# HIGH POWER COUPLERS

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Abstract The break of a high power input window is the most likely and dangerous accident for SC cavity systems. This is a motivation to compare and evaluate different designs and operating experiences and limitations of high power couplers for superconducting as well as normalconducting cavities. Equivalent information of klystron windows will be included for comparison.

## INTRODUCTION

Cavity resonators and travelling wave structures are the conventional tools of energyzing particle beams of big accelerators under UHV conditions. The energy transfer to the beams is possible by interaction of RF electrical cavity fields and the charged beam particles. The energy need of the beams is enormous in many cases. Practical examples at DESY are the PETRA 5-cell 500 MHz cavities which are driven at about 90 KW/m and the HERA superconducting 4-cell cavities which are designed to transfer the same amount of power to the beam. This high power need combined with the additional requirement of shortest possible accelerating structures leads to technical limitations of RF power transfer per unit length into UHV devices.
One of the devices which proved to be limiting is the RF power coupler of any accelerating structure. Its tasks are to receive transmitter power from waveguides or coaxial lines, to provide a transition from feed line towards cavity input, to match between both - different impedances and different temperatures in case of a superconducting structure - at a minimum of losses and at the same time to radiate average power of watts up to hundreds of kilowatts at CW or up to MW pulses through a dielectric window inside the coupler which separates the UHV world of the accelerator from the feedline atmosphere.
All these tasks were solved in many applications even with respect to the big variety of accelerator requirements and boundary conditions. But most of these solutions have their problems. And normally these problems become apparent by heating or break of windows. The likelyness of broken windows simply increases with the amount of RF power to be transferred. This is explainable by the fact that the RF high power window is a barrier which has to be passed by the energy in terms of

electromagnetic radiation. Average radiation through the windows can be $10^4$ times higher in intensity than sunshine through a glass window. The coupler window is normally a ceramic with low heat conductivity. Slight degradations of performance will result quickly in dramatic temperature increase and break due to thermal stress or even in melting. All the other parts of the coupler RF transport system are metal surfaces which only reflect the electromagnetic fields. They can be cooled effectively and they are resistant against thermal stress. Clearly and much more than in case of normalconducting cavities a break of the high power window of a superconducting cavity is a catastrophe for the total system comparable to damage of a high power RF tube window. Hence in a situation where superconducting cavities are ready to play an important role in upgrading performance of today's accelerators it is important to review the state of high RF power coupler techniques. As a consequence of the preceding explanations this will be done in the following chapters under special emphasis on window problems.

## TECHNIQUES

### Main Characteristics

At a beginning coupler design two main parameters are given: RF power need and operation frequency. Both are influencing the cross dimensions of the coupler which are roughly proportional to the ratio of power divided by frequency. After this important features of the coupler are fixed by decision of waveguide or coaxial line type. In most cases this decision also is decisive for the type of window.
In a coaxial design a coaxial window is natural. This implicates that the window needs two braze fillets, one for the inner conductor, one for the outer conductor.
In contrast to this a waveguide window needs only one outside braze fillet which is much easier in construction.
At next the designer has to find an optimum position for the most critical part which is the window. It can be near the cavity which would be a "cold" window in case of a superconducting cavity. Or it may be more remote. This would be a room temperature window in case of a superconducting cavity. It offers the possibility of exchange without unmounting the cryostat and it avoids technical difficulties of low temperature design. Examples for these general design decisions are shown in Figs. 1 and 2.
Fig. 1 shows one of the first high RF power coupler designs for superconducting cavities which now dates about 7 years back. It is a coaxial type coupler for 500 MHz, 50 kW constructed by the Karlsruhe KFZ RF superconductivity group for driving a 1-cell SC cavity at DORIS. The features are coaxial design with a "cold" window supporting a part of the inner conductor. This made necessary an additional "warm" UHV window in order to protect the cold window against condensation of gases on its surface. Four lambda/4 stub transitions were used to prevent heat flow via the coupler towards the cavity.In theory this coupler was a perfect solution to all tasks of a coupler. But in practice manufacture,

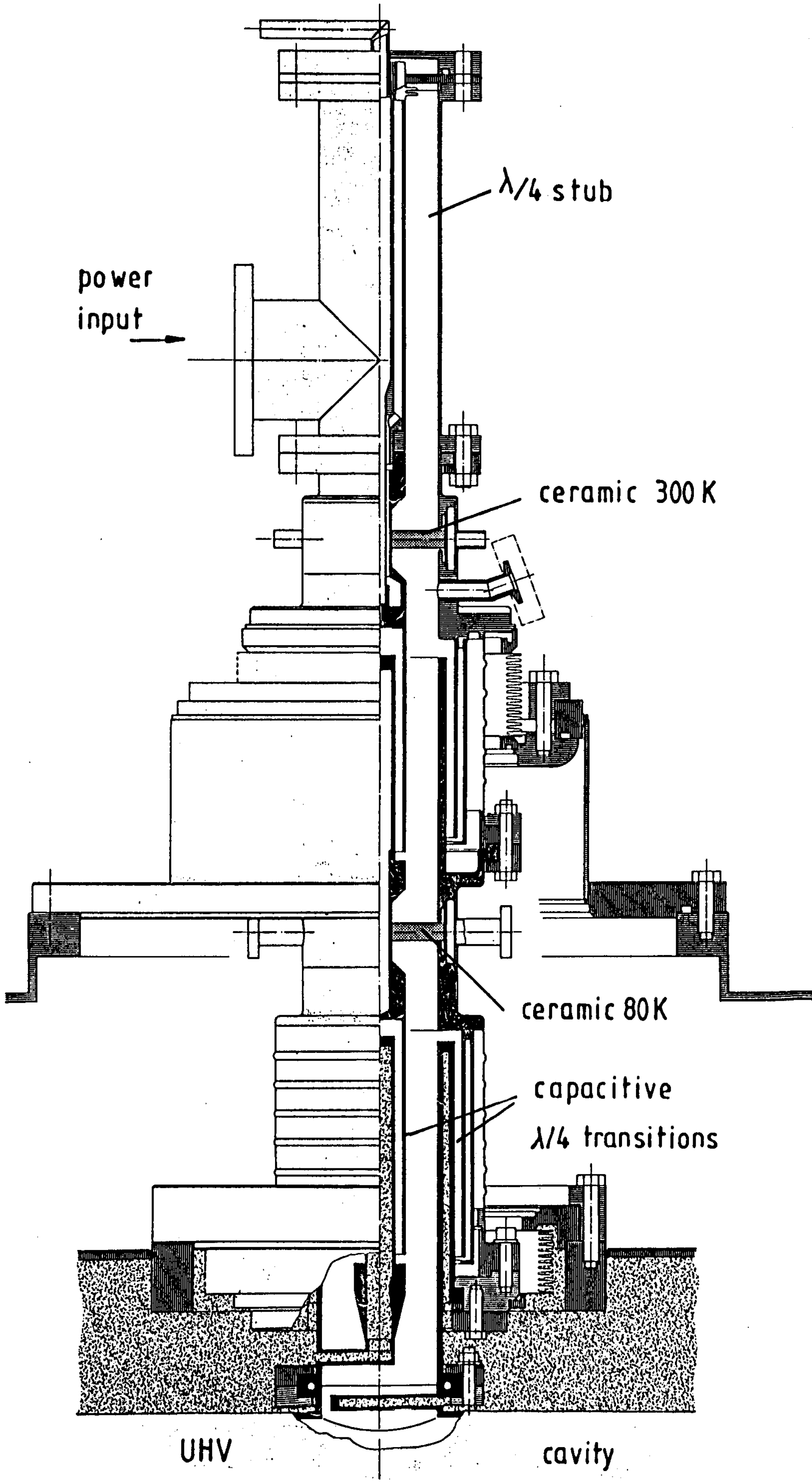
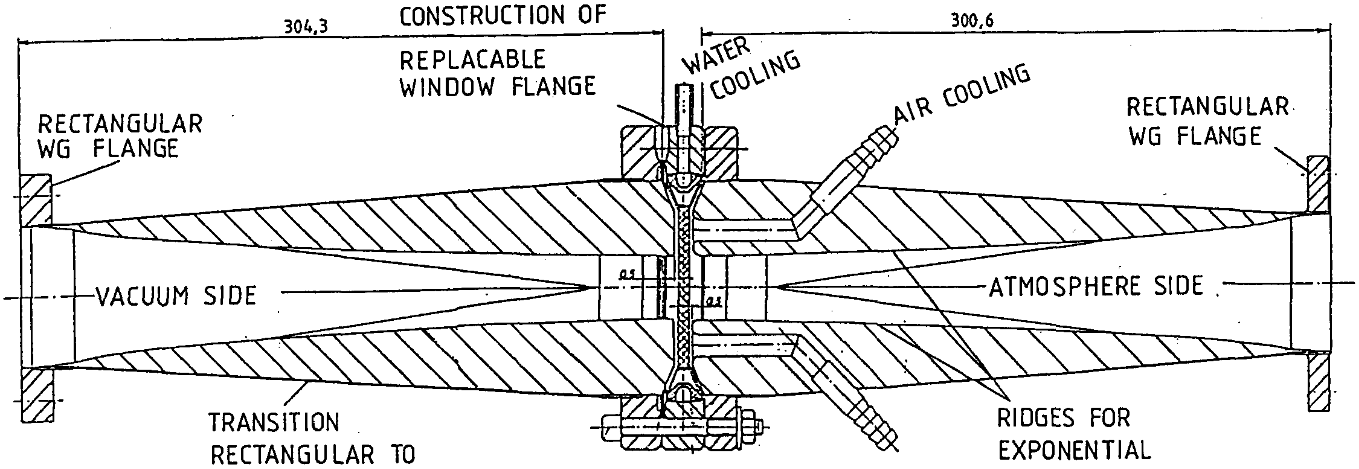



