EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN - PS DIVISION



CERN/PS 93-60 (RF)

# DISCHARGES ON CERAMIC WINDOWS AND GAPS IN CERN PS CAVITIES FOR 114 AND 200 MHZ

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*Abstract*

Failure of coaxial ceramic windows and ceramic gaps in the PS cavities, either feeding RF power to a cavity or providing a non-conducting vacuum barrier at the accelerating gap, have caused a significant amount of downtime for the whole CERN complex.

Investigation and tests indicate that discharges at the surface of the ceramic may be responsible for failures. The discharge mechanism seems to be multipactoring and a subsequent glow discharge.

Breakdown mechanisms are discussed and improvement of the window and gap reliability by correct dimensioning and surface treatment of the ceramics are reported.

Geneva, Switzerland
18/1/94

# 1. INTRODUCTION

The ceramic windows in the PS 114 MHz system have suffered failures below 2 kV and the ceramic gaps in the PS 200 MHz cavities have exhibited strong RF-loading in the 1 to 10 kV range. Discharges appear in an unpredictable manner. A window or gap may fail at the first tests or after a careful and long conditioning period, without a clear reason. Reliability seems to depend not only on the lowest losses and the smoothest surface but also strongly on the "prehistory" as how the window or gap was stored and cleaned or if it was under RF and vacuum in earlier tests.

# 2. EXPERIENCE AT OTHER LABORATORIES

Dwersteg / DESY [1] reports that thermal run-away of ceramics may be caused by multipactoring (Fig. 1). By slow conditioning, the threshold of 150 kW could be shifted to higher values for a coaxial window with cylindrical ceramics. The reason for the improvement has been found to be a very thin layer of copper on the ceramic, formed by sputtering or evaporating in the run-in period. In the graph (temperature versus power feed through the window), no run-away is reported up to 1000 kW, for a window using a ceramic disc.

Supposing that windows are better with very pure and low loss-tangent materials, at Chalk River [2] they tried to use polycrystalline, translucent $Al_2O_3$ and failed, while "normal" opaque $Al_2O_3$ worked. Multipactor and a high secondary emission are certainly responsible for failures. Saito, KEK, shows that pure $Al_2O_3$, especially the monocristalline sapphire exhibits high emission [3].

At the TRIUMF Laboratory good results have been achieved in a coaxial window (with a cylindrical ceramic for 2.2 kV at 92 MHz), by painting the conical shaped copper parts with Aquadag (suspended in water) a classical method [4].

On the other hand, looking for highest voltage breakdown values (which override the old Kilpatrick law [5]), limiting surface field emissions between metallic electrodes from Stanford tests [6] are reported to be at 350 MV/m for 3 GHz copper cavities. At CERN, 20 MV/m was obtained for superconducting cavities at 350 MHz [7]. (These high values may not be applied directly for our problems and are discussed in chapter 3.3).

At Karlsruhe [8], investigations were made with sapphire under cryogenic temperatures in waveguide windows for 3 GHz, supporting power in the MW range and no difficulties with discharges have been reported. (In this low temperature application, very low loss factors and a very high heat conductance have been achieved).

# 3. SOME POSSIBLE FAILURE MECHANISMS

## 3.1 Thermal Stresses

Because of the low average power losses of only a few watts, stresses and cracking from dielectric heating (under normal working conditions) can be excluded in our windows and gaps. Calculations with the computer code ALGOR showed no stresses [9].

For the window of the 114 MHz system, with a low voltage of 1.4 kV peak and a duty cycle of 30 % there will be no danger, but the ceramic gap (200 MHz cavity) could be destroyed by the 50 kV peak, when the normal duty cycle of 0.1% is largely exceeded (by faults in the pulsing system).

Other stresses could be introduced when the field is strongly non uniform (e.g. by using protection rings). This risk can be excluded in our design as well.

Thermal stresses are even lower in our BeO gaps due to their higher heat conductance. Thermal run-away may be caused at higher temperatures (bad cooling) because tg $\partial$ rises and heat conductance drops. At low voltage, thermal stresses from dielectric heating could not have been responsible for failures.

### 3.2 Dielectric Breakdown

Dielectric breakdown should also be excluded because the nominal average field strength is only 56 V/mm for the window and 500 V/mm for the gap. This is very low compared to limiting values from manufacturers data sheets. (AC tests with Vistal by Coors: 7 kV/mm for a sample with 10 mm thickness). Saito [3] obtained 8.4 kV/mm in his 3 GHz window tests.

### 3.3 Surface Field Emission

Scaling down the values reported at Stanford by the square root of the frequency we get 87 MV/m and 66 MV/m for 200 MHz and 114 MHz respectively. The discharge criteria for the Stanford copper cavity is a spark, for the CERN-AT superconducting cavity a 10% loss in a high Q, therefore the scaled down CERN values are at 6 times lower levels. Comparing our operational field strength (window: 0.06 MV/m, gap: 0.5 MV/m) with those obtained at Stanford and CERN, very high enhancement factors would be necessary (from whiskers or sharp edges) to generate field emission.

### 3.4 Multipactor [MP]

Depending on the distance between electrodes and the secondary emission coefficient (SEC), MP discharge may start below 100 V. The Hatch graph (Fig. 2) [10] shows the dangerous discharge voltage regions for a "relative distance" (represented either by the product of distance × frequency or preferably by the ratio of distance to wavelength, the latter being dimensionless). The response is drawn for a SEC of 2.3 for aluminium (alloy ?, in other tables SEC for Al is 0.95) and is valid for plane parallel metal plates. One finds out that there is no MP, if distances are below 0.2% of wavelength or voltages below 50 V rms; for 1% the MP would start at 0.2 kV rms and stop at 1 kV rms, for 10 % the MP is in the higher harmonic mode starting at 2 kV rms and stopping at 10 kV rms. With a SEC equal or below 1, there would be no MP.

In publications by Kollath [11], it is shown that the SEC increases with the angle of impact of the primary electrons. MP ranges depend also on the electron capture, which raises the start and stop voltages for coaxial structures [12]. Single side MP may occur when the RF or DC magnetic field bends the electrons back to the same surface [13-14]. Biasing the RF with DC voltage or a DC magnetic field disturbs the resonant condition and eliminate MP [15] but generally in the environment of magnets, discharges are observed to be stronger [16]. Along the ceramic surface with its high SEC of 2 to 9, the electron movement is described to be "hopping " [17-18].

For determining the MP range or finding better distances, the original Hatch chart is used as a guideline, neglecting at first the other mentioned factors. With operational voltages above the MP range, a powerful and steep RF pulse may break through the MP zone to a safe operation region.

Using the graph (Fig. 2) for the 114 MHz coaxial window with a distance between conductors of 25 mm, the predicted MP is approximately from 0.3 to 1.2 kV peak (= 20 to 80% of our nominal voltage) and the MP is in the fundamental mode (on the left side of the Hatch graph). For the 100 mm in the 200 MHz gap the MP is from 1.5 to 10 kV peak (= 3 to 20% of our nominal voltage) and in the higher harmonic modes (on the right side of the Hatch graph).

### 3.5 Glow discharge in a rough vacuum

The Paschen curve for DC [19], (Fig. 3) and work done by S.C. Brown [20], (Fig. 4) for RF, shows that discharge voltages may be low under a rough vacuum, depending on the product of pressure times distance. For example there is a minimum of 300 V DC with 1 cm and 1 mbar of $N_2$. At 1000 mbar it rises to 50 kV and at 0.1 mbar to 200 kV. The dotted line in Fig. 3 shows a measured DC breakdown curve for the gap of a PS cavity with 100 mm distance between the cylindrical electrodes.

