The cavity was formed essentially of eleven cells. The top of the first cell was replaced with a superconducting waveguide, acting as the continuation of the cup, propagating the fundamental TE_{10}.The waveguide field couples with the electric field components of the accelerating structure. The bottom of the cell, opposite to the coupling port, was used as a shorting stub to adjust the coupling between the waveguide and the accelerating cavity.

A cold ceramic window operating at 80K was used. To keep to a minimum the heat flow from room temperature to the helium bath, the coupler used low conductivity stainless steel wave-guides copper plated. Two section of such waveguide provided breaks in the heath path between 4.2 and 80 K, and between 80 and 300K.

3. WINDOWS

Windows are designed to separate the vacuum of the superconducting cavity from the atmospheric pressure of the transmission line. As electromagnetic interfaces, they must satisfy strict matching requirements, so that power is reflected and dissipated only in minute quantities. Since dielectric materials are used for the transmission of electromagnetic power [24], the manufacturing techniques usually involve complicated interfaces of conductors, dielectrics and brazing metals.

In addition, electronic phenomena at the windows can complicate the design. Multipacting at the windows can be particularly dangerous, as large amounts of power can be deposited in small areas of the dielectric, potentially leading to failure. Careful choice of geometry and coating with low secondary electron emission coefficient materials can mitigate this phenomenon [3].

Exposure to radiation can also lead to charging phenomena at the window surface [25], [26], [27], 28] leading to flashover of the accumulated charge and to damage of the window. Geometrical protection [27] as well as metallic films of proper thickness can be used to decrease the incidence of this problem. As in the case of multipacting coating, it is essential that the appropriate thickness be carefully achieved (10-15 Å); otherwise excessive RF losses will occur and the subsequent excessive heating will lead to window failure [29]. In some cases, multiple windows in series are used (CEBAF: one window at 300 K and one at 2 K, the latter used for sealing cavity pairs as early as possible in the assembly process; TESLA: one room-temperature window and one at 70 K [30]; APT: two redundant room temperature windows for protection against failure) [8]. In spite of the added protection and some beneficial features, multiple windows tend to complicate the design of the couplers, add cost and increase the number of critical components that can fail.

As mentioned above, windows for waveguide systems are usually planar and can occupy a large fraction of the waveguide cross-section, either in a single piece, or in multiple pieces [25], [31], [32], [33].Coaxial windows are usually planar [8], [22], [34], [35] cylindrical [9], [36], [37] or conical [38].

Active pumping near the windows is desirable [6], [25] to avoid discharge problems during outgassing events associated with varying power levels, but in most cases design complications make this solution impossible and pumping is achieved only through the cavity itself. In this case, more careful initial conditioning and close attention to operational interlocks become even more necessary.

4. SIMULATIONS

Over the past several years, an ever-increasing activity has been noticeable in the area of coupler design connected with simulations of various aspects of the coupler’s performance. Thanks to better software tools, a larger and larger fraction of the design of couplers can be made well ahead of the actual construction, thus removing part of the uncertainty of the coupler’s performance and avoiding the lengthy, tedious and expensive work of cut and try, which is particularly demanding for systems connected to superconducting cavities.

4.1 Electromagnetic calculations

4.1.1 Field distribution

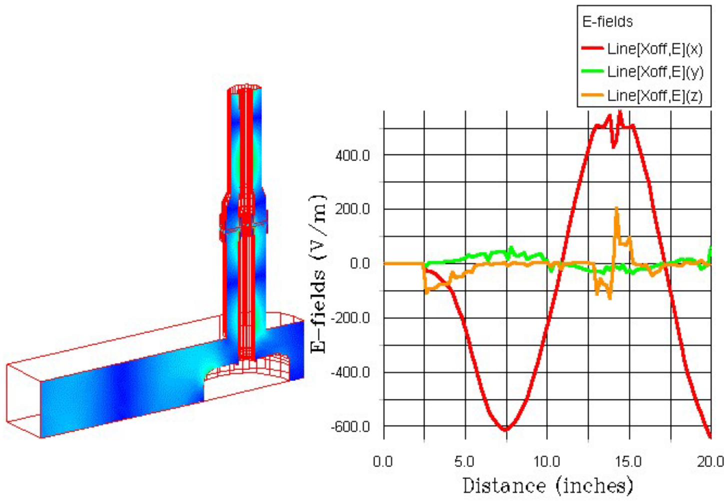


Fig. 8 Electromagnetic field simulations allow better designs of coupler components: here the SNS waveguide-to-coaxial transition and the window matching section are shown with the relevant electric field strengths. [46]

Programs such as HFSS™ [63] have been used by several groups to evaluate the field distribution in couplers and transitions and to improve the matching at windows and at waveguide/coaxial transitions. Such calculations have been carried out, for example, for couplers designed at Saclay [40], [41], at LANL [42], [34], [43], [44], [45], for Cornell windows [32] and for the SNS coupler [46] (Figure 8)

4.1.2 External Q calculations

The coupling strength of the coupler (external Q_{ext}) is a critical quantity, which needs to be set for each specific application. Calculations are also now routinely performed to determine the Q_{ext} in advance by matching cavity field calculations to the coupler's geometry field simulations. This has been done for the APT cavities [47], [48] and for the SNS [46]. In both cases, bench measurements give extremely good agreement with the simulations.