Fig.1

Power Coupler For 1-Cell SC-DORIS Cavity




BROADBAND HIGH POWER RF VACUUM WINDOW FOR PETRA SUPERCONDUCTING 9-CELL CAVITY

Fig.2

| CHARACTERISTIC | MATERIAL | | |
|---|---|---|---|
| | ISOTROPIC CVD BORON NITRIDE | ALUMINA | BERYLLIA |
| DIELECTRIC CONSTANT | 3.0 | 9.6 | 6.6 |
| DIELECTRIC STRENGTH [V/mil] | 1000 | 330 | 350 |
| LOSS TANGENT | 0.0003 | 0.0002 | 0.0003 |
| FLEXURAL STRENGTH [PSI] | 16,000 | 45,000 | 30,000 |
| THERMAL CONDUKTIVITY [W/cm·K] | 1.9 | 0.31 | 2.5 |
| THERMAL EXPANSION | $4{,}0 \times 10^{-6}$ | $8{,}3 \times 10^{-6}$ | $9.34 \times 10^{-6}$ |
| SECONDARY EMISSION RATIO (MAX) | UNKNOWN | 4.8 | 3.4 |

Characteristics Of Dielectrics For Window Applications

Fig.3

handling and operation proved to be very complicate. The warm window got a leak during operation.
Fig. 2 shows a warm coupler of the waveguide TE type with circular demountable disk type window. It was constructed for the DESY 1 GHz 9-cell superconducting cavity project in PETRA. In comparison to the first example this was an extremly simple construction. It transferred nearly 30 kW to the beam and was uncritical over a test period of several months.

## Materials

The windows of the above mentioned examples were made of aluminum oxide. Alumina is the predominant dielectric material used for windows of cavities and RF tubes in spite of its obvious limitations in thermal conductivity and its high dielectric constant.The relatively low thermal conductivity causes a large thermal gradient between the window interior and the cooled boundary. At high power levels, the resultant thermal stresses can exceed the strength of alumina and lead to cracking. Alumina's high dielectric constant is a disadvantage because of the large mismatch which must be compensated for by auxiliary reactive elements.
Fig. 3 [1] shows data of alumina in comparison to boron nitride and beryllia.
Requirements from the experience of high power tube developers are high purity of the alumina [1],[2] in spite of more difficulties at metalization and high density in order to eliminate voids. Both voids and impurities are considered to be starting points of puncture effects occurring at high field strength at dielectrically weak points. Some of the desired properties of a dielectric material for high power windows can be combined into a goodness factor [3] which applies especially to the dielectric heating problem:

$$GF = (\delta t \times k)/(\tan\delta \times \epsilon) \times F_c$$

where
- $\delta t$ is the maximum permissible temperature rise
- $k$ is thermal conductivity
- $\tan\delta$ is the loss tangent of power factor
- $\epsilon$ is the dielectric constant
- $F_c$ is a forced cooling coefficient

If the heating is caused by mechanisms like particle bombardment or surface losses due to conducting coatings, the factor has to be modified. Application of the factor indicates that the best window is beryllia which was often used in high power tubes. The problem of beryllia is its toxicity. A very interesting choice of window material was done at CEBAF. For their superconducting 1.5 GHz cavities they developed a polyimid foil window for powers of up to 3 kW. This mainly is a foil which is squeezed in between two waveguide flanges with a special sealing technique. At DESY this kind of window was developed even for powers of up to 800 kW at 500 MHz in WR 1800 as a gas barrier. But it proved to withstand pressure differences of up to 1 bar. This offers the possibility of using it as an additional back up window for superconducting cavities.

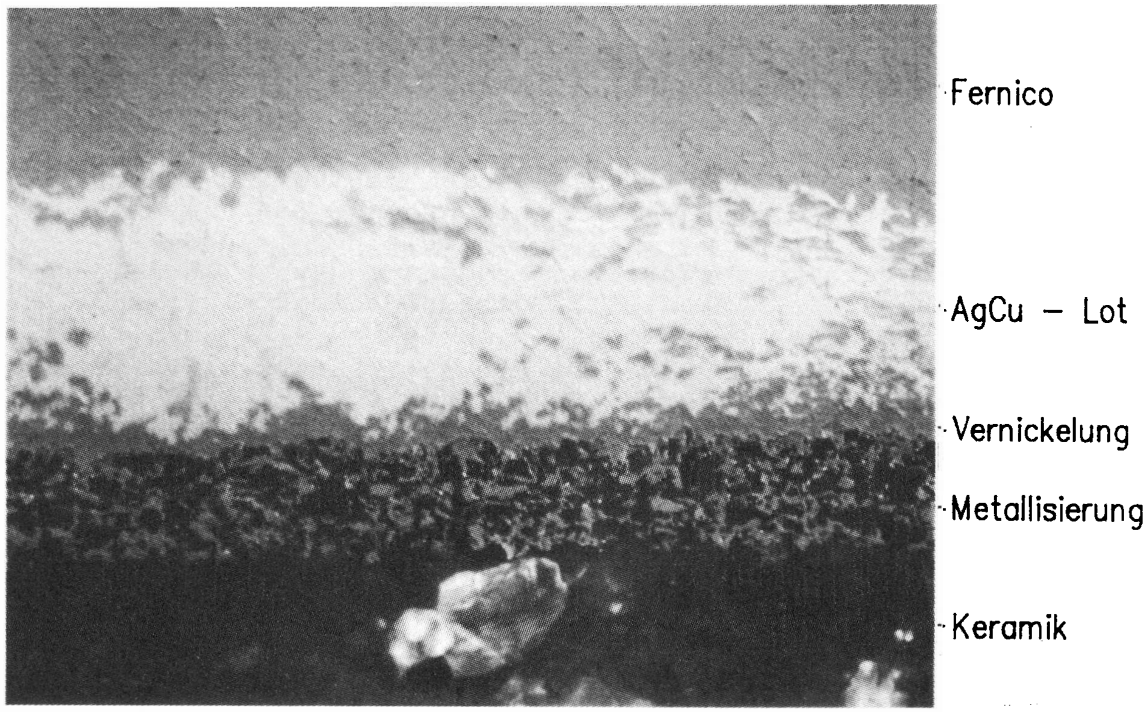
### Metal Ceramic Technology

A special technological problem is the realization of a uniform, stressfree, mechanically highly resistant, low loss, UHV proof connection between the window material and the metal boundary. Fig. 4 shows a typical cross section of metal to ceramic connection [4]. Metalization was a problem especially for the tube manufacturers 20 years ago when they were on the way to very high RF power tubes - several hundred kW CW or MW pulses - because diffusion of metalization into the ceramic can cause semiconductor regions [1] with additional losses and these may be starting points for internal puncture in high fields. As already mentioned, it is still difficult to metalize very high purity ceramics. For windows of today's superconducting cavities the existing metalization technique is no urgent problem because the power flow is not yet causing high enough fields: typically less than 2 kV/cm maximum. A standard metalization suitable for assembly with a range of brazes, including copper-silver eutectic, silver-copper-palladium, copper-gold and copper, is molybdenum or molybdenum-mangenese, plated with nickel. The braze fillet between ceramic and metal boundary is usually an eutectic alloy of copper and silver. At brazing the window into an assembly it has to be prevented that an overflow of braze or the ceramic metalization itself forms sharp edges at the triple point of vacuum, ceramic and metal boundary. Electric flux concentration at these edges - radius may be a few µm - can cause high electric fields even at low power flow. Thus giving raise to electron emission from the braze and to electrically charging the ceramic, a discharge or continous glow on the vacuum side may be initialized. Selection of the boundary metal usually has two possibilities. Possibility 1 is a very soft boundary metal which is allowed to be much different in thermal extension coeffecient, like copper. Possibility 2 is a still thin but thermal extension matched material like Fernico or Kovar (Fig. 4, Fig. 5)[4]. Another technique of joining 96 % alumina to niobium, copper or nickel was used for ICRF Heating project at Oak Ridge National Laboratory. The braze is Ticusil and no metalizing of the ceramic is necessary.

### Surfaces

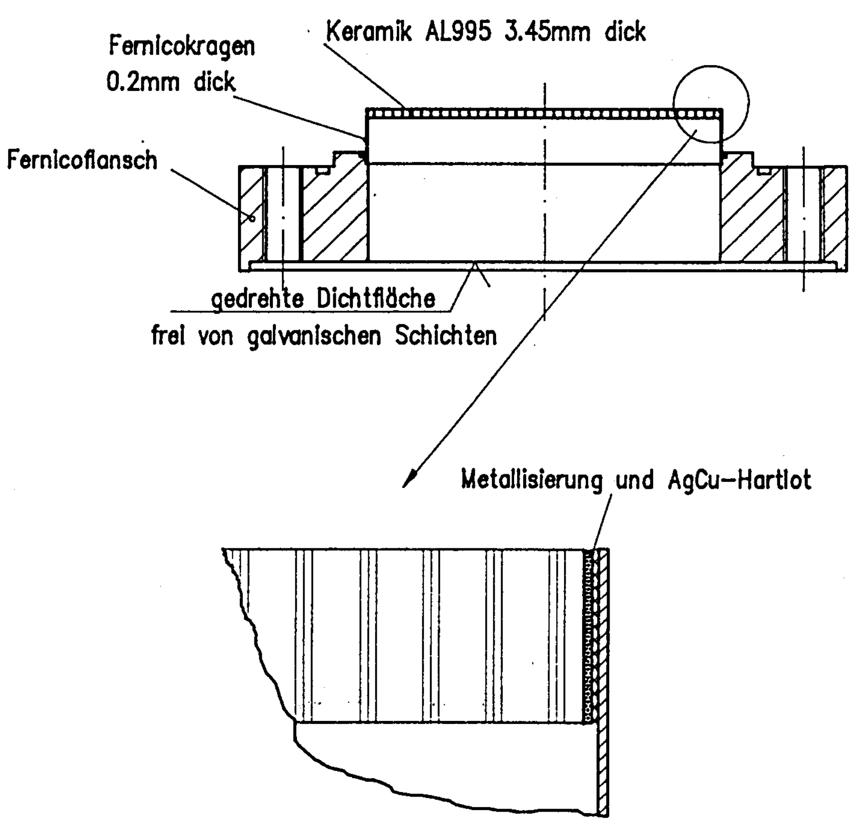
A decisive influence on proper function of a high RF power coupler is given by the surfaces exposed to the RF fields. The metal surfaces have to be clean, smooth and highly conductive. The ceramic surface should also be smooth and free of dust or metal particles because every inhomogenity even at the air side can cause an RF arc. On the vacuum side surfaces additional requirements have to be taken into account. Because of free motion of charged particles in a UHV environment the surfaces should withstand electron and ion bombardment. Even adsorbed gases at the surfaces which lead to vacuum break down and arcs under bombardment conditions must be removed. Hence considerable effort has to go into cleaning and baking of those surface parts. A final cleaning and smoothening is RF conditioning over hours or days.

