TECHNIQUES IN HIGH-POWER COMPONENTS FOR SRF CAVITIES – A LOOK TO THE FUTURE

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Abstract

In this talk fundamental power couplers and higher order mode (HOM) dampers for superconducting cavities are reviewed. Design principles, materials, manufacturing and interlock issues are discussed. Present operational experience is analysed, performance limitations are identified and outlook for future developments are presented.

1 INTRODUCTION

The primary task of the input coupler is to transfer RF power to the superconducting cavity. The RF contour of input couplers can be modelled by use of several RF design codes. In comparison to couplers for normal conducting cavities, there are several major differences for the design criteria as well as for operating conditions:

A, The input coupler connects the room temperature part of the accelerating system with the cryogenic environment (4.2K or 2K). The static and dynamic heat load by this connection should be kept low so that it does not dominate the total heat load of the complete cryostat design.

B, The cold part of the coupler line will act as a cryo-pump, thus collecting layers of condensed gases. Sudden desorption of these gases might ignite a glow discharge or trigger a spark under the influence of the RF fields. This is a specific concern because of the electron bombardment during a multipacting event.

C, The superconducting RF losses in the cavity are negligible in comparison to the beam power. The input coupler is matched to the demand of beam power only. Therefore a sudden change or even loss of the beam current puts demanding conditions to the RF control circuit in keeping the cavity voltage constant and/or avoid large reflected RF power.

D, It should be noted that the coupler ends at the beam pipe. A penetration of the cavity cell would create local magnetic field enhancement or produce unpredictable multipacting resonances.

Rectangular and coaxial wave guides are used as input coupler lines. Both types have specific advantages, which will be discussed. There is remarkable progress in operational power level of input couplers in the last years: several 100 KW of RF power in operating accelerators and up to 2 MW for prototype testing

Reliability of components is measured by counting number of trips per time. In this respect input couplers show up as critical component. Careful data logging, however, uncovered, that often a trip of a coupler is triggered as secondary effect of some other leading fault. A specific concern is the time consuming conditioning of input couplers. This can be explained by multipacting events and possible cures for improved design/procedure will be discussed.

Higher order mode (HOM) couplers should extract beam induced power at frequencies higher than the accelerating mode. Following the same arguments as for the input coupler, HOM couplers are not allowed to penetrate the wall of a cell but are placed along the beam pipe. Two types of HOM couplers are in use:

- electric or magnetic pick ups with some inductive and capacitive elements to enhance coupling at desired frequencies and to suppress fundamental mode coupling. These HOM couplers reach damping values in multi-cell cavities equivalent to a damped resonance with Q-values around 10.000. The extracted average HOM power is below some 100 watts.
- broad-band absorbers with a high absorptive ferrite layer being placed inside the beam tube at some distance away from the cavity. Here equivalent Q-values around 1000 can be reached for single cell cavities. The beam pipe diameter must be large enough to start propagating just above the fundamental mode frequency. The extracted HOM power reaches several KW.

2 INPUT COUPLER DESIGN PRINCIPLES

2.1 Wave guide vs. Coaxial Couplers

Rectangular wave-guide and coaxial couplers are in operation at different accelerators (See Table 1). Both types of couplers have specific advantages and disadvantages:

Table 1: Input couplers in superconducting accelerating systems with operational experience above 50 KW.

	F[MHz]	dim.[mm]	Power[Kw]
CESR III [1]	500	341x102	300, cw
HERA [2]	500	Dia. 103	100, cw
KEKB [3]	508	Dia. 120	370, cw
LEP [4]	352	Dia. 102	100, cw
TRISTAN [5]	508	Dia. 115	70, cw
TTF [6]	1300	Dia. 40	250, pulsed

Peak electric fields: For one MW travelling wave power the peak electric field for a standard wave-guide at 1.3 GHz is 400 KV/m, a coaxial line with an outer diameter equal to the high (small side) of the wave-guide is 800 KV/m. This value will decrease if the coax line is increased up to the same cross section as being covered by the wave-guide. Therefore there is no clear benefit for either design in this respect.