4.1.3 Multipacting calculations

Along with better understanding of field distribution in couplers and with the improvement in tracking programs for multipacting in accelerating structures, a great improvement has been effected in understanding electronic activities inside the couplers' structures and in estimating location and magnitude of multipacting phenomena [49].

Such efforts have been carried out at Cornell for the waveguide geometry [19], [20], and at Saclay for various window and coaxial geometries [40], [41], [50], [51], [45]. Activities in Finland in collaboration with TESLA and other laboratories have led to the study of the multipacting characteristics of several coupler geometries [52], [53], [54], [55]. From these studies a great deal of information has emerged which points to the fact that multipacting is generally unavoidable in couplers, as the amplitudes and phases of the forward and reverse wave change along various parts of the structure. Figure 9 and figure 10 give an example of the output of the multipacting simulations. The final result of the simulations is that electromagnetic design alone is insufficient to avoid multipacting. Materials and surfaces must be carefully controlled and conditioning must be implemented in order to decrease the negative impact of this phenomenon. As a side result of the multipacting simulations, it is now possible to design a proper biasing method in order to disrupt the multipacting orbits and their effects. Calculations with bias can be performed with the present multipacting modeling tools [56].

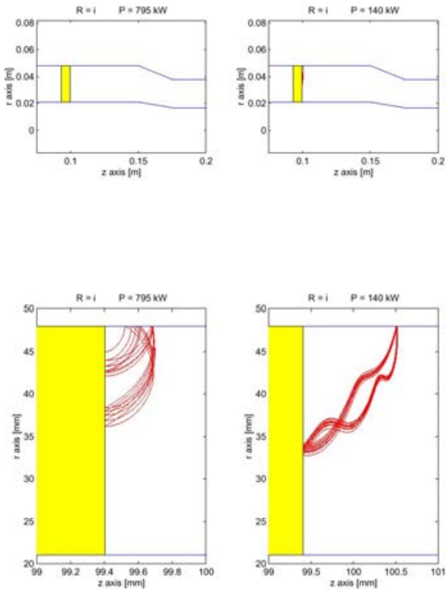


Fig. 9 Multipacting simulations at the SNS coupler's window. The ability of predicting dangerous phenomena, like multipacting at specific locations in the couplers, leads to better designs. [54]

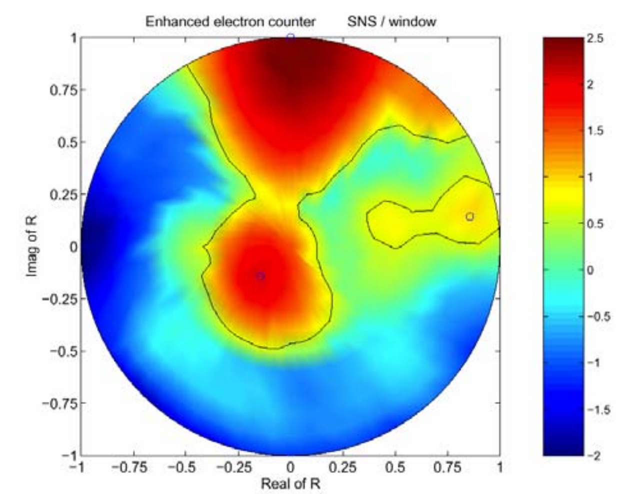


Fig. 10 The results of multipacting simulations in couplers can be summarized by graphs like the one shown above: the red areas show regions of the complex reflection coefficient where multipacting can occur [54].

4.2 Thermal calculations

Another area, where numerical calculations help in designing the coupler characteristics, is the determination of the thermal properties. For coaxial geometry, this has been done at the APT [57], [58] and at the SNS [35]. Both center conductor and outer conductor thermal profiles can be determined in this way under RF loading conditions. Similar calculations have been done for the waveguide geometry by other authors, taking into account the optimal length and thermal groundings to minimize cryogenic losses [15].

An area that requires additional attention is the modeling of the thermal profile of the coupler/cavity interface. Here the RF losses are small, but if the temperature is not properly stabilized, the superconductor's critical temperature could be exceeded due to the highly nonlinear losses caused by the thermal loading from the coupler.

4.3 Mechanical stress calculations

Since some of the coupler designs rely on very delicate ceramic-to-metal brazing, it is important to evaluate the mechanical properties of the couplers to prevent costly mechanical failures. Whereas in most cases couplers are assembled on the accelerator premises and a failure of a coupler in transfer only affects the coupler itself, in the case of the SNS the assembly is done elsewhere from the installation point. A failure of a coupler during transport would have very costly consequences. In the future, this construction mode will become more and more frequent. Wilson [35] has evaluated the mechanical stresses on the SNS coupler, and the results indicate that the design should withstand the accelerations and stresses associated with the transport from one laboratory to the other.

5. DEVELOPMENT OF HOM COUPLERS FOR SUPERCONDUCTING CAVITIES

A single mode Accelerating cavity (as an ideal Lumped LC resonator) is the dream of any accelerator designer. Real cavities have many resonant modes corresponding to the solutions of the Maxwell equation inside the cavity volume. Particles traveling along an accelerator send information about position and speed to the following particles through the radiated electromagnetic field. This cross talk is enhanced at the occurrence of the resonance of the high modes of the cavities. If you are unlucky, (and you are always) particles will interact together via the radiated fields, giving rise to beam instabilities limiting the maximum current the accelerator can handle. In S/C cavities, due to the long decay time of the fields, the deposited energy need to be dumped on a load, lowering the threshold for the beam instabilities.