One of the most important lessons which also were learnt already long ago by the tube manufacturers is, that surfaces under




Schliffbild einer ASTM – Probelötung

Fig.4



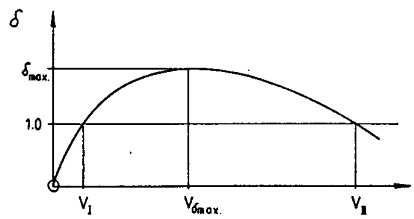

Metal-Ceramic Connection

Fig.5

exposure to charged particle impact should have secondary electron yields of less than unity because otherwise even the best coupler and window design may not survive high RF power over more or less long time . Surfaces of high secondary electron yield are subject to single surface multipacting under certain electromagnetic field conditions. The consequences are excessive heating, pressure increase, arcing and melting of surfaces. Especially the ceramic surfaces are known to have high secondary electron emission coefficients. In case of normal electric fields on their surfaces they should be coated by low yield materials on their UHV side. This method has proved to be quite effective in preventing multipactor, glowing and charging effects on windows. A number of conducting coatings have been found, which suppress multipactor. The most commonly used materal is metallic titanium in thicknesses of 50 up to a few hundred Angström units. Fig. 6 [5] shows data and a typical curve of secondary electron emission $\delta$ as a function of energy of impinging electrons. The value of titanium is less than 1. Temperature dependance of $\delta$ is negligable for pure metals.
Other multipactor inhibiting coatings are TiNx, TiNxOy, $Si_3N_4$, $Cr_2O_3$ [2], copper black, gold black. After careful cleaning procedures all these coatings are deposited to the surfaces by sputtering techniques in special atmospheres under pressures of several $10^{-5}$ Torrs up to Torrs. The coatings are more or less conductive. Minimum allowed film resistivities are about 20 MΩ/square. Aspired values are about 100 MΩ/square [6]. In case of coatings less than 40 Angström, the observed secondary emission has spectrum and intensity of the substrate [7]. The conductivity of the coatings increases total losses of the ceramic windows. On the other hand they reduce or prevent charge accumulation on the ceramic surfaces. It is not clear how important this may be. In addition to coating of the ceramic surface it is not unusual to coat also the metal surfaces of the environment.

## WINDOW TYPES

Besides the windows shown in Figs. 1 and 2 the number of possible geometries is as large as the variety of applications. Some waveguide types of windows used for klystron applications are shown in Fig. 7.
Window designs for about 1 MW CW klystrons are shown in Figs. 8 and 9. The window of Fig. 9 is a very successful type which is in use at the PETRA cavities already since a lot of years in the version of Fig. 10 and was also selected for the KEK superconducting cavities. Fig. 11 shows the main coupler for the DESY superconducting cavities. This type of coupler was transferred from the LEP normal conducting cavities and is also used for the LEP superconducting cavities. An interesting coaxial window is shown in Fig. 12. It was developed for the ICRF Heating activity at Oak Ridge National Laboratory.
A general classification of coupler and window designs is very difficult. The decision for a special design and shape is quite empirical within the limitations and specifications of an actual task given by: Frequency range, power, thermal and geometrical boundary conditions, supply conditions for example of cooling media etc.. Even coating of window surfaces is not a stringent

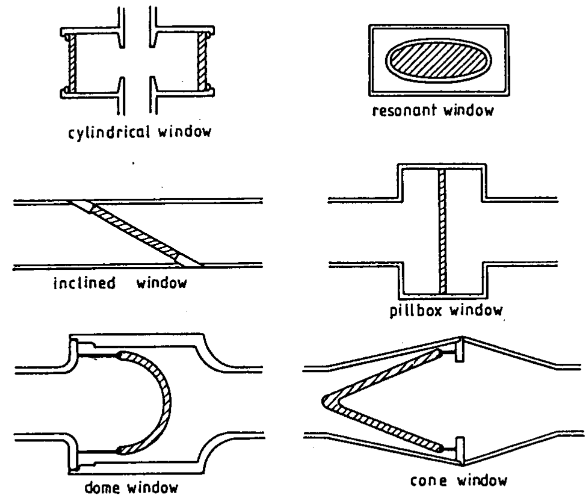



Secondary emission coefficient $\delta$ as a function of velocity of bombarding electrons expressed in electron volts.

| Material | $\delta_{max}$ | $V_I$ (eV) | $V_{\delta max}$ (eV) | $V_{II}$ (eV) |
|---|---|---|---|---|
| Be O | 3.4 | | 2000 | |
| $Al_2O_3$ | 1.5...4.8 | 20 | 350...1300 | 1200 |
| $Ag_2O$ | 1 ... 1.2 | | | |
| $Cu_2O$ | 1.2 | | | |
| Al | 0.95 | - | 300 | - |
| Cu | 1.3 | 200 | 600 | 1500 |
| Nb | 1.2 | 175 | 375 | 1100 |
| Ag | 1.4 | 150 | 800 | > 2000 |
| Au | 1.4 | 150 | 800 | >2000 |
| Ti | 0.9 | - | 280 | - |

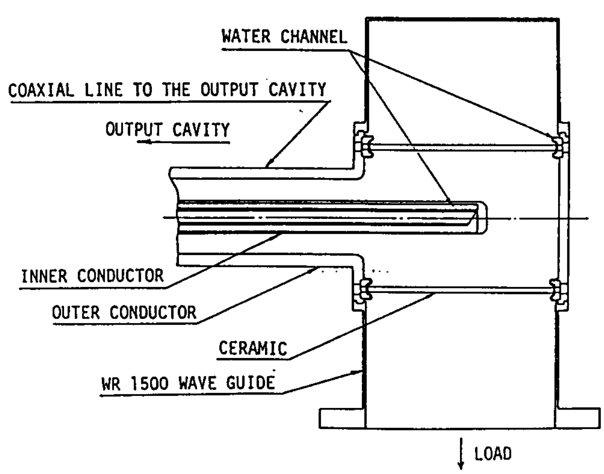
Secondary Emission Coefficient $\delta$ Of Several Materials

Fig.6



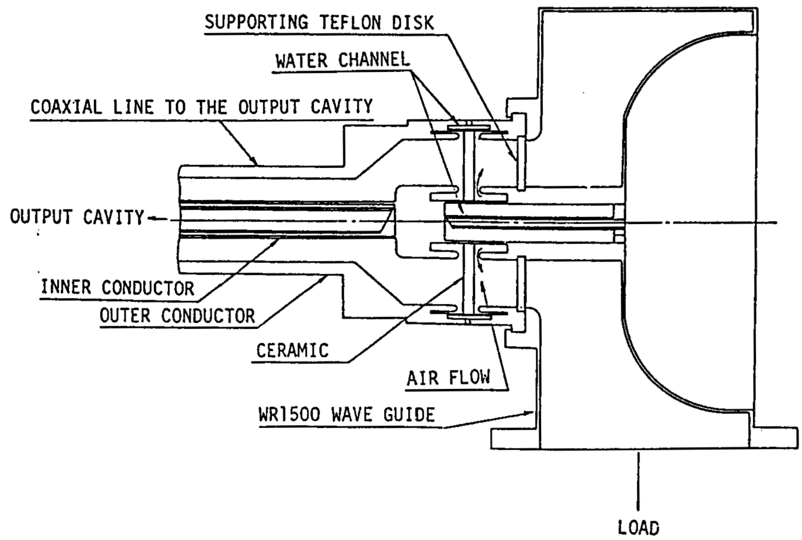

Output Line Windows Used In High Power Klystrons

Fig.7



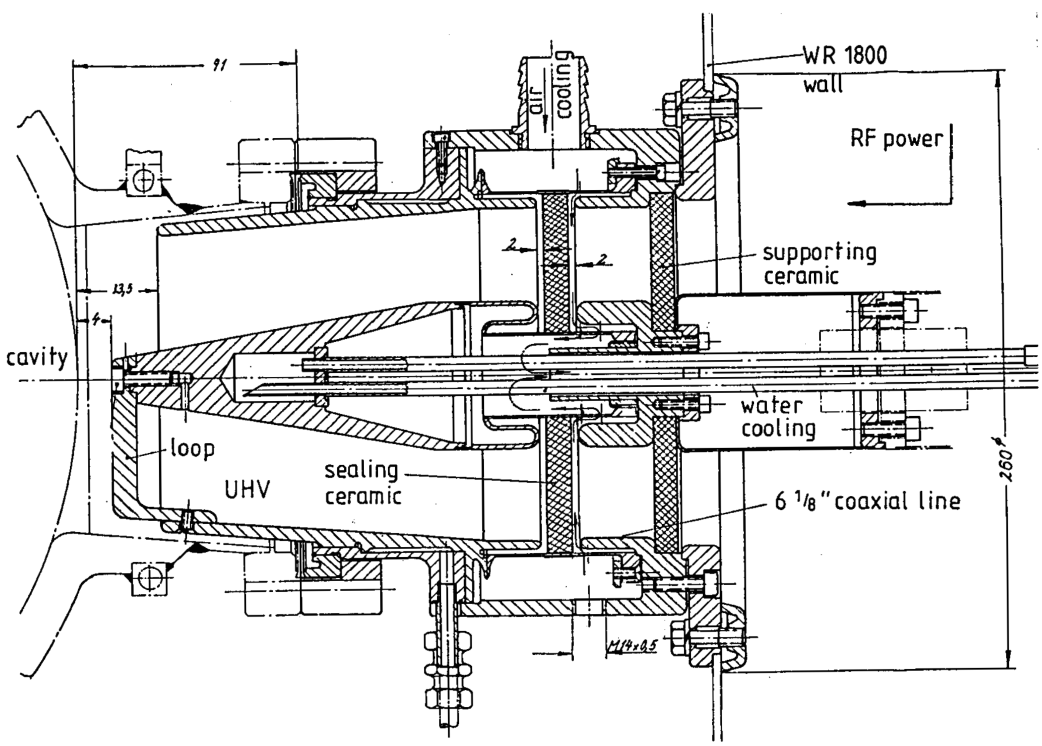

Cylindrical Ceramic Window For E 3786 Toshiba Klystron (Old Model).