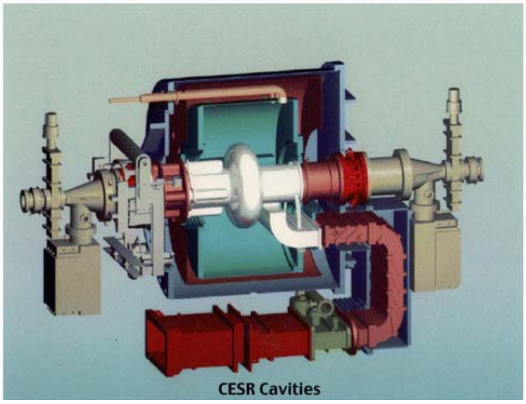

Figure 1 : CESRIII accelerating module with rectangular wave-guide input coupler and broad band HOM absorber at the warm end of the beam pipe.

RF losses: For the above example the longitudinal losses are about 1KW per meter in both cases. For the coaxial line about 1/3 of this loss must be cooled from the outer conductor whereas the dominant part is produced at the inner conductor. This part can be cooled without loading the cryogenic circuit (one warm window design) or is intercepted at the second (cold) window at 70K.

Mechanical design: Manufacturing of a rectangular wave-guide with good Cu plating into the corners is more difficult than for a round pipe. Furthermore flanges in a round pipe are easier to design and to handle.

Variable adjustment of the coupling strength: An adjustment of the coupling strength of the input coupler might be very helpful in compensating change in coupling due to fabrication tolerances, cavity field unflatness and change in beam current. With a coaxial coupler this can be done by moving the inner tip closer to the beam pipe. Rectangular wave-guide couplers do not offer an easy way of changing the coupling strength. Minor coupling adjustments can be pursued by a 3 stub tuner at the up stream end of the coupler line [7]. But it will result in additional standing wave voltage along the coupler line.

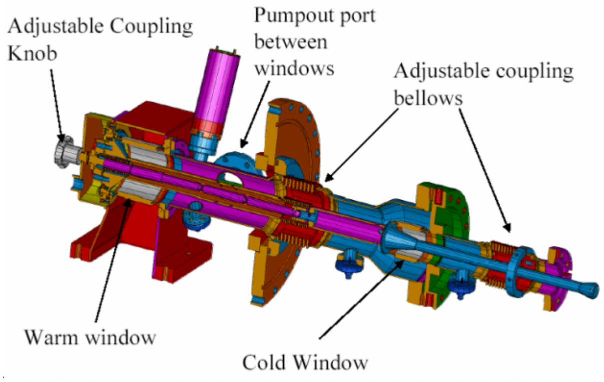

Figure2: TTF3 input coupler as example for a two window coax design with adjustment of coupling strength

2.2 Windows

RF windows separate vacuum from air. In most cases they are made from Al_2O_3 ceramic of 95% or 98% purity. Because of its high secondary electron yield coating with Ti, TiN or other anti multipactor coating is strongly recommended. Standard microwave design codes will assure a RF matched layout.

A commonly observed failure mode of RF windows is metallic coating of the ceramic by RF sputtering or glow discharge. The resultant local heating can produces mechanical stress and fracture. Sometimes arcing is observed without obvious reason. Cleaning of the ceramic by grit blasting was reported as efficient repair [8].

One or two windows are in use for input couplers feeding superconducting cavities. In the second case the downstream ("cold") window can be assembled to the cavity under strict clean room conditions thus reducing the risk of cavity contamination. The upstream ("warm") window is assembled after placing the cavity string into the vacuum vessel. The vacuum between both windows must be pumped separately.