Coherent instabilities limit the beam current in circular machines (coupled bunch instabilities) or in linear accelerators (regenerative, cumulative and multipass Beam Break Up). These instabilities are mainly caused by the long-range wake fields excited by the beam bunches going through the cavities. The best way to increase the threshold is to fasten the decay of the excited fields, in other words to damp the higher order modes of the cavities. Typical Q values under 10^5 or 10^4 for the most dangerous parasitic modes are required in present designs of accelerators.

By chance the accelerating mode is the fundamental mode of a cavity, the mode at the lowest frequency. A device having an high pass frequency response, will allow to extract the RF power radiated by the particle beam, leaving unaffected the RF power fed to the cavity (and to the beam) by the main coupler; in this way the overall cavity response approach the ideal response of a lumped LC circuit.

Various devices and especially designed for superconducting cavities have been developed during the last years. The main differences lie in the type of coupling -hole, probe or loop used to couple out from the cavity the unwanted modes and in the way of keep to a minimum the coupling with the accelerating mode. Nevertheless, all the last versions follow the same rule: they couple to the cavity fields through the beam tube and not directly in the cells. The risk of multipacting and of thermal breakdown is thus avoided. However, care must be taken in the design of cavities with the so-called trapped modes, resonating at frequencies above the cut-off frequency of the beam tube, but having the field going rapidly to zero outside the cavity.

5.1 Estimation of the extracted power by HOM coupler

The cavity codes like Superfish [59] or Urmel [60] OSCAR2D [61] help in designing couplers that will be mounted on the beam tube. Once the electromagnetic fields at the foreseen location of the coupler known; assuming:

The coupling port does not changes too much the field pattern

The RF coupler behaves like an ideal filter without reflection (terminated on the characteristic impedance).

We can easily deduce an approximate value of the real damping that will be effectively measured on a copper prototype.

5.1.1 HOM waveguide cou1pling

The predictions can be hazardous because the theory generally developed concerns only small coupling holes (see for instance [62]). We could use instead 3D cavity codes as HFSS™ [63] or MAFIA [64] combined with one of the two later to evaluate the power flow through the waveguide terminated on a RF load. Otherwise, the waveguide coupler and the matching waveguide stubs are designed by cut and try.

5.1.2 Lumped coaxial filters coupling

The estimations, deduced from field level calculations with Urmel or Superfish, agree very well with the measurements.

For a probe coupler the electric flux on the probe tip furnishes the current induced by a cavity mode:

$$I = \omega \varepsilon E S \qquad (5)$$

Where E is the electric field from a mode averaged over the probe tip and S is the antenna area.

The power dissipation on a matched resistive load R is given by

$$P = \frac{I^2 R}{2} \qquad (6)$$

The external Q of this simple coupler terminated on a resistive load R for a mode with stored energy U is computed from the external Quality Factor definition (equation 1)

$$Q_{ext} = \frac{\omega U}{P} = \frac{2U}{R\omega \varepsilon^2 S^2 E^2} \qquad (7)$$

In the same way for a loop coupler, the magnetic flux going through the loop furnishes the voltage induced in the loop by a cavity mode:

$$V = \omega \mu H S \qquad (8)$$

Where H is the mode magnetic field at the loop location, averaged over the loop area S; the power dissipation on a matched resistive load R is given by

$$P = \frac{V^2}{2R} \qquad (9)$$

The external Q of this simple coupler terminated on a resistive load R for a mode with stored energy U is

$$Q_{ext} = \frac{\omega U}{P} = \frac{2RU}{\omega \mu^2 S^2 H^2} \qquad (10)$$

5.1.3 The coupling via beam tube and its limits

The external Quality Factor evaluation is valid for any choice of the HOM position. Usually the location of the HOM coupler (as for the main Couplers) is on the beam tube, to avoid introducing (as already happened in the CERN-DESY-KFK cavity) strong modification to the cavity geometry in the high field region of the resonator. This choice helps to reduce to a minimum the possibility of producing field limitations either by increased RF losses due to local field enhancements or by enhanced field emission

The most efficient HOM coupler will be inadequate whenever the field level will be vanishing at the location of the coupling port. Measurements on a single cavity [65] showed the existence of modes above cut-off of the beam tube, which couple poorly to the propagating waveguide modes of the beam tube itself.. The situation is even worse in the case of a multicell cavity .as these trapped modes appear at a frequency well below three times the fundamental mode frequency [66](the usual cut off frequency of the beam tube.

The cavity codes predict these troublesome modes. For example, figure 11 shows the plots of the electrical field of two modes above cut- off for a 5-cell cavity with large iris aperture (ϕ/λ=O.35). One mode (top) belonging to the fifth dipole pass band remains confined inside the cavity (no field in the beam tube) in contrast with a lower frequency dipole mode (bottom), which couples clearly to the propagating TE_{11} mode of the beam tube. We expect for these trapped modes a very poor damping by the HOM couplers but we could hope to evacuate the power by propagating waves through the beam pipes.