Fig.8




Disc Type Window Developed For 1.2 MW Klystron E3786 For KEK TRISTAN.

**Fig. 9**




Main Coupler For PETRA 5-Cell 500 MHz Normal Conducting Cavities

**Fig. 10**

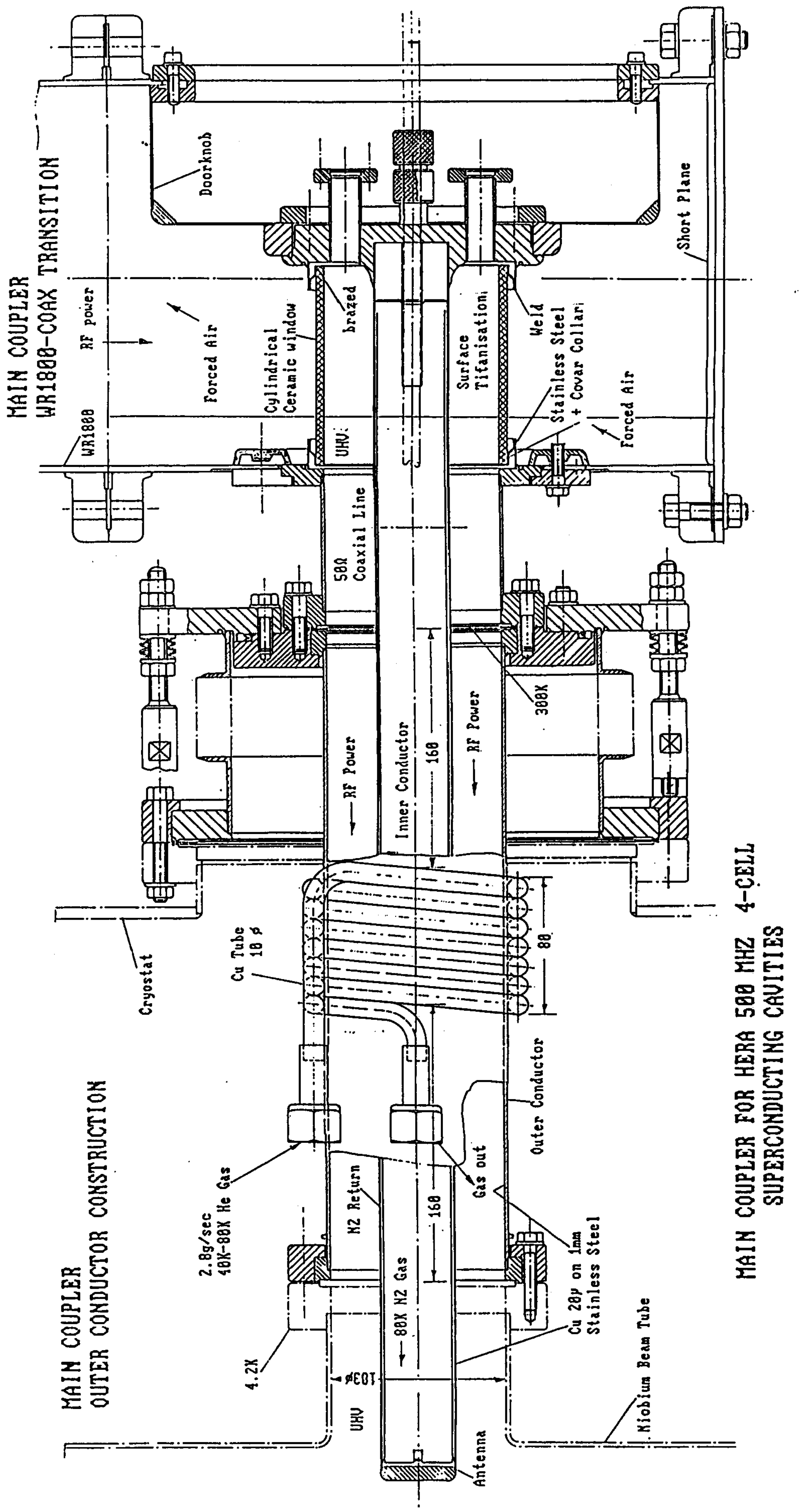
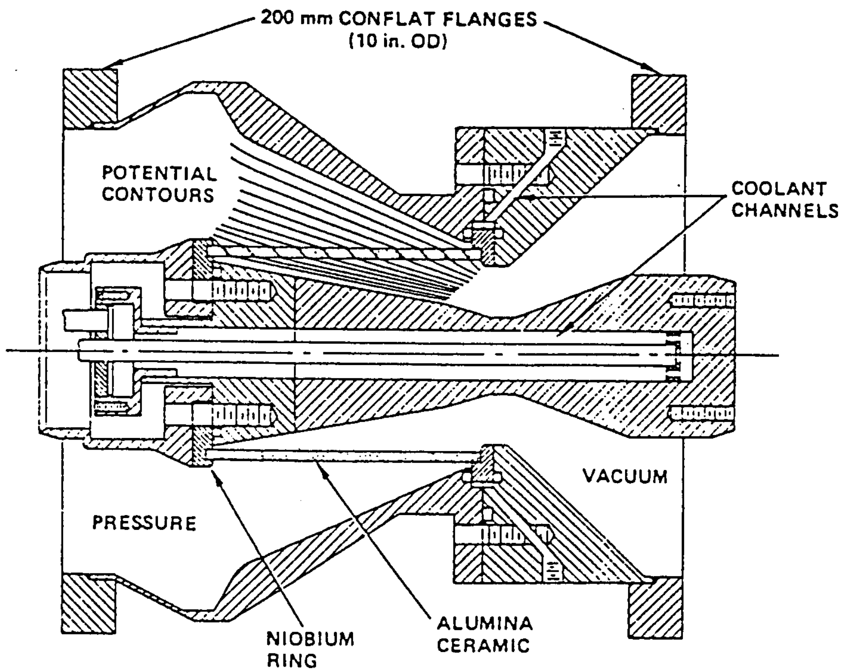

MAIN COUPLER
WR1800-COAX TRANSITION
WR1800
RF power
Forced Air
Doorknob
Cylindrical
Ceramic window
brazed
UHV
Surface
Titanisation
Weld
Stainless Steel
+ Covar Collar
Forced Air
Short Plane
50Ω
Coaxial Line
300K
RF Power
Inner Conductor
160
RF Power
Cryostat
Cu Tube
10 ϕ
80
Outer Conductor
Gas out
MAIN COUPLER
OUTER CONDUCTOR CONSTRUCTION
2.8g/sec
10K-80K He Gas
N2 Return
160
80K N2 Gas
Cu 20μ on 1mm
Stainless Steel
4.2K
UHV
Antenna
Niobium Beam Tube
MAIN COUPLER FOR HERA 500 MHZ 4-CELL
SUPERCONDUCTING CAVITIES

Fig.11




ICRF Heating By 50-Ω Long-pulse RF Feedthrough Designed To TEXTOR Specifications.

Fig. 12


Operation without Conditioning

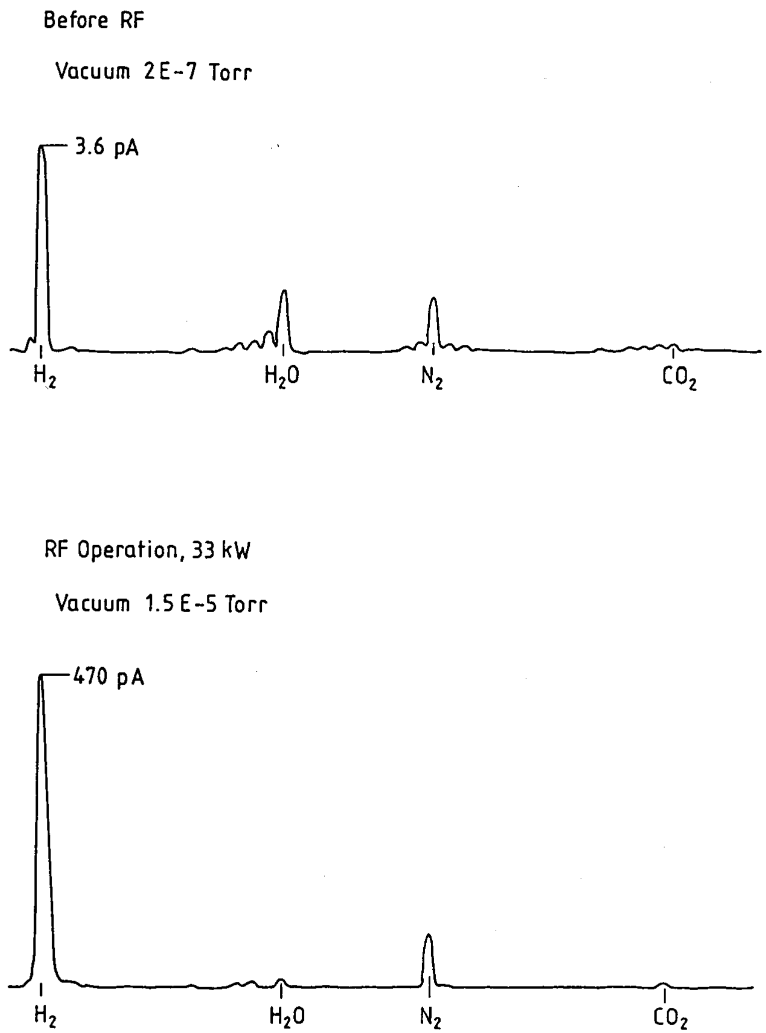
Fig. 13

necessity. For example the Valvo 500 MHz 800 kW CW tube has no coating. The DESY normalconducting cavity couplers also have no coating on their window. But coatings are necessary and helpful, if multipacting occurs. Design of couplers and window types having neither locations nor operation conditions which allow multipacting, charge accumulation, field emission, arcing, sputtering, is still difficult as recent designs of high power tubes and couplers show.