#### *3.5.1 Glow discharge path*

In vacuum a thin film of gas may be present on the wall of the ceramic, especially if it has a rough surface structure. A glow discharge can be produced along this thin film. Bombardment of the ceramic by multipactoring electrons could continuously refill this gas layer to a thickness that would produce a strong RF load, especially if the pressure is close to the Paschen minimum. Depending on the RF losses in this gas discharge, strong heating of the ceramic could occur. From the measured discharge voltage one could deduce the pressure in this path using the discharge response for RF, as measured and calculated by S.C. Brown.

## 4. COAXIAL WINDOWS FOR 114 MHZ AND 1.4 KV PEAK

The $Al_2O_3$ disc window with a characteristic impedance of 30 Ω (Fig. 5), is a version originally designed for the 200 MHz cavity in the CERN SPS, directly fed by a 60 kW amplifier. In the PS system it provides an insulated vacuum to air interface for coupling the RF power of 20 kW from the amplifier over a 30 m long cable into a cavity having a Q of 56000 [21]. The ceramic surface is sputtered with a thin layer of titanium and the copper surfaces are sputtered with a much thicker titanium layer. (The improved window, described later in 4.3, has a reduced distance and no coating on the ceramic or metal).

### 4.1 Difficulties with the windows

Some of the original windows failed in the SPS but as the PS was operating only at 1/3 the power, 1/3 the duty cycle and 1/2 the frequency, it seemed that the safety margin was more than adequate for the PS application. However, this did not turn out to be the case.

It took a week to run-in the PS cavity [22] (including this window, dampers and tuners) and it was difficult to determine where the discharges occurred. The first tests were stopped when a sudden high reflected power and a pressure rise was experienced while increasing the power stepwise to a few kW. Inspection of the window showed a thick layer of copper deposited from the coupling loop onto the ceramic and metal surfaces. At another window, the wide copper bar of the loop was replaced by a small diameter copper tube (for less capture of MP electrons). This allowed conditioning to full power. However, after a normal run-in and a quick restart the cavity again showed a full reflected power and a permanent vacuum leak. This time the ceramic was covered by a silver coloured layer of material from the solder of the ceramic to metal joint. In some cases the ceramic cracked after a discharge when the RF power was not cut off quickly enough.

A non-cracked window with a copper deposit could be repaired by sandblasting the ceramic and the copper surface, to completely remove the accidentally sputtered-on layer (and also the original titanium coating). The run-in for this window was shorter and it held full power without any further discharges.

The window repaired by sandblasting worked better, because this treatment removed any whiskers from the solder joint and the overlapping thick Ti-layer from the metallic surfaces which may have caused discharge. Some success was also achieved by inserting a metal ring at the inner and outer diameter of the ceramic to shadow the solder, which has a high SEC.

### 4.3 Improvement in a new design

The soldered version was replaced by one with fasteners (Fig. 6) for an easy exchange of a faulty ceramic disk. An attempt was made to move the potential danger of MP (which was for the original window at 20 to 80% of the operational voltage and supposing that the anti MP coating was not perfect) to lower levels. The Hatch graph shows that below 8 mm of distance we should be at the lower edge of MP.

In first trials we had problems with the vacuum tightness, so the "mountain and valley" structure of the surface (Figs. 11-12) was polished to achieve a leak-free fit with the Al-wire joint (now Cefilex-C joint). To our surprise, the polished version needed only minutes to sweep away the weak glow on the ceramic. These "test samples" have worked satisfactorily in the PS since two years.

### 4.4 RF tests of windows with a quarter wave test resonator

Using the window (without loop) as the end capacitance of the resonator produces the same voltage at the ceramic as under operation but with much less drive power. With a 200 W amplifier the new windows could be tested at four times the operational voltage (equivalent to 320 kW at 50 Ω).

A typical first run-in for a new window (Fig. 7) shows power and pressure rise versus voltage especially in the MP range for 66, 114 and 200 MHz. In the table of Fig. 8, old and new windows are compared.

Results:
- As expected the MP voltage levels are higher for higher frequencies and bigger distances.
- No conditioning time is required for 66 MHz, only a few minutes for 114 and 200 MHz (for improved windows).
- Whereas the old type window (Ti coated at metal and ceramic) required several hours for conditioning.
- No surface coating was needed (for improved windows).

These tests are non destructive because a discharge lowers the voltage by the reduction of the Q-factor and by the mismatch.

### 4.5 Improvement by electronic protection

The first windows were damaged by conditioning too quickly, the occurrence of amplifier errors (self-oscillation, cable resonances) and a slowly reacting protection circuit. The only protection was in the final stage of the amplifier, by mains switch-off after indication of an overcurrent in the screen grid due to strong mismatch of the amplifier to cable and cavity.

Signals are now available from the vacuum (current of the ion pump) and the reflected and forward power, to cut the RF input drive in milliseconds, by a pin switch. The signal from the vacuum is the most important; it indicates discharges generated by a few watts of RF power, while a reflection threshold of 5% (with respect to a forward power of 20 kW) would allow a destructive power dissipation of 1 kW at the window.

## 5. CERAMIC GAPS FOR THE 200 MHZ CAVITY

An $Al_2O_3$ or BeO tube of 100 mm length (Fig. 9) is located at the maximum voltage of an air pillbox cavity. The inside of the tube is under vacuum and is part of the beam pipe of the PS. The operational voltage is 50 kV peak, pulsed (1 ms in 1 s) generated by a 25 kW amplifier. Eight cavities are installed in the PS [23] and one in the test area (Fig. 10).

## 5.1 History of problems

After installation in 1977 no failures were reported but the correct voltage could not be reached on all cavities in the PS.

Spare gaps from old stock were suspected to be contaminated with oil (oily smell) but after cleaning they still could not be conditioned. After polishing the inside of these dirty gaps, some of them could be conditioned and worked for six months. After exposing them to atmospheric pressure and subsequently re-establishing the vacuum they could not be re-conditioned and had to be removed from the PS. Oil contamination of the ceramic surface was assumed responsible for discharges. In fact, 25 years ago the PS still had oil diffusion pumps and the old oil-contaminated vacuum chambers of the PS were replaced only seven years ago. Until now, at start-up, an oil filled rotary pump is used which is followed by a turbo pump and finally by ion pumps.

Two old gaps, recently withdrawn from the PS, showed a dark grey layer but they have been working up to full voltage. They had been installed close to the pumps since the beginning.

## 5.2 Inspection of gaps

Bad gaps showed a cloudy yellow-brown surface inside with some black spots. Chemically checking the deposit for metals showed traces of chromium, nickel and iron and very little of titanium. Analysing the brown layer via an electron beam method (EDAX), the emitted X-ray spectrum showed lines for Al and O and on darker parts additional lines for C and N.

Recently removed gaps showed a dark grey layer but have worked well for years. Checking the dust of this layer which could be wiped off easily, showed evidence of carbon, probably cracked oil. So this un-intentionally deposited layer seemed to have built up a thickness just enough to prevent MP, and thin enough so that no extra RF power was dissipated.

## 5.3 Surface structure

The electron microscope reveals a ceramic surface with much fine structure (Fig. 11). Grains have sizes of up to 50 µm. Polished ceramic looks better but still shows deep holes. The pores cover about 10% of the surface. Surface roughness measurements (Pertometer), (Fig. 12), showed a high roughness depth Rt which is at least ten times worse for ceramics than for metals compared to the same average roughness Ra. It is understandable that the rough mountain structure with deep valleys is difficult to clean and represents a large surface for degassing. (For comparison, degassing rates of metals under RF may be found in Mathewson [24]).