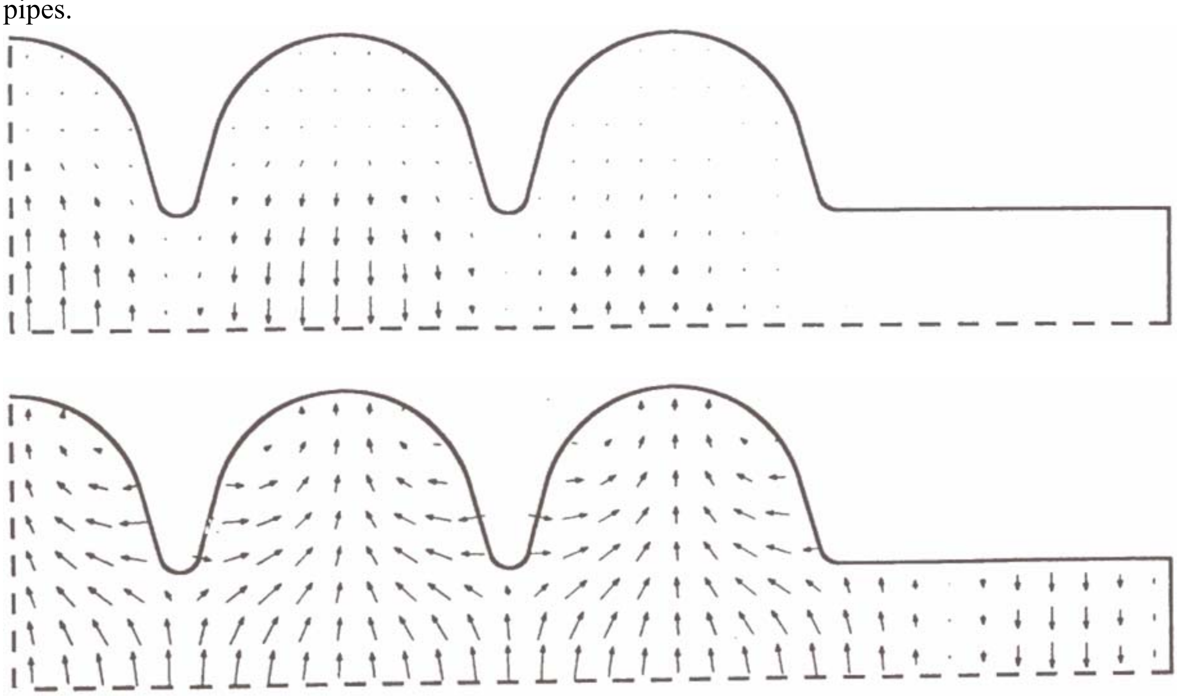


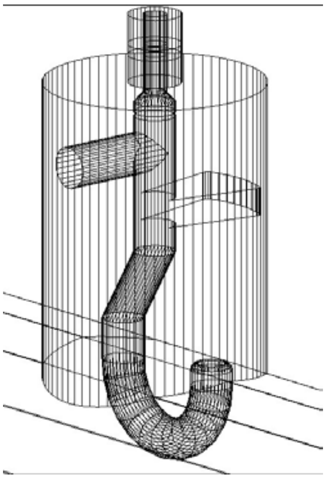
Fig. 11 Plots of the electrical field of two dipole modes, both above the cut-off frequency of the beam pipe .Due to the field configuration the first mode is trapped in the center cells, with a minimum propagation down the beam tube.

5.2 What is required of real life HOM coupler

5.2.1 The RF requirements

In addition to the damping of all dangerous modes as much as needed, we require from a HOM coupler that the coupling with the fundamental mode must be kept as small as possible. In the case of the waveguide coupler, this requirement is naturally obtained by a correct choice of the cut-off frequency and length of the waveguide.

Due to the large size of waveguides, coaxial couplers combined with a Superconducting notch-filter, for suppression of the fundamental mode, are preferred for low frequency cavities as in the case of the LEPII RF system.



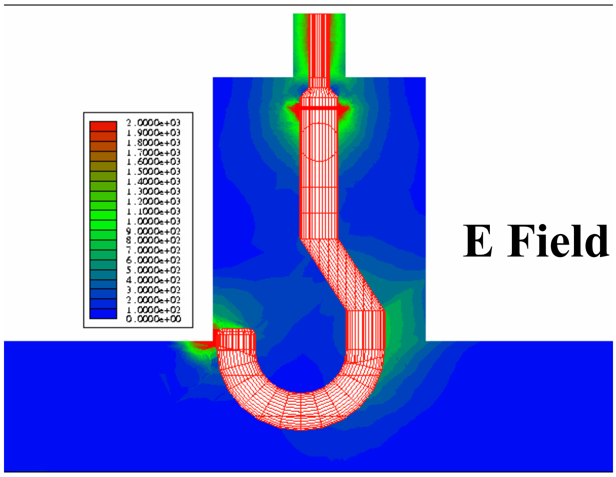


Fig. 12 Lumped beam tube HOM coupler, including a fundamental mode notch filter. The right side picture shows the E field distribution In the coupler.

On the other hand, great deal of care must be used in tuning the notch filter to avoid coupling a significant amount of RF power from the accelerating mode.

This effect will reduce the Q_o value of the accelerating mode, impairing the transfer of power to the beam, and increasing beyond any affordable limit the power dissipated on the HOM RF load.

Cryogenics also play a strong role, mainly in the design and on the cooling of the inner parts, to avoid excessive heating and quench of the coupler. In the few gigahertz range, both types of HOM couplers have been developed in different laboratories.