## OPERATION AND PERFORMANCE

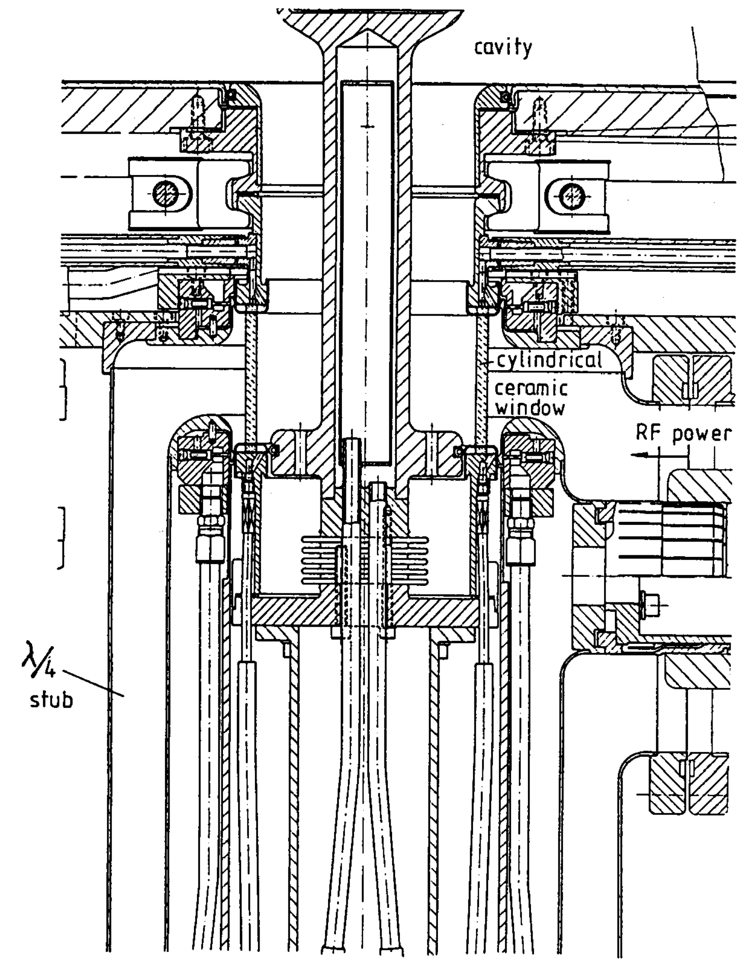
### Conditioning

High power RF couplers are devices where a lot of different technologies meet. The KfK coupler of Fig. 1 for the superconducting DORIS cavity is an example to show visually the complexity of the task to combine many functions within one limited unit.
RF-field and transmission line techniques, UHV-techniques, metal-ceramic joining and material technology, high voltage and current techniques, machine engineering, cooling and cryotechniques as well as surface technologies are involved. But this complexity has not necessarily always to find its image in complicated designs.
In spite of this variability of designs and the variety of applications and techniques there are common features of operation and performance. The first operation phase of every high power coupler for tubes, normal- or superconducting cavities is conditioning. If RF power is switched on without any prior conditioning, then the result may look like shown in Fig. 13. This is the vacuum side of the PETRA window of Fig. 9 after several minutes of operation at 20 kW without prior conditioning. Obviously an arc was ignited due to local pressure increase. Starting from the inner conductor and after melting a hole to the normal pressure side there were good conditions for the arc to absorb enough of the 20 kW forward power to melt also the alumnum oxide window. An additional effect was generation of sufficient nitric acid to destroy all the system surfaces.
Normally every PETRA window withstands 180 kW CW test power after conditioning.
Conditioning is a very important procedure of final cleaning especially of those surface parts which envisage high RF electric or magnetic field loading. This process is critical especially on the vacuum side and is closely related to a lot of pressure changes which indicate that materials like dust, sharp edges, gases were removed from the surfaces. Each surface layer and position seem to have their special power level for cleaning. The material desorption locally leads to charged particles due to ionisation, a big variety of light effects and even to arcing which rises very quickly like an avalanche. In such cases of high pressure increase and high reflections power has to be reduced or to be switched off immediately. Pumping speed of the system should be high because effective conditioning is only possible at power levels near the pressure increase area which is of course near to arcing. For this operation area pressure ranges from




Mass Spectrum At Conditioning An RF High Power Coupler

Fig. 14



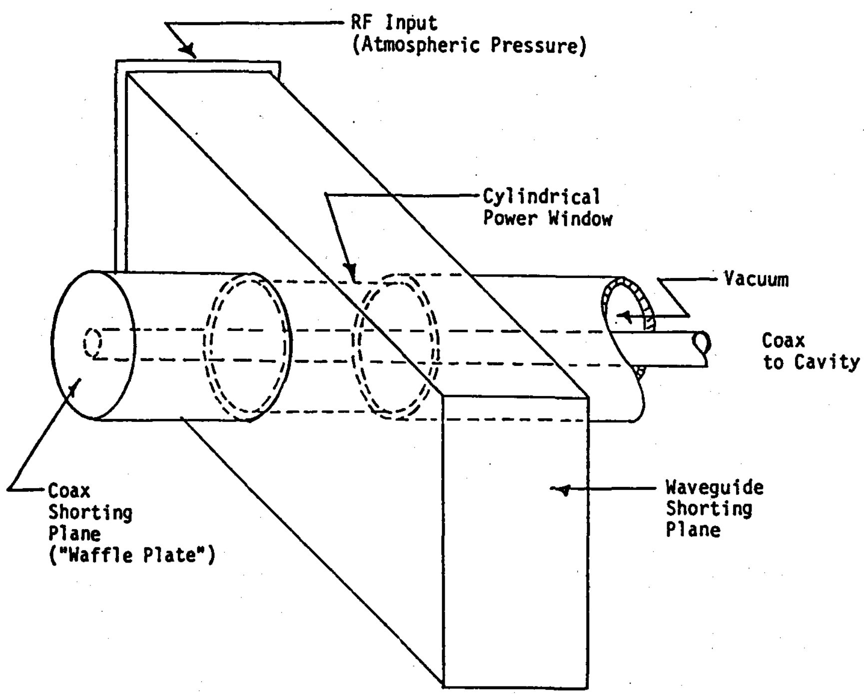

Coupler Of Travelling Wave Drift Tube Structure (200 MHz) For The CERN SPS

Fig. 15

several $10^{-7}$ Torrs up to about $10^{-5}$ Torrs, these values being dominated by $H_2$ partial pressure. A typical mass spectrum of conditioning is shown in Fig. 14. The operation space between pressure increase and arcing is very small because of the avalanche characteristics. Hence the developers of cavity couplers use RF power pulsing even for CW couplers. If an arc were to form, the short pulse length limits its duration. This allows limitation of the RF energy which goes into gas bursts and discharges. Additionally it is possible to jump over multipacting barriers in a defined way. The pulse duty can be automatically regulated by the vacuum with the goal being 100 % if the pressure stabilizes to low values.