## 5.4 DC test in air and vacuum

Tests were carried out to find differences between good and bad gaps. Varying the pressure inside the gap from atmosphere to $10^{-8}$ mbar and measuring the leakage current (>10 µA) a response close to the typical Paschen curve (Fig. 3) was obtained. However no difference was found between a bad and a good gap. The maximal available voltage was 60 kV. (Precautions were taken to avoid external leakage current by rounded surfaces and guard electrodes).

The good gaps with their dark-grey layer, recently removed from the PS, showed a resistance of 10 MΩ measured with 5 kV, a day after being exposed to air. A week later the resistance had increased to 100 MΩ. (Oxidation of a metal layer or a drying-out of water in the layer could be an explanation).

## 5.5 RF power tests

The test resonator was a pill box cavity (as in the PS) with a Q of 8000 (or 2000 when preloaded). Forward and reflected power were monitored as well as the gap voltage (at a calibrated loop). Here the cylindrical ceramic is at the highest voltage point of the cavity. A TV-amplifier (as for the PS) supplied up to 25 kW, CW or pulsed. The duty cycle was varied from 1 ms in 1 s (operational in the PS) to 10 ms in 100 ms and CW at lower gap voltages.

The vacuum inside the cylindrical gap is achieved by an oil free membrane pump followed by a turbo pump (180 l/s) and an ion pump (400 l/s). The current of this ion pump indicates the outgassing of the ceramic surface under RF field, which is, indirectly, also an indication for the occurring light emission. Light is observed by an optical window (Fig. 10).

A small electrode at 100 mm distance to the glow discharge collects electron emission, giving up to 5 V at 1 MΩ (could be used for protection). A mass spectrometer showed that the main outgassing under RF discharges came from $H_2$ (M = 2) and CO or $N_2$ (M = 28), a strong line with or without RF was $H_2O$ (M = 18), predominant during pumping down.

A new gap showed a weak blue glow in the middle, weak pressure rise and weak reflected power in the range of 6 to 15 kV peak (rough prediction from the Hatch graph: 1.5 to 10 kV peak). At higher voltages these effects disappeared. Sweeping through the whole voltage range or remaining at peak voltage close to 70 kV the gap improved (sparks at the air side started above 70 kV peak). After some days without RF a new conditioning time of a few minutes was required especially for the low voltages. A typical response for a bad gap (dismantled from a PS cavity) is shown in Fig. 13. It could be partly conditioned to work above 15 kV peak. With some bad and dirty gaps the voltage could not be increased to more than a few kV, showing strong outgassing (pressure increase from $10^{-9}$ to $10^{-5}$ mbar) intensive light and high reflection. Within a week of continuous trials with short RF pulses and CW, heating up the ceramic by its own losses or from an external heat source did not reduce the outgassing or the RF loading essentially.

The light on the inner wall of the ceramic was of several continuous colours. A short ring of red at the ceramic touching the electrodes, blue to sky-blue towards the gap mid distance. If conditioning was possible the light reduced to a blue ring at mid distance [25]. Protecting the sharp corners of the metal to ceramic joints by rounded copper rings did not diminish the glow discharge. Pushing a ring to half length of the gap (inside) caused the colour pattern of the glow to repeat twice over the gap length. The RF loading was weaker, as it would be with two glow discharges in series. Raising the pressure by opening a needle valve, the whole volume of the tube was filled with a bluish glow, starting at $10^{-4}$ mbar. Voltage dropped to 100 V. Closing this inlet valve (still pumping) the glow reduced again to a thin film at the ceramic only and the discharge voltage was several kV. If the valves between the gap and the pump were closed, maintaining the glow, the pressure climbed up to a saturation value of $10^{-4}$ mbar, filling again the whole volume with a thin fog of light (covering ceramic and metal). This may be an indication that the thin film of light corresponds to a gas layer of $10^{-4}$ mbar (and reaching in this film some kind of Paschen minimum).

The recently removed old and good gap with the dark-grey layer was tested and showed no discharge, light, outgassing or reflection. After wiping-off the layer with a cloth (weak adherence), this gap showed all the signs of a bad gap and could no longer be conditioned. Wiping-on some graphite powder did not improve the gap but created, in addition to the bluish light, a zone of brightly lit particles.

## 5.6 Test of small ceramic samples

Small $Al_2O_3$ samples were placed in the RF field inside a good gap, with the surface parallel to the field. They were from different manufacturers, with rough surfaces and as-fired, glazed and resistive painted surfaces, to find out if light emission depends on surface quality.

Samples from Wesgo and Friedrichsfeld (as used for gap and window) showed a weak sky blue glow, decreasing slowly in intensity. Other samples had a strong red glow, a translucent $Al_2O_3$ sample (expected to be the best) had a strong sky blue glow and then became red hot and cracked. Glazed samples had a weaker light but became hot. A sample with a green burned-in resistive paint showed no light but heated and cracked. The polished sample had a weaker glow.

## 5.7 Effects of polishing

Some bad gaps were then roughly polished with diamond powder. After pumping and several hours of conditioning it was possible to diminish the glow, the pressure rise and the reflected power. Unfortunately these gaps failed again, for unknown reasons, after being installed for some months in the PS. On the other hand, the polished ceramic discs in the coaxial windows, without layers on the metal or ceramic, still work in the same environment but under lower voltages.

## 5.8 Effects of glazing

Glazing is less expensive than polishing and it gives a very smooth surface. In our RF power tests glazed gaps emitted a weaker glow than unglazed new gaps but it was impossible to condition them within a week. The increase in the dielectric loss factor was negligible (measured at low level).

## 5.9 Effects of adding a sputtered coating

Trials were made with layers of titanium or chromium to reduce the high SEC of the ceramic. The layer was made thick enough to prevent electrons reaching the ceramic, but thin enough to avoid additional RF losses. Saito, KEK, [26] has made tests for wave guide windows showing that with a thicker layer the SEC decreases and the RF losses are increased. They took the thickness of the layer as reference.

At CERN the thickness is not measured, but the resistance between the electrodes is easy to obtain in the sputtering process, and is used as reference. This is certainly a rough definition, because the relation between resistance and thickness depend on the sputtering process (voltage, current density, geometry, gas, pressure) and the structure of the ceramic surface.

Sputtering is done under $10^{-3}$ mbar of argon with a Ti or Cr rod in the centre line of the gap, connected to -1.3 kV. In approximately 10 steps of 10 min for Ti or 10 steps of 1 min for Cr the desired resistance was reached. (After each step the resistance of the layer is measured).

Our reference resistance Re is measured (between the two electrodes of the gap) immediately at the end of the sputtering, still under argon pressure. This value rises at least 1000 times when exposed to air, due to oxidation. It remains high under vacuum and also when heated by RF. Negative temperature and voltage coefficients were observed. The layer resistance is also frequency dependent being very high at DC and falling to approximately Re at our frequency of 200 MHz.