5.2.2 The "engineering" requirements

The RF properties of the couplers are the reason why laboratories try hard to simplify the design and reduce the cost as much as possible. Often the HOM coupler designer faces conflicting "engineering" requirements:

- **Low cost** (the number of HOM coupler in a cavity is quite large)
- **Effective Cooling** of the SC parts exposed to high fields for preventing from thermal quench
- **Compact structure** and minimal size to fit in the cryostat
- **Demount ability** to allow surface treatments or thin film deposition of the cavity alone
- **Avoid large RF windows** (if possible) in contact with helium to avoid damage to the cavity in case of vacuum failure

5.3 Coaxial HOMcouplers development

Designing coaxial HOM couplers we need first to choose the way of suppressing the fundamental mode and then to control the RF elements to design a fairly flat high pass transfer function to properly transfer to the RF Load the energy deposited by the beam on the cavity modes resonating at a frequency higher then the one of accelerating mode.

Coaxial lines do not have a low frequency cut of; but start to carry RF power from zero frequency; we need in some way to break the path for low frequency signals; a capacitor along the inner conductor does the wanted job of transmitting unaffected only the RF signals above the fundamental. Usually this is not enough to keep to a reasonable value the transmission of the fundamental mode.

For an antenna or loop coupler we must compensate the stray capacitance between the probe tip and cavity walls or the self-inductance of the loop. Numerical methods are used to optimize the RF circuit before the final step of measuring the transmission curve of a coupler prototype.

The design starts with a first rough trial design used to set up a 3D mechanical model of the coupler. The mechanical model is used to perform a 3D FEM RF analysis (usually using HFSS ™ or MAFIA) of the coupler computing the RF fields, cut off frequencies and Scattering parameters on the frequency range foreseen for the coupler.

Once the wanted frequency response obtained, a full analysis of the Cavity-Main Coupler-HOM coupler transfer function is mandatory, to check for unwanted and unforeseen effects, in the global RF system, produced by the mutual interaction between the different components of the RF system.

Last a full-scale mock-up is built to verify the correctness of the numerical simulation and perform a sensitivity check of the Coupler response against the build up of mechanical errors produced by the build up of the mechanical tolerances.

Figure 13 shows the measured and the calculated response curves for the HOM coupler shown in figure 12

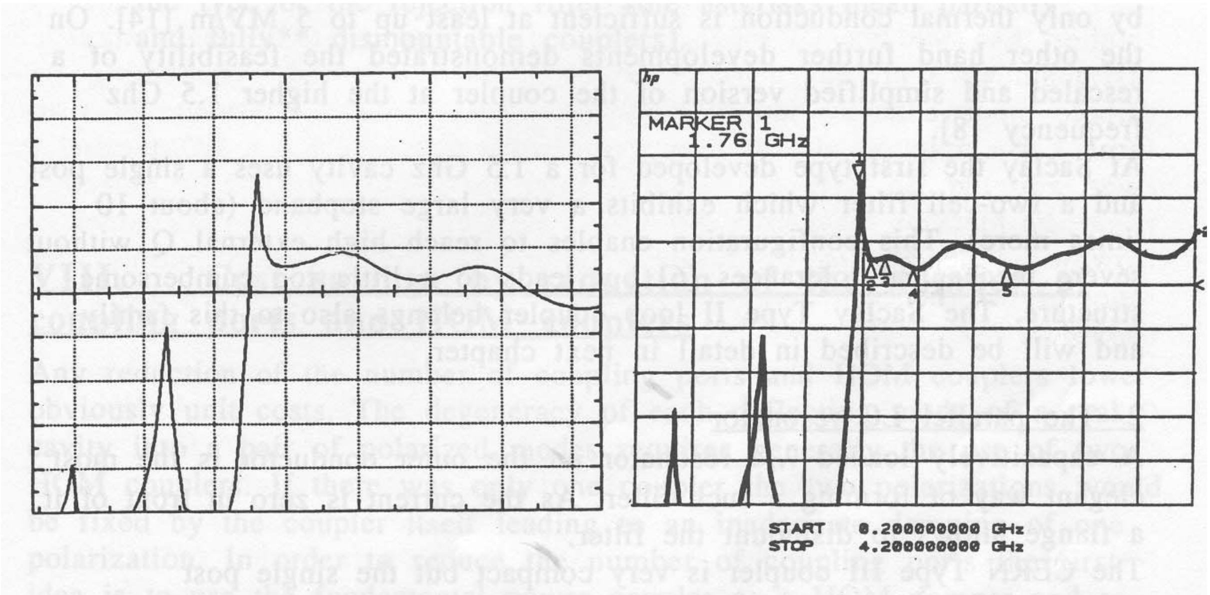


Fig. 13 Computed (left) and measured (right) Transfer function of a Prototype coaxial HOM Coupler. Developed in Genoa for a reduced beta L-Band cavity at 1.4 GHz Trasco project.

Coaxial Couplers mainly evolved from the design developed in the early ’80 for the Storage Ring RF systems as TRISTAN [68] and LEP[69].

The High pass frequency response is given by a capacitive gap in the central conductor; the rejection of the fundamental mode is obtained either through a series LC-resonator across the coaxial line or a parallel LC-resonator in series with the central conductor and the load.

A further adopted scheme was a distribute filter built using stepped impedance compact waveguides to perform the rejection task.

5.3.1 The series LC resonator

The first example of this type of HOM is the CERN Type I coupler [69]. It is fully dismountable but requires three small sapphire rods for a precise centering within the coupling port.