2.3 Cryogenic layout, cooling

Static and RF heat will flow to the cold end of the coupler. The outer wall of the wave-guide is intercepted at 70K (and at 4k if the cavities operate at 2K) or is cooled by a counter flow cold circuit to reduce cryogenic loading. The inner conductor of a coaxial line can be cooled by water or cold cryogenic gas. In the case of a second "cold" window the heat transfer across the ceramic might be sufficient at moderate average RF power like TESLA (2KW)

3 MULTIPACTING

Multipacting is a vacuum phenomenon in high power RF components. It is characterized by two ingredients:

- There exist resonant electron trajectories, which hit the same surface ("one point") or two opposite surfaces ("two point") in multiples of RF cycles. The order of multipacting is given by the travel time in units of RF cycles. Lower order multipacting is more stable, i.e. more dangerous. In coaxial lines multipacting of order 6 and lower turned out to be of trouble.
- One impinging electron produces more than one secondary electron. The secondary electron yield depends on impact energy and condition of the surface. Clean Cu surfaces show a maximum secondary yield around 1.2, but contaminations or absorbed gases will increase it by typically 50 percent. RF windows from Al_2O_3 have an extraordinary high value of around 6.

Figure 3: LEP coupler as example of a one window design

A multipacting resonance will create an avalanche of electrons. One important consequence is the desorption of gas molecules from the surface. This is especially dangerous at the cold part of couplers where cryo-pumping can collected large amount of gas layers.

Multipacting trajectories have been investigated by several numerical codes [9, 10]. Rectangular wave-guides and coaxial lines can now be described in “susceptibility” charts, which predict resonant trajectories. The analysis also includes RF conditions of travelling wave, standing wave and any mixture of both configurations. Also windows in coaxial lines have been included in the analysis. It is therefore possible to predict multipacting resonances at an early stage of RF design. One striking finding for coaxial lines is that the RF power at which a resonance occurs scales with the 4th power of the coax dimension.

Fig: 4 shows the typical multipacting trajectory in coaxial lines: electrons are accelerated from the outer conductor and return to the same surface without hitting the inner conductor (one point multipacting in electrical fields). A DC bias between the inner and outer conductor of a coaxial line will influence multipacting resonances [10]. Simulation predicts and experiments prove that resonant trajectories can even be suppressed by the right amount of bias voltage (2.5 KV in the case of TTF couplers).

For more details about coupler design and development issues see [11].

4 BROAD BAND HIGHER ORDER MODE ABSORBERS

At KEK and Cornell ferrite material is used for broad band absorber in the beam pipe. At KEK a HIP process is applied to place the absortive layer to the beam pipe. At Cornell small tiles are brazed to an arrangement of cooling plates (see Fig. 5). RF power of 2.5 KW are absorbed in beam operation. Cooling efficiency up to 10 KW RF power was demonstrated in RF bench measurements.

5 CONDITIONING OF INPUT COUPLERS

“Conditioning” is a verbal phrasing of the fact, that RF power cannot be raised immediately to maximum value in a new coupler. Couplers have been equipped with different kinds of sensors to analyse the conditioning effect and/or to act as interlock:

- vacuum monitors are most commonly used, but in the presence of a cold surface with cryo-pumping effect this monitor is not very sensitive
- small coaxial pick ups will detect electron or ion current
- light sensors (photo multiplier or diodes) will sample light effects
- infrared sensors can measure the window temperature; PT100 sensors placed at the window flange are a cheaper way to get some information about temperature increase.

Although individual couplers can show specific reaction during conditioning, there is some common behaviour as being reported from several laboratories:

- vacuum is deteriorated, often with a dramatic grows rate at specific power levels
- pick up current (mostly electrons as determined by some bias voltage) is observed at the same time
- light is detected simultaneously at the same sharp power levels.

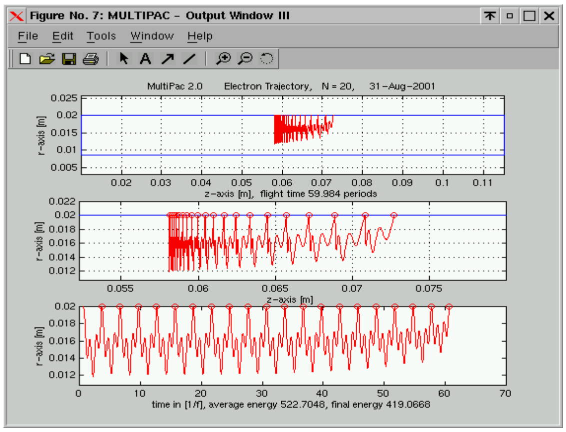

Figure 4. Multipacting simulations in coaxial lines: upper picture shows trajectories from outer conductor along the coax-line; middle picture as above but enlarged; lower picture shows the radial coordinate of the trajectory against time (in units of RF cycle time).[10]

The most plausible explanation is that multipacting electrons bombard the surface and desorbe condensed gases. A residual gas analyser (RGA) determines water during early stages of conditioning, followed by dominant Hydrogen at a later stage. At a lower level Hydrocarbon and Carbon Oxides are present. Recent experiments at CERN with bombarding metal surfaces by electrons of 500 eV [12] result in the same residual gas composition during treatment time.