The explanation could be, that the metal molecules are insulated by an oxide layer. High DC voltage punches through the thin oxide layer, yielding a lower resistance. For RF the molecules are connected together, capacitively, and the resistance is low as well. RF-power tests were made with Ti layers corresponding to a Re of 100 down to 0.1 MΩ.

| | | |
|---|---|---|
| Results: | 100 MΩ: | weak glow and outgassing, conditioning: 1 hour. |
| | 10 MΩ to 1 MΩ: | no glow, works immediately. |
| | 0.1 MΩ: | no glow, but RF-losses too high. |

The end-of-sputtering resistance "Re" of 0.1 MΩ corresponds roughly to the RF load produced by this protecting layer (at our frequency). However, the DC resistance across the gap remained high, with or without vacuum (>10 GΩ, measured with 5 kV). We have chosen for most of the gaps a Re of 5 MΩ (= 25 MΩ/square for our gap geometry). In our tests we found no difference in MP behaviour between Ti and Cr. Both layers had a very good adherence. Ti gives a light grey, Cr a dark grey surface colour.

Experience from Garwin, Stanford [27], showed that Cr (air oxidised) is more reliable than TiN for MW pulses at 3 GHz. We found that Cr is sputtered-on quicker than Ti. The question is, does it sputter-off quicker under bad vacuum conditions and discharges? A sputtering graph for DC and under Argon shows the efficiency for different materials (Fig. 14) [28]. One finds that silver and copper sputter easily, nickel and chromium are in the mid range and titanium, silicon and carbon would take much more time to achieve a given layer thickness.

### 5.10 Protection against damage from discharges (for gaps)

With the pulsed mode in normal operation (1 ms/1 s duty cycle) there is no danger of damaging the gap. A relay interlock from the screen current (higher reflection) is sufficient even if the switch-off action is slow. During tests, the ceramic in several gaps was cracked accidentally when working with much longer pulses (100 ms/1 s) and in trying to condition "by force". An additional interlock from average power, vacuum pressure and temperature could have prevented damage.

## 6. CONCLUSION

### 6.1 Discharge mechanism

The main RF load may be due to a glow discharge in a thin film of gas at the ceramic, excited by multipactoring electrons bombarding the ceramic.

Damage is due to the high heat dissipation in this glowing path.

- The ceramic may crack by stresses from high temperature gradients.
- The ceramic-to-metal solder joint may melt.
- The ceramic may be coated by a metallic layer from evaporation or sputtering.

Rough surface structures of the ceramic seem to enhance these effects.

It is preferable to use small distances to lower the power involved in MP regions.

### 6.2 Protection against damage

Rapid protection based on detection of outgassing, electron emission or light is more efficient than relying on reflected RF power only.

### 6.3 Experience with the coaxial feeding windows for 114 MHz, 1.4 kV peak

The new design has worked in both cavities without discharges for two years. Separate window tests were successfully done for gap voltages equivalent to 320 kW at 50 Ω.

The improvements were:

- reduced distances between inner and outer conductor,
- polished ceramic surface,
- rapid vacuum interlock.

Discharges in 50 Ω feeding windows may easily be overlooked if reflection is the only discharge criteria. Sputtered coatings were not tested here, because there was no need for this relatively low applied voltage.

### 6.4 Experience with the cylindrical ceramic in the accelerating gaps at 200 MHz, 50 kV peak

The old and newly fabricated gaps with a sputtered-on layer of titanium or chromium (with our "end of sputtering" resistance of 5 MΩ) show no discharges.

Negligible or very short conditioning times were required in our test stand. However, some of the coated gaps, once installed in the PS ring needed days for run-in (with the low operational RF duty cycle of 1/1000). Polishing the inside wall of the ceramic gave only a short-time improvement.

### 6.5 General remarks

In this report the behaviours of RF windows and gaps are studied under moderate power levels and in a restricted range (66 to 200 MHz) applying simple rules as the Hatch- and Paschen graph. Contrasting results are achieved and a lot of open questions remained. Explanations based on the experimental evidence are still somewhat speculative and more investigations would be necessary to bring results from here and other laboratories to a common denominator.

Nevertheless the above work allowed us to improve the reliability considerably on windows and gaps for the PS cavities.

## 7. ACKNOWLEDGEMENTS

Thanks are due to the following for their particular contribution to this work.

G. Serras, P. Konrad and M. Birau for RF measurements.
S. Talas, M. Corcelle and G. Baud for mechanical construction.
A. Burlet, R. Menazzi and M. Brouet for vacuum.
J. Adam and G. Jesse for investigations with the electron microscope.
J.C. Baronnet and C. Boudineau for roughness tests.
M. Girardini and J. Charon for the sputtering.
A. Krusche for discussions and encouragement.

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[27] A.R. NYAIESH, E.L. GARWIN, F.K. KING, R.E. KIRBY, Properties of Thin Antimultipactor TiN and $Cr_2O_3$ Coatings for Klystron Windows, J. Vac. Sci. Technol. A4 (5), Sept./Oct. 1986, p. 2356.

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## 9. LIST OF FIGURES



<u>Distribution</u> : (Open)