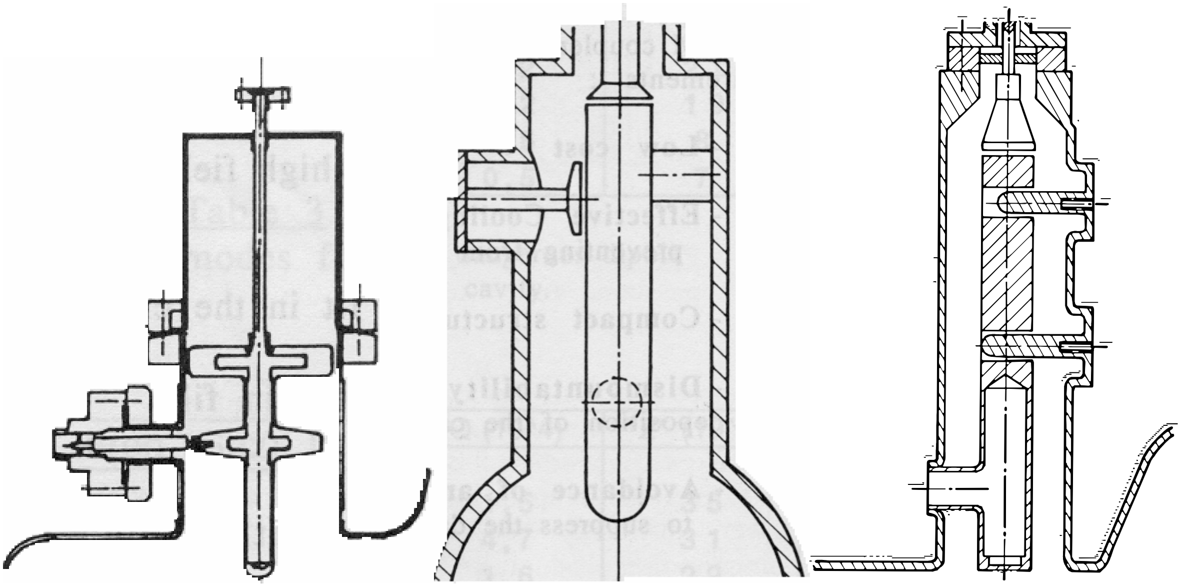


Fig. 14 Series LC resonator HOM Couplers: LEP I (left) DESY center and CEA-Saclay (Rigth)

The couplers developed at DESY for the 500 Mhz HERA cavities uses 2 inductive posts which are welded to the cavity walls [70]

At Saclay the first type developed for a 1.5 Ghz cavity uses a single post and a two-cell filter which exhibits a very large stopband This configuration enables to reach high external Q without severe mechanical tolerances but leads to a little too complex mechanical structure. The Saclay Type II loop coupler belongs also to this family.

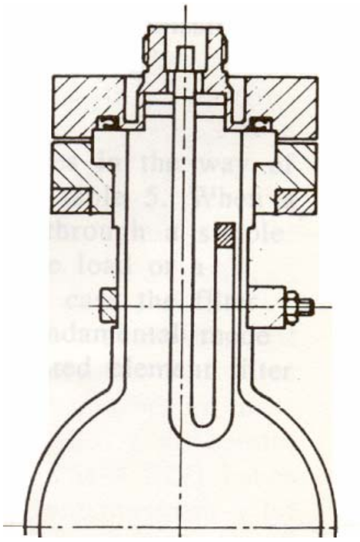


Fig. 15 CEA-Saclay loop coupler: The rejection of the fundamental mode is obtained by the resonance of the Inductance of the loop with the stray capacitance of the loop itself against the outer conductor of the coupler.

5.3.2 2- The parallel LC resonator

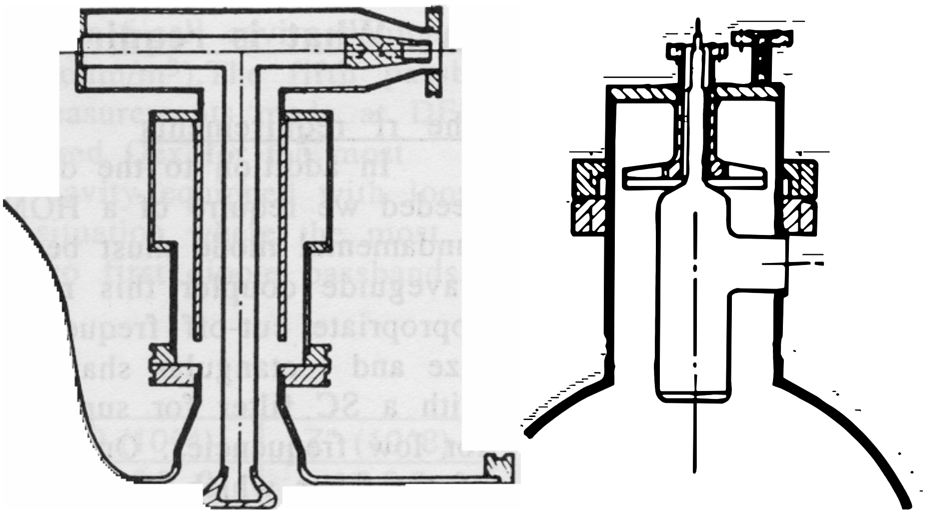


Fig. 16 KEK type HOM (left) and CERN III HOM right.

A capacitive loaded λ/4 resonator on the outer conductor is the most elegant way of forming the Fundamental mode rejection filter. As the current is zero at the λ/4 end, a flange at this position allows to dismount the filter.