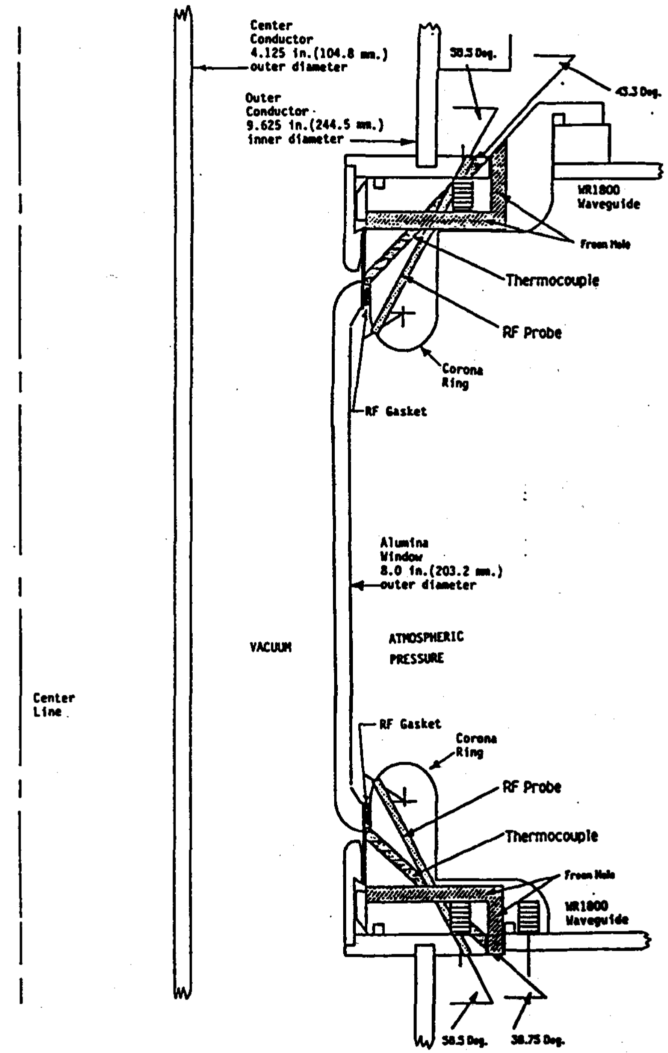
Performance and Long Time Operation

Conditioning is a first test for a new window design. If it is possible to reach design power, then this is no guarantee that the design will endure forever. In many cases design work has to be continued stepwise by improvements based on experiences during some time of operation. This may be demonstrated by follwing cases.
The CERN SPS travelling wave drift tube 200 MHz structure needs 600 kW of CW power which are fed by two couplers [8] of the construction shown in Fig. 15. Originally the BeO ceramic was uncooled and the connecting watercooled Fe-Ni-Co rings including the neighbouring coaxial outer conductor parts were gold coated. Under RF power this coating was sputtered to the inner conductor and to the ceramic surface. This resulted in a nicely conducting window and large reflections. The remedy was coating the ceramic with titanium of 500 MΩ total resistance and additional coating of the environment by 0.5 µm titanium. Another example is the Cornell CESR cavity window which was under construction in 1978. It was designed for about 500 kW CW at 500 MHz. Fig. 16 shows the principle design and Fig. 17 shows details of the window construction as it is today [9]. In 1985 these couplers still got into big difficulties by a series of cracked windows which were coated with $TiO_2$. In spite of a lot of work spent it turned out to be very difficult to find the reasons for the failures and corresponding cures. The effects were excessive heating, multipacting, partial melting of an inner copper corona ring, copper depositions on the ceramic, vacuum bursts before cracking. Today's situation is: The window coating changed to titanium, cooling was improved, the inner copper corona ring was removed, processing and baking techniques improved, and a diagnostic system installed which should detect critical situations like abnormal temperature increase early enough. These two examples and other recent examples like the 67 MW 2.9 GHz R & D pulse klystron development at SLAC, the 1 MW 500 MHz CW klystron development of Toshiba or the window problem of SRS in Daresbury show how difficult it is to predict or even to analyze the operation behaviour of a given coupler and window design. Obviously the tube manufacturers built couplers and windows which are much more powerful and reliable in CW and pulse operation than those of the existing acceleration cavities.
It is difficult to give general statements about power capability and reliability of high power tube windows and cavity windows and the reasons for their different power capability are not obvious.




CESR RF Cavity Coupler Schematic Diagram

Fig.16



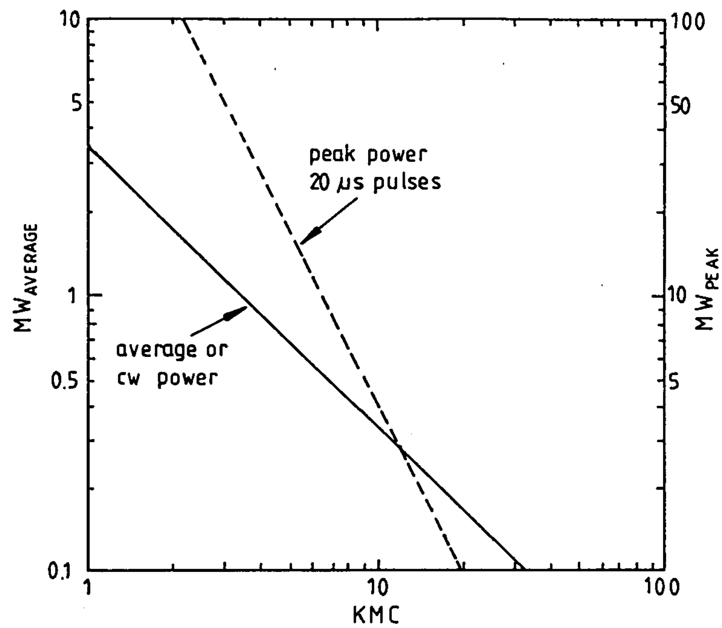

CESR RF Cavity Coupler, Power Window,
And Diagnostic Probes.

Fig.17

The PETRA cavity window type of Fig. 9 will reliably operate uncoated up to 120 kW CW. But the same type of window is working as a high power klystron window uncoated up to about 1 MW CW and coated up to about 1.2 MW CW [2] at 500 MHz. Obvious differences between cavity and klystron windows are - besides reverse energy flow - that those klystrons are driven at very stable matched output conditions under control of effective interlock systems, because a klystron is very expensive, whereas cavity windows are - depending on beamload - driven somewhere between open and short circuit load. Thus standing waves can cause RF load situations equivalent to up to four times the actual forward power - depending on window position. Often there is no specific window interlock. In addition the high importance of tube output power and reliability forced the tube manufacturers already 20 years ago to perform thorough investigations on window designs. From there Fig. 18 [3] is taken. It shows the calculated performance of a thin circular BeO window of best material in $TE_{111}$ mode and is scaled from measured results of highest achieved power at failure at S-band. Average power is limited by thermal cracking, peak power by arcing. The linear dimensions are scaled inversely with frequency.
It is obvious that the transmission power of a problem free window would be no bottleneck for today's cavity power requirements. For superconducting cavity application the question of window reliability may be still more important than the power transmission rate.
Fig. 19 shows a failure probability statics vs. operation hours of Valvo klystrons YK 1300, YK 1301 used for PETRA and DORIS [10]. The overall lifetime of these high power klystrons is about 17,000 h. Hence the lifetime of their windows is much higher. At the PETRA and DORIS cavities the same type of window has a failure rate of about 2 % per year. This was observed now over roughly 8 years with 125 cavities at 5000 h operation per year. Several windows are in operation since more than 100,000 h.

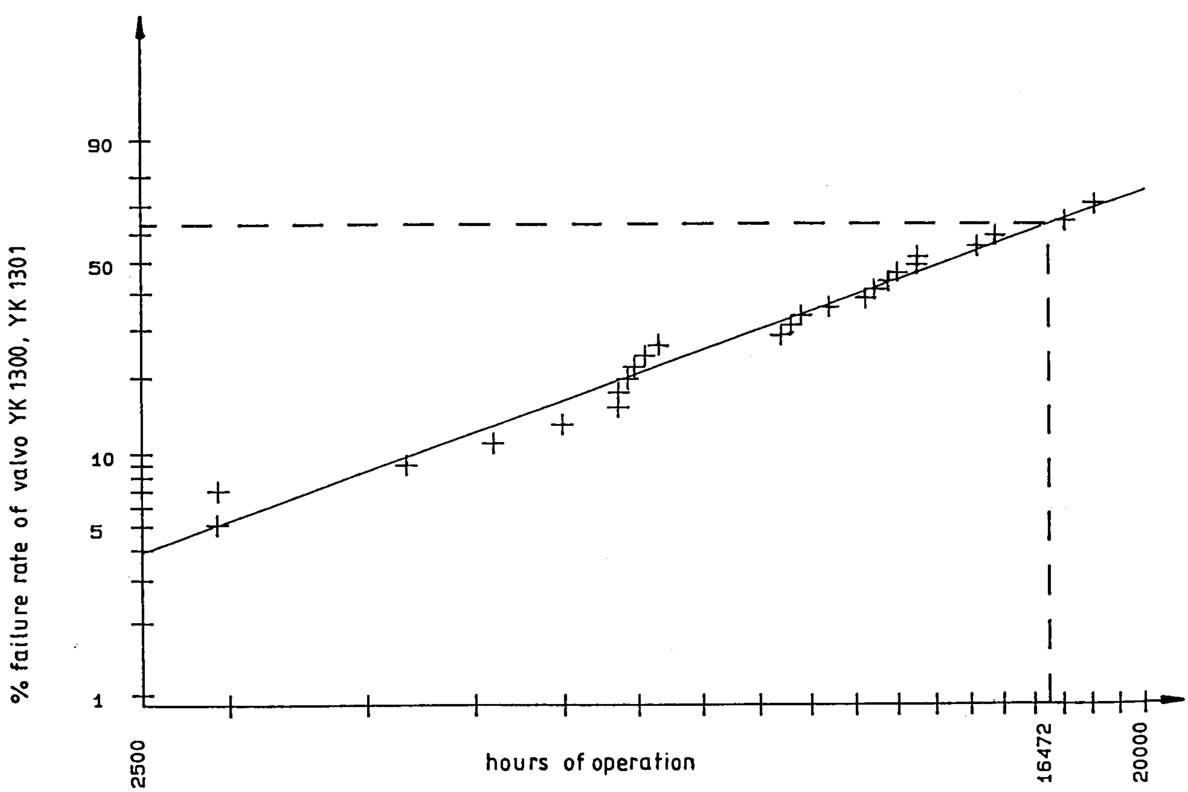
## RECENT EFFORTS

For an actual impression of today's state of techniques on the field of RF high power couplers and windows it is indispensable to have a look at recent developments which were persued with high effort.
One example are the activities at KEK on 500 MHz 1 MW CW RF power tubes and windows in cooperation with Toshiba as well as development and improvement work on couplers and windows for normal- and superconducting KEK cavities.
The corresponding KEK knowledge and experience yield may be reported here [2].
A cylindrical window design shown in Fig. 8, even coated proved to be capable of not more than 800 kW CW. The superior design is the coaxial window of Fig. 9 in both cases, coated and uncoated, too. The cylindrical windows will crack after some time of operation because they are sensitive against fine particles on their surfaces which serve as starting points of charge accumulation discharges and break down mechanisms. This is shown in Fig. 20. Fig. 21 shows the effect of glow discharges and multipactoring on the cylindrical window surface. The