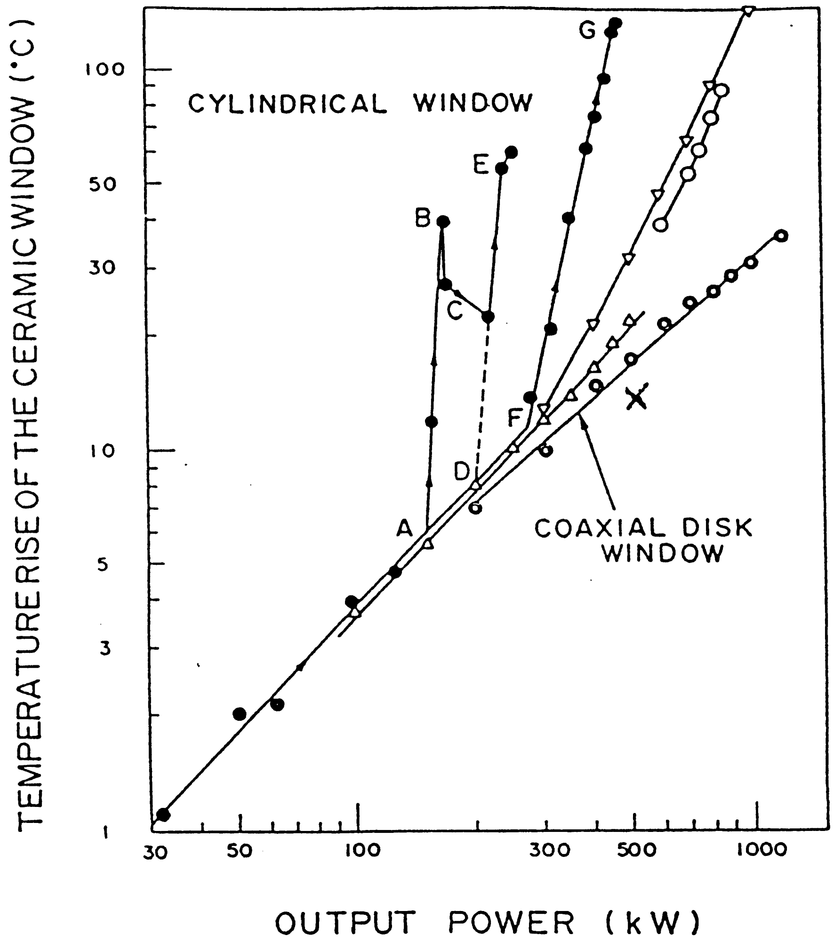


**Fig. 1**

**Typical run-away of ceramic windows [1]**

Temperature of the ceramic versus power passing through the window

A-B: abrupt rise due to multipacting

F-G: after running-in

X: no abrupt temp. rise for a ceramic disc

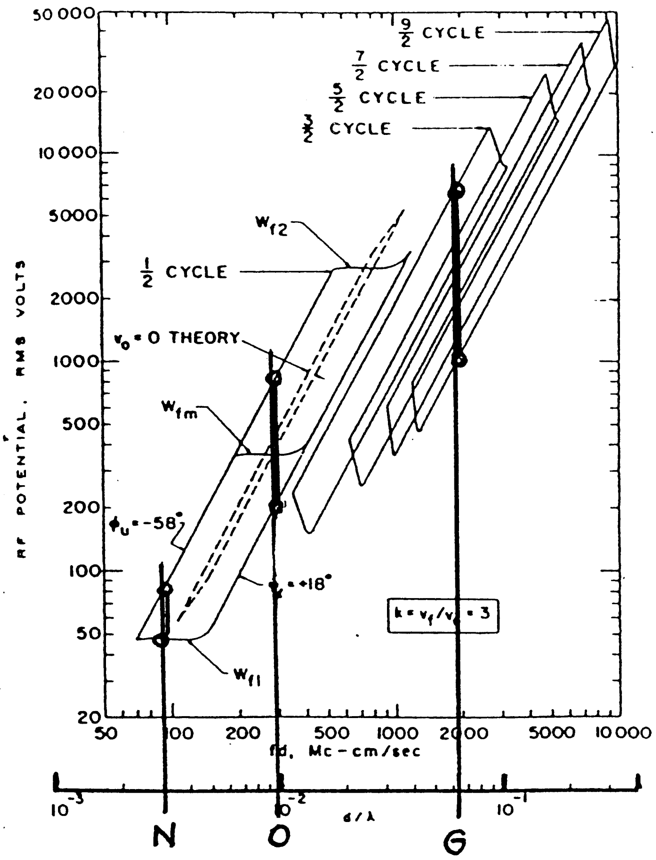


**Fig. 2**

**The HATCH-GRAPH [10]**

Indicates voltage ranges for relative distances d / λ (in respect to wavelength) susceptible to multipactoring

Vertical lines situate the range for CERN windows and gaps

N: New improved window (8 mm, 114 MHz)

O: Old window (25 mm, 114 MHz)

G: Gap for cavity (100 mm, 200 MHz)

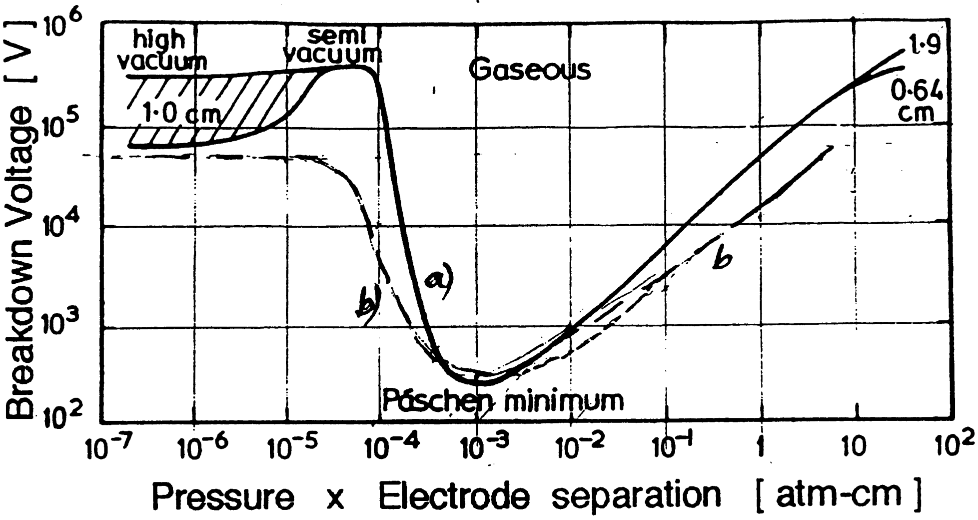


**Fig. 3 - The PASCHEN-GRAPH [19]**
DC breakdown voltage versus the product distance × pressure
a) from literature
b) measured at our gap with d = 100 mm