The CERN Type III coupler is very compact but the single post supporting the inner conductor and used for cooling is welded to the cavity [69].

The KEK coupler is fully dismountable and includes a T stub at the exit allowing the cooling of the inner conductor

5.3.3 3- The distributed element filter

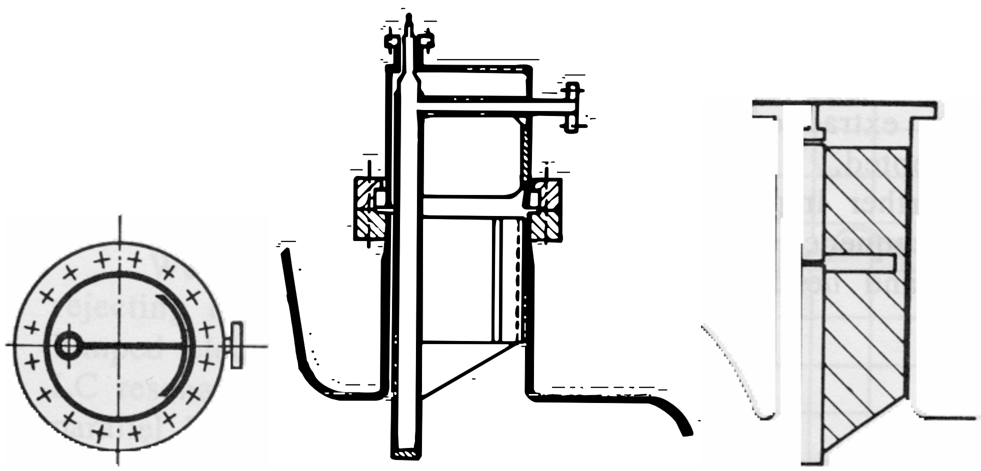


Fig. 17 Distributed element HOM filter Cern Type II a(left) and Type IV (right).The Coupler behave like an annular wave guide with a cut of Frequency.

This family (figure 16) is derived from the lunar guide, which has a cut-off frequency like a waveguide. To shorten the needed length for a sufficient attenuation either a distributed condenser along the sheet close by the outer conductor (CERN Type II) or a local LC resonator formed by a little aperture in the lunar guide (CERN Type IV) has been added [69]. While the second is welded to the cavity walls, the first is fully dismountable but with a filter only cooled by heat conduction with the risk of thermal quench.

The design of the HOM Couplers evolved from the three basic types by further refining and by crossed implementation of the more attracting features of the different Types.

The most successful design was the HOM coupler used In the LEP II cavity shown In Figure17

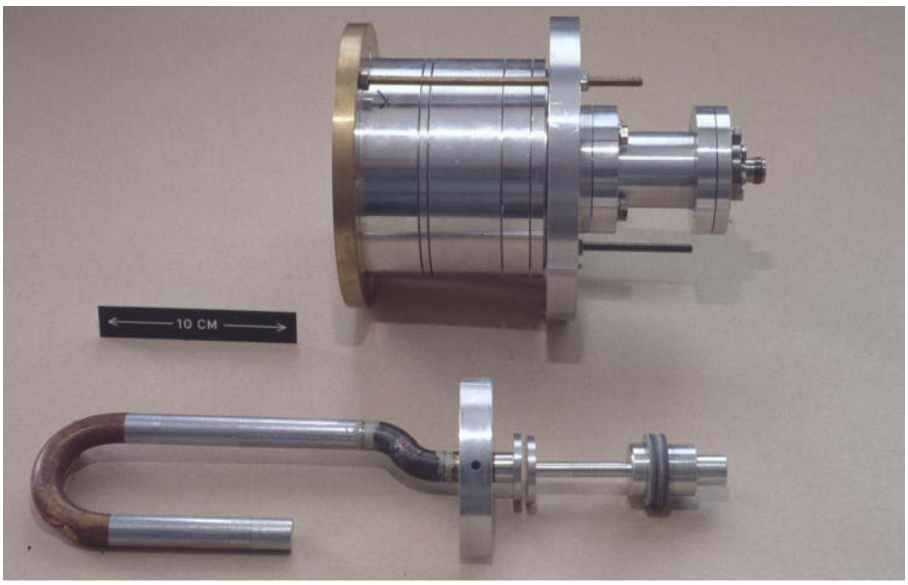


Fig. 18 LEP II cavity HOM coupler.

The design of the last generation of HOM couplers for the LHC cavities is even simpler: HOM couplers clearly show the evolution toward a lumped element circuit.

The E-Field coupled HOM uses a lumped capacitor to produce a series resonance at the fundamental mode frequency across the coaxial line; the H-field coupled HOM uses the stray capacitance of the loop to produce the same effect. In Both couplers the two poles High Pass transfer function is forced by the lumped capacitance at the end of the central conductor and the inductance of the Coaxial line.

The Couplers are fully demountable, Helium cooled, and need only one weld between the central and the outer conductor (figure 18).