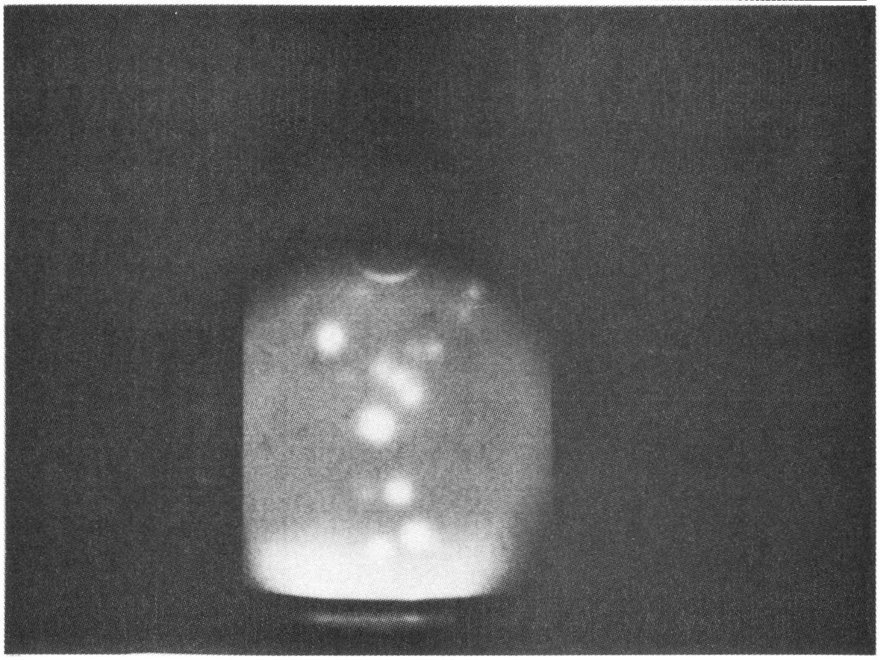

Performance Of Typical Be O Window
Vs. Frequency.

Fig. 18



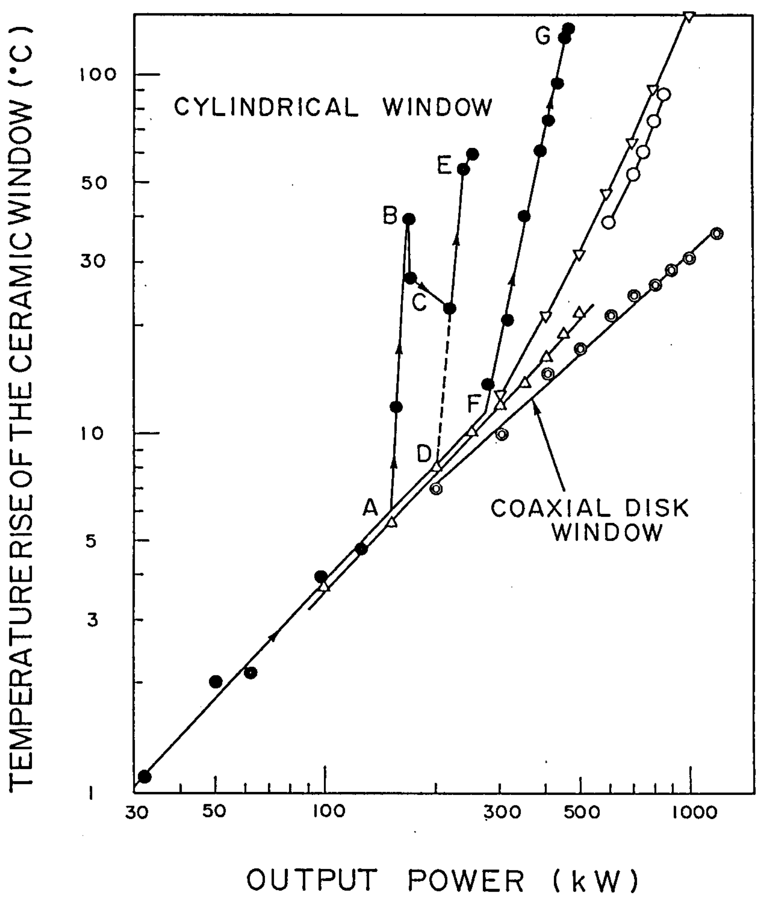

High Power Tube Failure Probability

Fig. 19



Discharges and Multipactoring inside Cylindrical Ceramic

Fig.20




Temperature Rise Of Ceramic
Due To Multipactoring.

Fig.21

measurements of temperature increase vs output power show also the characteristics of coaxial type windows. At low power temperature increases linearly with power. In the uncoated case the cylindrical window temperature level increases rapidly at the multipactor threshold level of 200 kW, point A. By a lengthy procedure of RF aging the threshold level can be increased like B-C, D-E, F-G. It turned out that during this process a small amount of copper was deposited to the ceramic surface. This is a sign of utility of coatings. A lot of effort was put into the investigation of coating materials which were already mentioned. A test set up for studying the effectivity of coating materials and procedures was installed. An impressive documentation of suppression of multipactoring by TiN coating is given by Fig. 22. An alumina sample in an RF field is shown. Its left side is uncoated. The overall by far most important result from the KEK work is the indispensability of coating for high power RF ceramic windows.

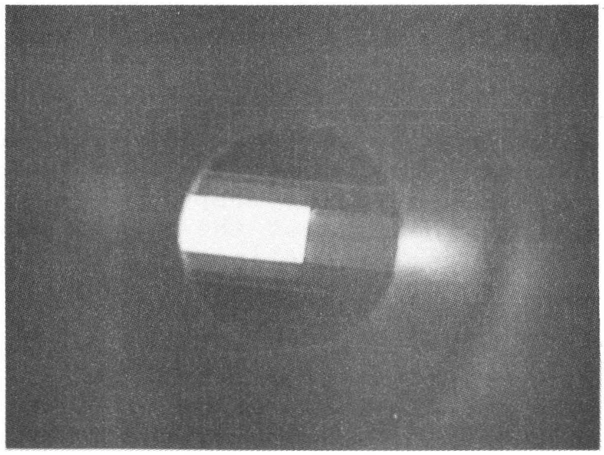
Another extensive activity of investigation on the field of cavity windows was performed at SRS Daresbury.

Their coupling hole window design is shown in Fig. 23. After successful operation of SRS during 1982 they had to exchange about 20 windows in 1983 either after the ceramic cracked or when the window temperature was observed to increase dramatically. The windows were designed to take a throughput power of 100 kW at 500 MHz and to sit in the fringe fields of a cavity dissipating 40 kW CW. Before installation each window was coated with copper black as an anti-multipactor coating on its vacuum side. Besides fracturing there were high conductivity patches - resistance about 10 MΩ/square - found on the center of the window. But it happened also, that at the same place all coatings were removed from the ceramic surface. These effects were accompanied by vacuum disturbances, purple glowing on the ceramic surface and heating.

For curing they tried different window positions, different coatings, better cooling and at the same time for understanding they analyzed ceramic surface appearences, roughness and depositions on windows over the whole cycle of unused to cracked ones. Also they studied vacuum conditions, operation temperatures, discharge phenomena. Additionally in 1988 they started a work with intention of a computer simulation of the effects which lead to the window failures. The computer simulation uses the MAFIA code for 3 dimensional field modelling and the program ANSYS for temperature and stress modelling.

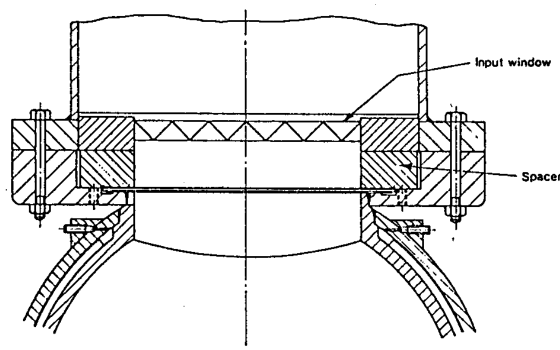
Fig. 24 shows a contour plot of cavity fundamental mode field performed by MAFIA [11]. The failure rate was decidingly reduced by the following measures: Removing of the window by 22 mm back from the cavity fields, reduction of water temperature for window cooling by 10 $^0$C, improved interlock conditions for the windows like continuous control of ceramic temperatures. Their investigation of anti-multipactor coatings turned out that copperblack was superior to five different tested materials including TiN. Without coating the windows failed very quickly.

In spite of this success the following sentence from a Daresbury publication on the window problem is reported: "The cavity window problem has been circumvented rather than cured, as the detailed failure mode is still not yet fully understood [12].



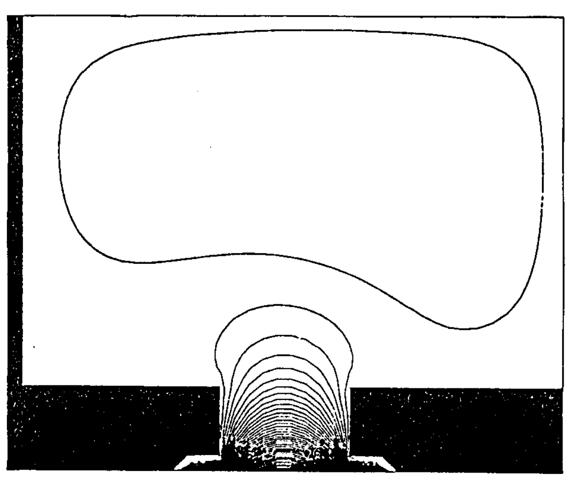
Effect of Antimultipactor Coating

Fig.22




Daresbury SRS Single Cell Cavity
Window Geometry With The Spacer Ring.