In this sense conditioning is the removal of surface bound gases by electron bombardment. Efficient conditioning means to operate at a high and stable desorption rate but to avoid a vacuum burst, which could initiate sparking, or sputtering. In situ bake out and high pumping speed in the coupler line (especially at the window) are important ingredients for fast conditioning.

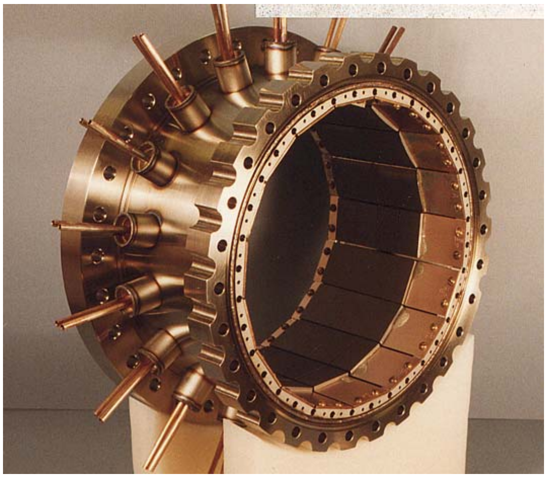

Figure 5: Broadband HOM damper at CESRII. One can see the absorbing tiles at the inner beam pipe surface.

6 DISCUSSION AND OUTLOOK

Performance limitations are observed in normal and superconducting cavities at local surface electric fields around 100MV/m. Field emitted current plays an important role in initiating local plasma, sparking, surface erosion or cryogenic loading. As pointed out in the introduction, surface fields in couplers carrying 1 MW RF power are around 1 MV/m. Therefore it is obvious that present power limitations in couplers must be caused by different phenomena.

Condensed gases on cold surface result in very specific effects in couplers for superconducting cavities. Multipacting electrons will partially release these molecules and RF discharge or sparking might be ignited. This effect tripped RF operation at LEP, HERA and CESR. At HERA it showed up for the first time after some month of normal operation. Application of a DC voltage between inner and outer conductor of a coaxial line (”DC bias”) proved to be an effective remedy against multipacting resonances. Some improvements could be gained with 10 Gauss magnetic fields at the rectangular wave-guide at CESR. A short warm up cycle of the coupler will “degas” the surface but cannot help on long term. Conditioning of coupler at warm test-stands is helpful for first processing but it misses the major detrimental effect of cold coupler surfaces.

The design of future couplers must examine the geometry to be free of multipacting resonances rather than to apply the complexity of DC biasing. In coaxial lines the multipacting levels scale with the fourth power of the dimension. Therefore an as large as possible diameter should be chosen. This will increase the pumping conduction as well. Improved vacuum cleaning techniques as well as in situ bake out of the coupler/cavity assembly will reduce the level of residual gases. This technique should be incorporated in the cryostat design.

The two main arguments for a one or two window design are related to cleanliness and safety issues. High gradient cavities (E_{acc} large 20 MV/m) must be treated and handled under strict clean-room conditions. It is therefore inevitable to close the cavity vacuum in the clean-room with a “cold” window at an early stage of assembling the accelerating unit. Charging of this window by dark current was observed at the Jlab linac. It can be avoided by more distance to the beam pipe or some shadowing geometry as in the TESLA coupler design. Quantitative measurements, however, about the requirements and effectiveness are still missing.

At medium gradients (E_{acc} smaller 20 MV/m) the assemble of the coupler with the window might be possible with the not ideal conditions of a local clean room box around the cryostat.