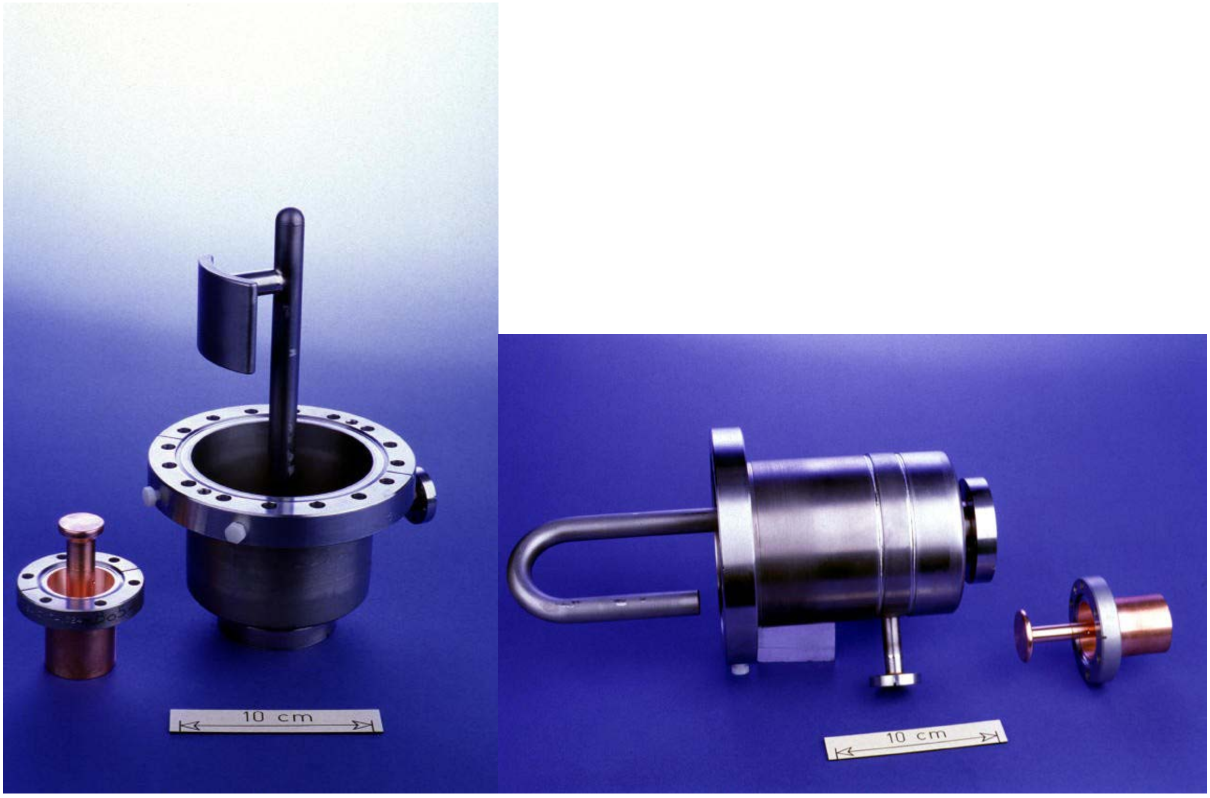


Fig. 19 The LHC Cavity HOM Couplersare the natural evolution of The LEPII HOM Couplers. The HOM use either E-Filed coupling (left) or H-Filed Loop coupling (right) to damp the Q value of the most dangerous modes of the cavity.

5.4 Waveguide HOM coupler development

The main advantage of the waveguide coupler is its high pass feature without the need of any tuning. The evanescent wave in the guide excited by the accelerating mode of the cavity must be sufficiently attenuated before arriving to the rf load. However, a guide length of a few attenuation length (at the fundamental mode frequency) is needed because the cut-off frequency is generally very close to the fundamental mode frequency. The first waveguide joint flange needs to be far enough from the beam tube for a negligible dissipated power.

In addition, a matching stub is required on the beam tube at the opposite side of the HOM coupler.

In the CEBAF/Cornell cavity [71] as the cut-off frequency is slightly higher than the first HOM's frequency, the fundamental coupler plus one extra stub is used for the the extraction. In order to avoid a pinning of the dipole mode polarizations by the main coupler, the Y configuration (two arms for extraction and one arm as matching stub) for the HOM couplers was adopted (Figure 19).

Further improvements at Cornell [72] allowed to couple out the lowest frequency modes through a modified coupling port of the HOM coupler and hence to eliminate the large stub on the fundamental power coupler.

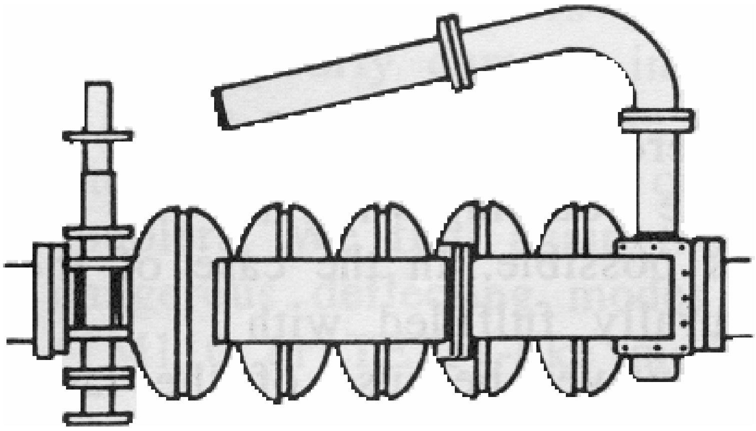


Fig. 20 The CEBAF module with the Input Coupler Waveguide (left) and the Two HOM waveguide couplers on the right.

The HOM coupler scheme is quite similar to the one used In the Cornell Muffin Tin cavity [9]; the extracted RF power is dissipated on a specially developed RF absorbers housed in the last part of the Waveguide section.

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