Fig.23



Contour Plot Of SRS Single Cell Cavity Fundamental
Mode Into Waveguide

Fig.24

CHARGED PARTICLES IN ULTRA-HIGH VACUUM

Apparently all of the effects beginning at the nonlinear increase of window heating vs. power flow, point A of Fig. 21, are common to that type of window failures mainly reported in the preceding chapters. Clearly nonlinear heating of the vacuum side surfaces, purple or red glow discharges, or continous light, vacuum disturbances accompanied by arcs, material transport between adjacent surfaces are caused by charged particles.

Charged particles, ions and electrons are easily produceable because there is enough power in the electromagnetic fields.

The chance to complete all the phenomenological descriptions of a particle motion problem by some basic quantitative considerations - should not be omitted here.

With

| | |
|---|---|
| m | particle mass |
| v | particle velocity |
| t | time |
| e | positron charge |
| j | $=\sqrt{-1}$ |
| $\hat{E}$ | peak electric field, typical value for about 100 kW forward power is 1 kV/cm |
| $\omega$ | $= 2\pi f$; f RF frequency |

from the coupler motion equation

$$m\,dv/dt = e\hat{E}e^{j\omega t}$$

the particle speed

$$v = -j\ e/(m\omega)\ \hat{E}e^{j\omega t}$$

is readily derived.
This means that the electrons are oscillating in the electric field with a maximum speed of

$$\hat{v} = 2.8 \text{ mm/nsec} * \hat{E}/(\text{kV/cm})/(f/\text{GHz})$$

The peak oscillation energy follws to be

$$\hat{U}_d = e^2\hat{E}^2/(2\omega^2 m) = 22.3 \text{ eV} * (\hat{E}/(\text{kV/cm})/(f/\text{GHz}))^2$$

and the oscillation amplitude is

$$A = 0.45 \text{ mm } \hat{E}/(\text{kV/cm})/(f/\text{GHz})^2 .$$

If there are additional magnetic fields H of flux $B = \mu_0 * H$ then the electrons are subject to an additional transverse force

$$F = evB$$

corresponding to the Lorentz law. The Lorentz force generates a circular motion of radius

$$r = E/(\omega B),$$

E being the accelerating force.

With a line impedance $Z_w$ relating E to H

$$Z_w = E/H$$

the radius can be rewritten to be

$$r = (Z_w/\Omega)/(8\pi^2 f/\text{GHz}) \text{ cm}.$$

r equals 1 cm for a typical value of 80 Ω at 1 GHz and it depends linearly on local impedance. Corresponding to the expression of v the particle oscillation has $90^0$ phase shift towards the electrical field. In cases of a mismatched line or near compensating imaginary impedances the magnetic field is shifted also by $\pm 90^0$ degrees with respect to the electric field. This fact causes a superimposed transverse drift motion to the electrons. The peak acceleration value of this motion is

$$m\hat{v}^2/r = e\hat{v}\hat{B} = (2\hat{U}d[\text{eV}])/(r[\text{cm}]) = 45 \text{ eV/cm peak}$$

at 1 GHz, 1 kV/cm.
For positive charges this mechanism is shown in Fig. 25.
All of this leads to the following consequences:
At a typical situation of 1 GHz, 1 kV/cm, 80 Ω impedance the oscillation energy of electrons is big enough to exceed the threshold level of secondary electron production at a ceramic surface (20 eV needed, Fig. 6) and to ionize hydrogenium ($\lessapprox$13.6 eV needed).
Positive particles will migrate towards areas of inductive behaviour because here both particle motion and magnetic field are delayed by $90^0$ (Fig. 25b, c). Negative particles will migrate towards areas of capacitive behaviour. So these migrations are much dependent on local field configurations like standing wave distributions. Metal surfaces and ceramic surfaces normal to the electric field or to drift motion will be bombarded. The bombardment evaporates gases from the surfaces which leads to local pressure increase.

A proper combination of surface secondary electron yield, magnetic flux density B and cyclotron frequency

$$\omega_z = e/m*B$$

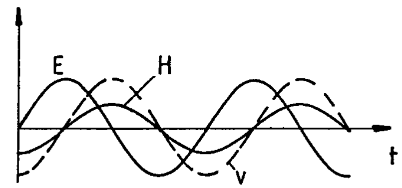
can cause resonant single surface bombardment under condition of

$$\omega_z \approx \omega/\text{integer}$$

at electron oscillation energies higher than the secondary emission threshold value [13]. This leads to very high electron loading and surface heating if the secondary emission coefficient δ is higher 1. Roughly the surface heat load $P_s$ increases rapidly corresponding to

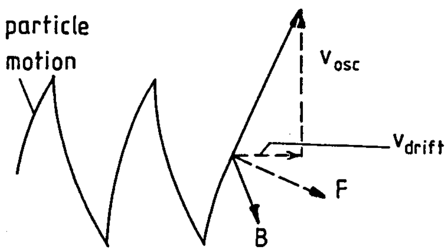
$$P_s = \text{const} * f * U_d * \delta^{ft}, \text{ t time.}$$

In pure electrical fields the particles only get the oscillation energy $U_d$ and no power is taken from the electromagnetic fields a)



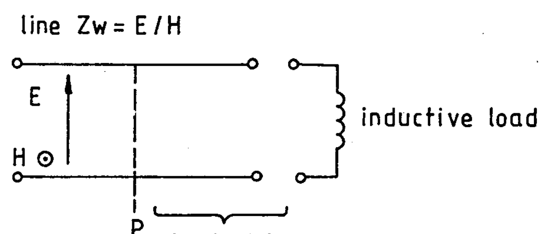

assumption: 90° delay of H field leading to synchronism of H and v.

b)




oscillation due to electrical field + superimposed drift motion.

c)




example of a plane P with 90° phase delay of H.

Positive Particles Facing An Inductive Load

Fig.25

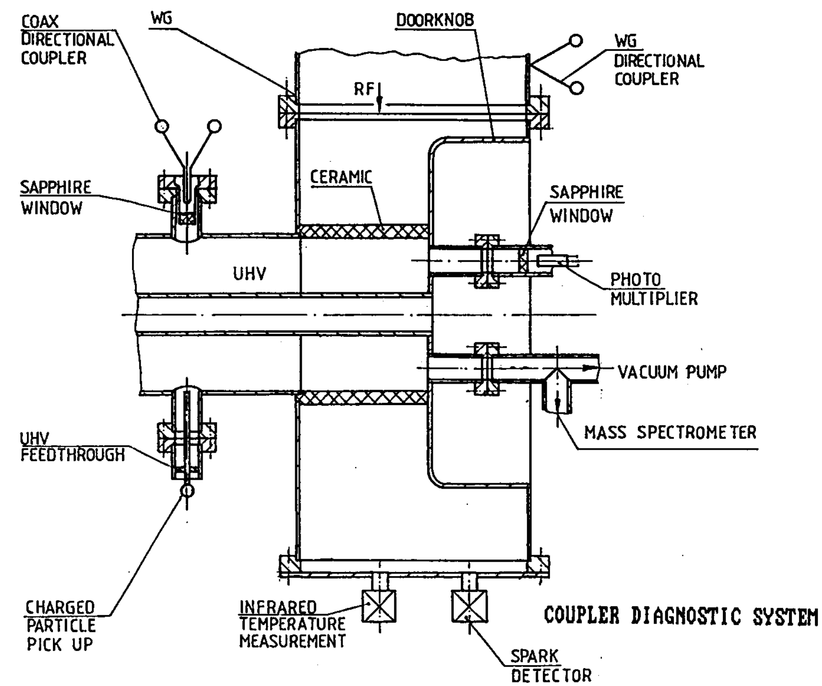



Fig.26

if there are no collisions. But due to its oscillation an electron transverses a way s of

$s = f * 2A$ per second

which scales to about $10^6$ m/sec at 1 kV/cm, 1 GHz. This leads to about $10^5$ collisions per second in a vacuum of $10^{-2}$ Pa ($\approx 10^{-4}$ Torr). Those high collision rates at pressures higher than $10^{-3}$ Pa explain the avalanche characteristics of gas discharge in high electromagnetic fields. With increasing pressure the AC currents and thus energy transfer to a discharge can grow up quickly to cause high reflections and dissipation of transmitter power. This means that the currents are comparable to the wall currents. Hence it is easy to produce all the energy levels between sputtering and melting of surface materials at high RF power. On the other hand the energy required to form a separated neutral atom from solid copper at 300 K is less than 3.5 eV [14]. In practice separation of copper atoms from a solid surface starts at impact energies of gas particles higher than 100 eV [15]. Ionisation and migration of those separated atoms lead to the observed material transport mechanism.

## CONCLUSIONS

After delineating the tasks of high power couplers and windows with respect to superconducting cavity applications an introduction was given to the techniques of window design and preparation. The following chapters describe practical design examples and operation experiences. Information on maximum window performances and long time reliability is included. An addditional chapter was dedicated to recent efforts on the field of high power RF CW couplers, because especially from there the state of today's techniques is deriveable.
It turns out that there are phenomenons commonly observable at all high power windows. These are due to the important influence of charged particles especially in the UHV part of high power couplers. Hence the last chapter serves to give some basic quantitative impression on the charged particle problem. This problem seems to be a clue of the main limitations of today's high power CW couplers whereas pure engineering problems are less severe. Nearly all coupler designers contribute to this problem by providing proper surface coatings. But one related aspect seems not yet sufficiently taken into account in most designs. There are successful high power devices without any coating on their window surfaces. With respect to the last chapter this proves that the window shape and geometric position relative to the electromagnetic field distribution, and hence particle motion directions can be optimized to have a minimum of particles on critical surfaces.
On the other hand multipactoring situations may be not totally avoidable in complex geometries. This means that even good window designs have to be monitored, controlled and protected by effective interlock systems during operation. A diagnostic system which performs this task at DESY couplers for superconducting cavities is shown in Fig. 26 [16].

Considering the recent development efforts and the fact, that superconducting cavities because of their higher gradients and their complexity may require more powerful and more reliable couplers, respectively, than normalconducting cavities, there is still a big deal of coupler and window development to be done.

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