The probability and consequence of a window fracture is often controversially discussed. In a two window design a leak of the outer window will be detected, the cavity is protected by the inner window. In a one window design the cavity can be contaminated, a small leak is difficult to detect because of the large pumping speed of the cold cavity surface. The experience with input couplers with RF power above 50 KW at CESRII, HERA, KEKB, LEP and TRISTAN sums up to about 80.000 operating coupler-weeks (at continuous wave operation). Several small leaks were detected but no disastrous accident happened. This is partially due to the consequent application of sensitive interlocks by vacuum, temperature, light or current sensors. At TRISTAN and HERA (both couplers have one RF window) the cavity performance after a leak at the window was recovered to the nominal value of 5 MV/m after warm up and pumping.

Input coupler for superconducting cavities operate under pulsed (linac) or continuous wave (storage rings) conditions. The pulse length is around one msec (partially due to the long filling time of the superconducting cavity). In respect to multipacting or arcing 1 msec operation is very near to steady state conditions. The main difference is the thermal load which requires more effort in cooling design and circuitry. In a one window design the inner conductor can be cooled by water if the additional cryo-load be the warm pipe is acceptable. Cryogenic gas cooling is required for a two window design because of the 70K intercept at this window.

During pulsed operation the RF wave experiences standing wave pattern during filling (typically several 100 μsec), travelling wave during beam acceleration and a high power transient after RF power switch off (by emptying the stored energy of the cavity). Coupler conditioning without beam will establish standing wave conditions so that only high electric field regions are processed. Furthermore the switch off transient with high RF peak power (factor of 4 higher than the klystron pulse !!) cannot be simulated. Amplitude modulation at the end of the pulse will reduce but cannot eliminate the high peak power transient. Sweeping the cavity resonance or modulation of the bias voltage are methods under investigation, but no standard procedure has been developed so far to completely condition all coupler surfaces. Most "cold" couplers requires unacceptable long time for conditioning so that new methods must be explored. Reducing the residual vacuum pressure by improved degasing of coupler part and installation of in situ bake-out installation are principle methods to reduce the need of RF conditioning.

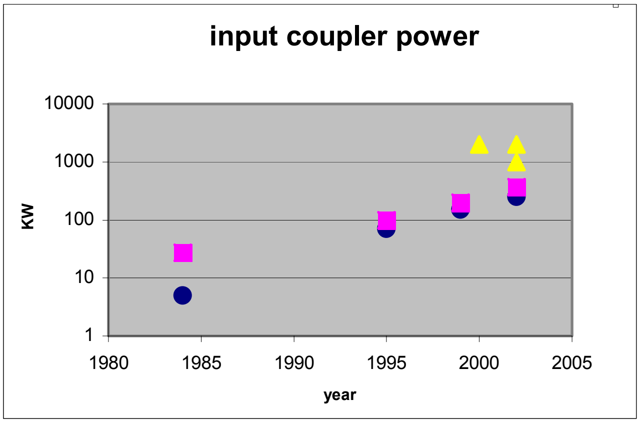

Fig.: 6 Input coupler Rf Power in beam operation (square = max., circle = typical condition). Data of 1984 represent the result of 12 prototype tests; data of 1995 represent operation of LEP, Tristan and HERA; data of 1999 and 2002 are related to KEKB and CESRIII operation. Triangulars are RF tests of prototype couplers for APT, TTF and SNS.

7 SUMMARY

Input couplers for superconducting cavities are in operation at levels above 50 KW for more than 80.000 coupler-weeks without serious problems or accidents. The maximum values for operation and prototype testing are 380 KW and 2 MW, respectively.

Cold coupler surfaces absorb many layers of residual gas which is released by impacting electrons due to multipacting resonances. Sensitive interlocks are in use to avoid resultant plasma sputtering or arcing.

Improved surface cleaning methods before and after installation are required to reduce the amount of conditioning. DC bias (coaxial lines) or DC magnetic fields (rectangular wave-guides) proved to reduce multipacting phenomena. Two key design tasks in future coupler design are to completely suppress multipacting resonances by geometric means and to supply maximum pumping speed to cope with possible vacuum bursts.

8 ACKNOWLEDGEMENT

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