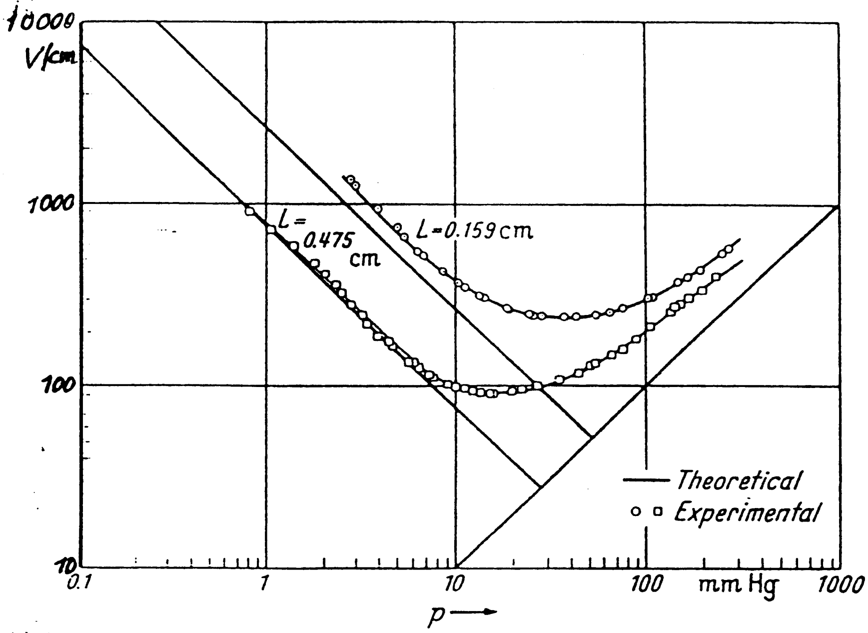


**Fig. 4 - The BROWN-GRAPH [20]**
RF breakdown field versus pressure for 3 GHz
"Looks similar to data with dc fields"

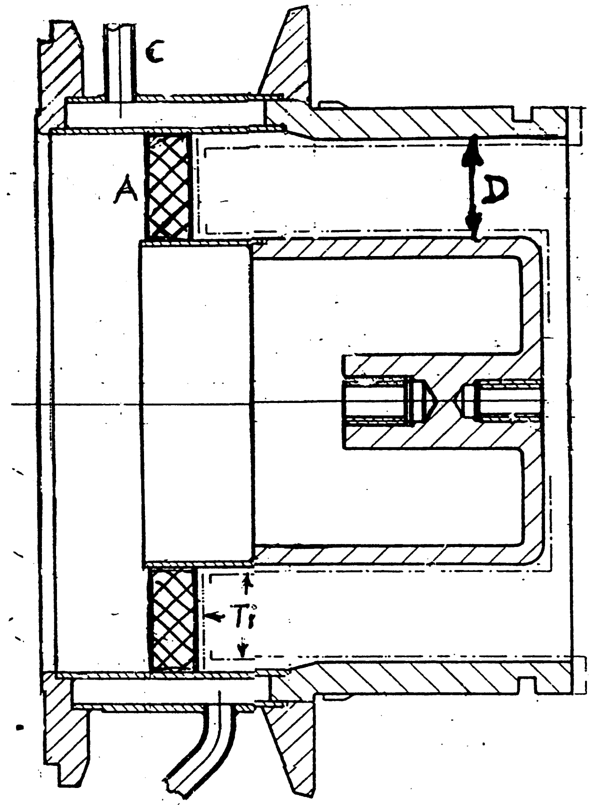


**Fig. 5**

**The old window (SPS type)**

- distance D = 25 mm
- ceramic soldered in
- loop screwed on

Ti : Titanium layer on copper and ceramic
A : $Al_2O_3$ disk
C : water cooling

CABLE CAVITY

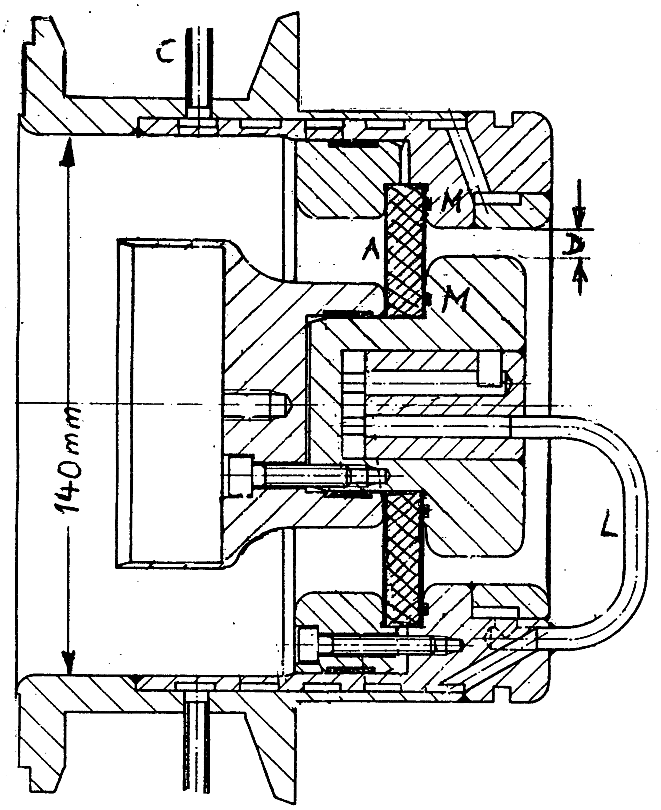


**Fig. 6**

**The new window (PS type)**

- distance D = 8 mm
- ceramic fixed with fasteners
- polished ceramic
- no sputtered layers
- coupling loop welded on

A : $Al_2O_3$ disk
L : coupling loop
M : metal joint
C : water cooling for inner conductor, outer cond. and loop

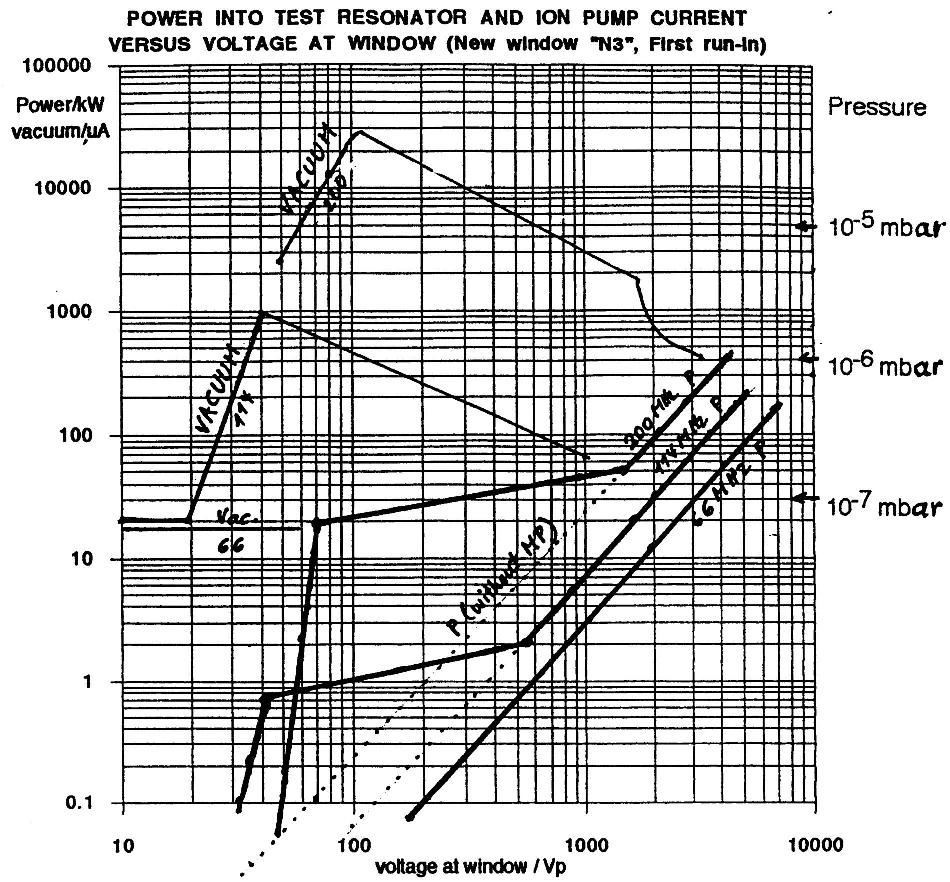


**Fig. 7 - Typical response of a new window**

| RESULTS OF FIRST RUN-IN OF WINDOWS *) (without loop, at a quarter wave resonator) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| type of window | | old (SPS) | | | old, sandblast | | | new design | | |
| distance<br>metal surface<br>ceramic surface | mm | 25<br>thick layer of titanium<br>thin layer of titanium | | | 25<br>copper<br>mat | | | 8<br>copper<br>polished | | |
| frequency | MHz | 66 | 114 | 200 | 66 | 114 | 200 | 66 | 114 | 200 |
| max heat power<br>(from MP) | W | 3 | 25 | 100 | 0 | 20 | **) | 0 | 1 | 10 |
| at peak voltage | V peak | 200 | 300 | 500 | | 600 | | | 40 | 80 |
| loading by MP | Ohm | 6667 | 1800 | 1250 | | 9000 | | | 800 | 320 |
| expected MP (Hatch)<br>lower level<br>upper level | <br>V peak<br>V peak | <br>●<br>● | <br>●<br>● | <br>●<br>● | <br>90<br>360 | <br>270<br>1100 | <br>250<br>2800 | <br>no<br>no | <br>66<br>120 | <br>80<br>320 |
| outgassing peak ***)<br>(no RF: 5E-8 mb) | mb | 2E-5 | 5E-5 | 1E-5 | | 2E-5 | | | 2E-6 | 3E-5 |
| conditioning time | | several hours | | | 1 hour | | | minutes | | |
| remarks | *) | the big variations in measurements come from the "prehistory" e.g. different time under vacuum or tested with RF previously | | | | | | | | |
| | **) | was conditioned previously by a run-in at 114 MHz : no MP | | | | | | | | |
| | ***) | in test chamber of 10 litres, pumped by a ion pump with 30 l/s | | | | | | | | |
| | ●) | there should be no MP, due to the low SEC of titanium | | | | | | | | |

**Fig. 8 - Results of measurements at old and new windows**

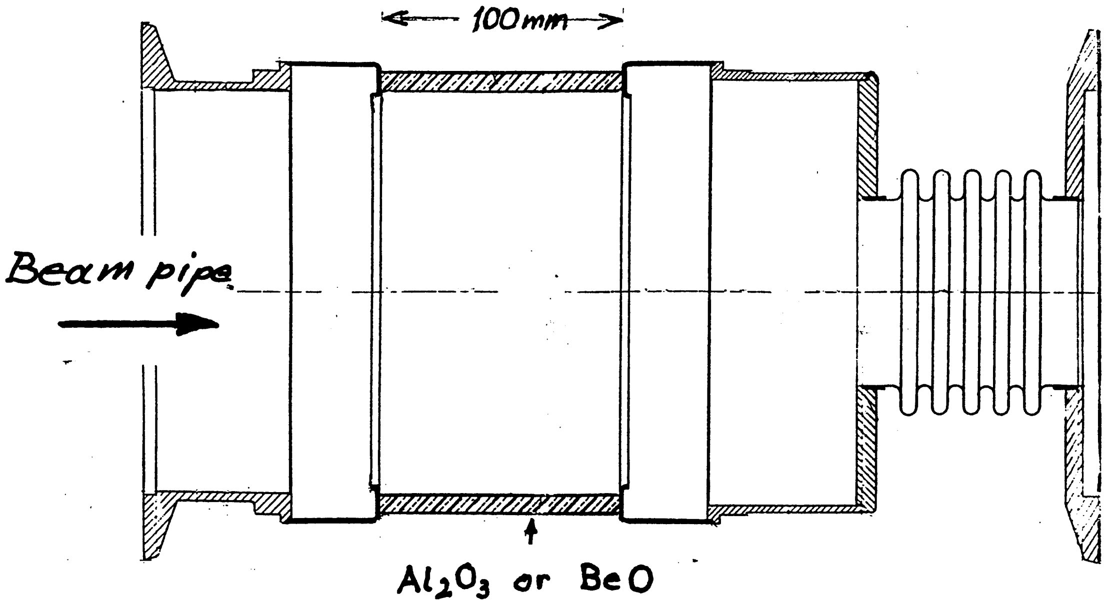


**Fig. 9 - The Gap for the 200 MHz cavity**

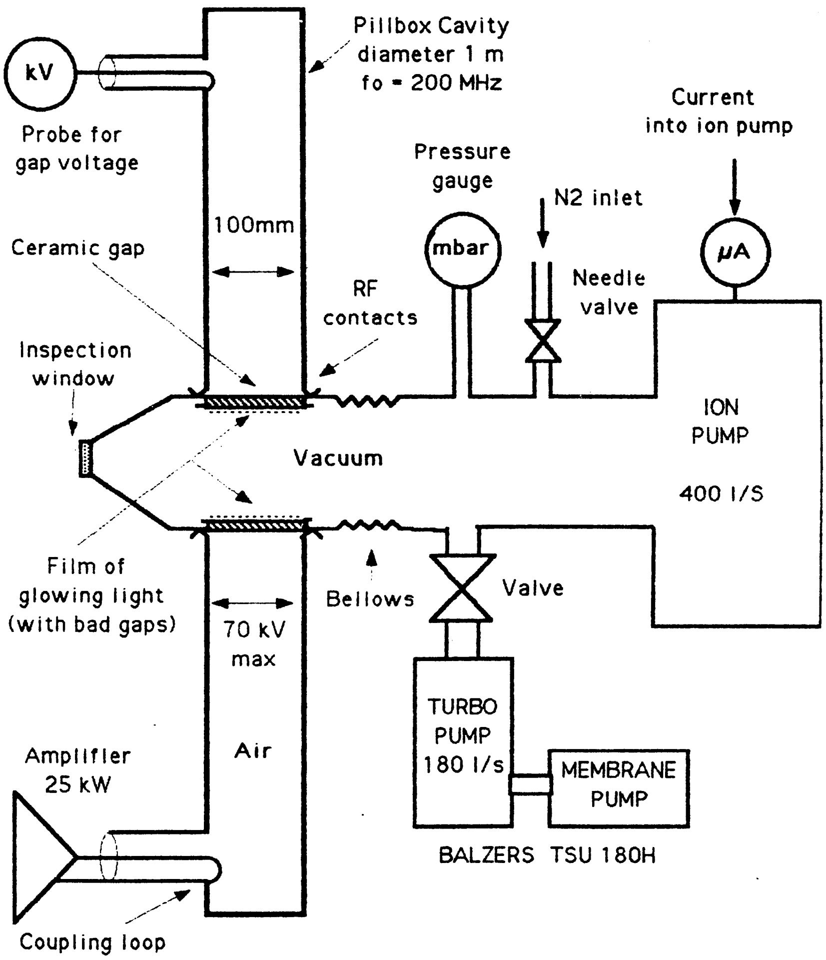


**Fig. 10 - The test cavity with the vacuum system**

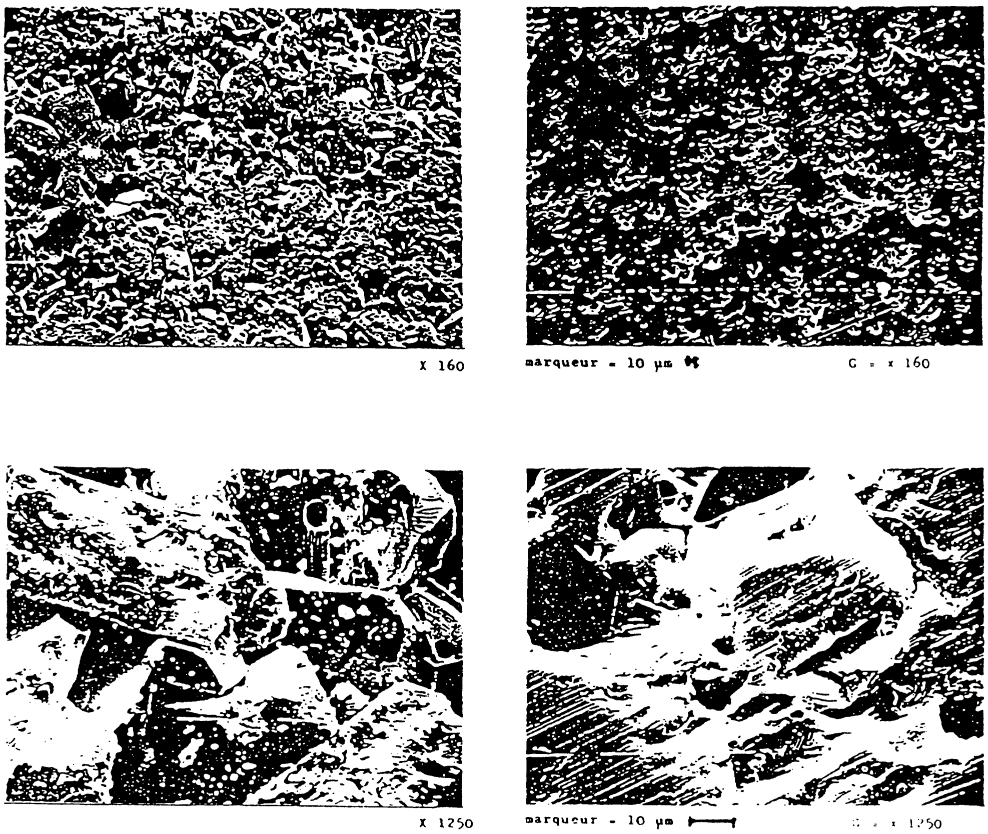


**Fig. 11 - Surface of the $Al_2O_3$ gap**

- left : unpolished
- right : polished (mat)
- below : enlarged

The polished version could be conditioned and reused

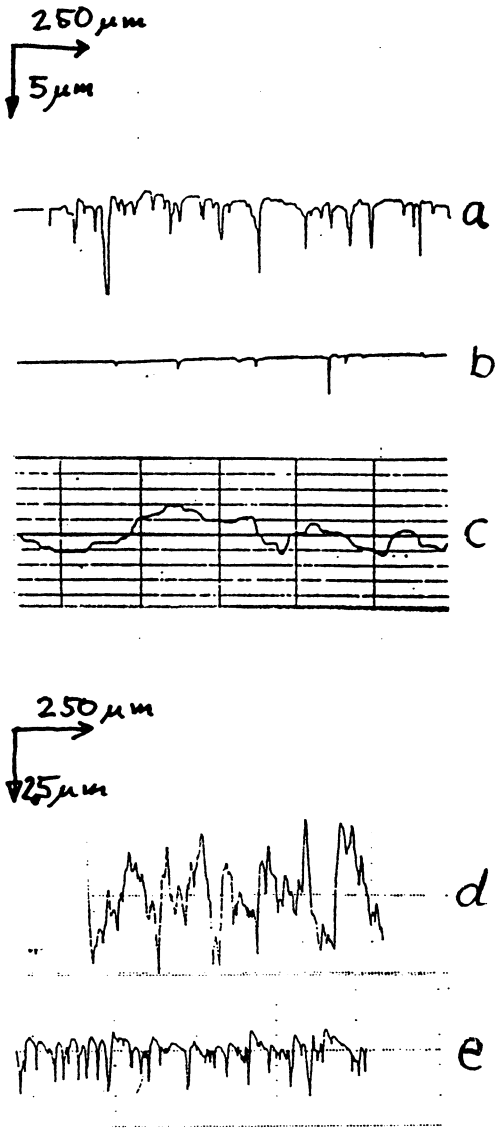


**Fig. 12 -Roughness of $Al_2O_3$ (and stainless steel for comparison)**

Ra = average depth [µm]
Rt = maximum depth [µm]

| | | | Ra | Rt |
|---|---|---|---|---|
| **a)** | disc mat | | 0.35 | 4.5 |
| **b)** | disc polished | | 0.03 | 1.8 |
| **c)** | (stainless steel) | machined | 0.25 | 2.0 |
| **d)** | tube for gap | rough | 1.7 | 10 |
| **e)** | tube for gap | polished (mat) | 0.6 | 4.6 |

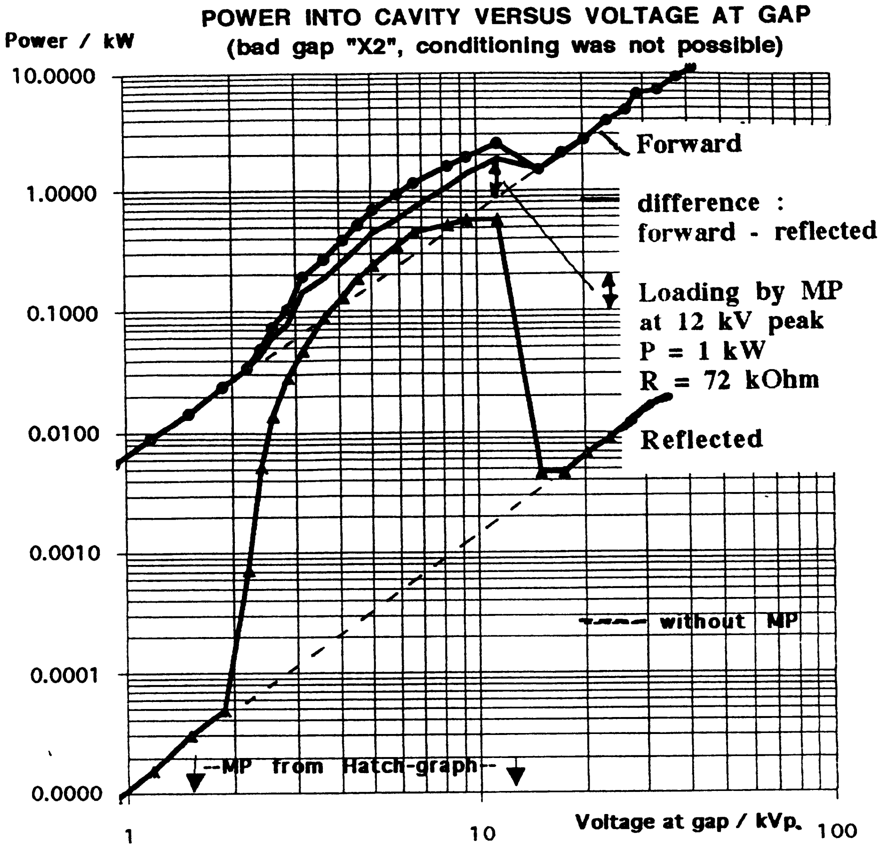


**Fig. 13 - Typical response of a bad gap**

- forward and reflected power due to multipacting
- heat dissipation <u>on</u> the ceramic at 12 kVp. from MP: 1000 W

<u>in</u> the ceramic (from tg $\partial = 3 \times 10^{-4}$): 73 W

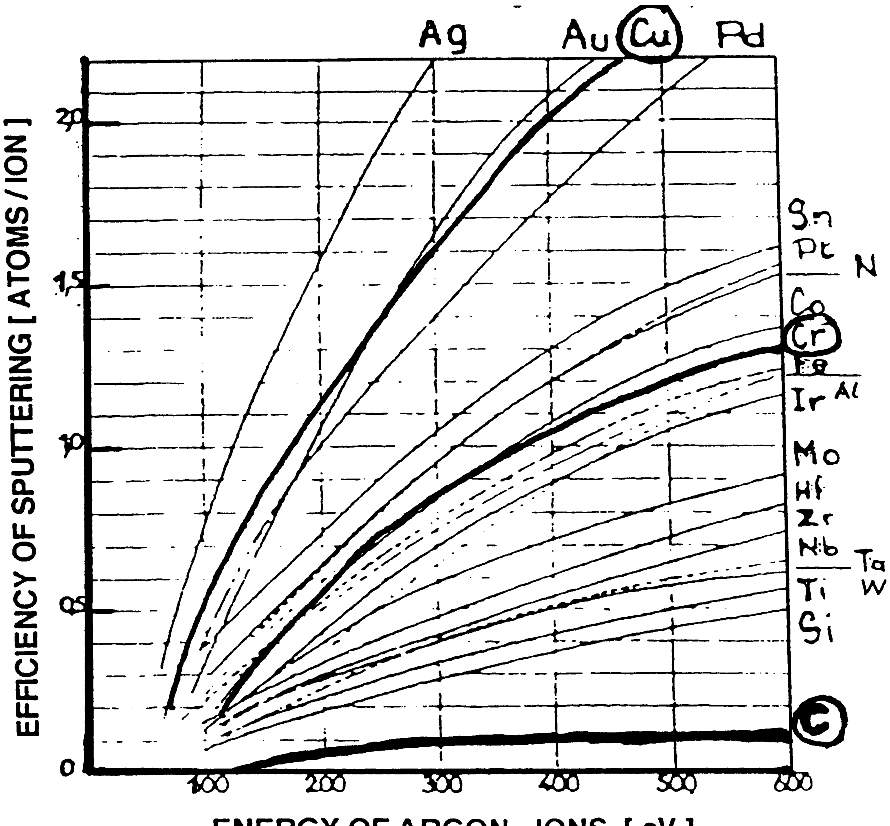


**Fig. 14 - Efficiency of Sputtering [28]**