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# CONDITIONING OF THE 114 MHZ CAVITY

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## ABSTRACT

Practical experience on how to run in a cavity for voltages up to 500 kV is shown and improvements for safe conditioning are discussed. Problems during first conditioning periods have been encountered more with the accessories such as dampers and RF windows.

A new RF window is constructed for tests with optimized distances for our frequency, applying the multipactor theory.


## 1. DESCRIPTION OF THE SYSTEM

The system [1] consists of one or two cavities (Fig. 1) in the PS ring to accelerate $e^+$ and $e^-$ to 3.5 GeV. The RF is fed from a 50 kW amplifier over 40 meters of coaxial cable (for cavity data see Appendix). The vacuum in the cavity is obtained via 2 ion pumps (400 l / s), the rough vacuum is made at start-up by turbo pumps over the beam pipe. To put the cavity under atmospheric pressure it is filled by $N_2$.

## 2. MULTIPACTOR

Multipactor (MP) happens when an electron is accelerated from one electrode to the other, hitting the opposite surface where more electrons are produced (secondary emission). If the electron travelling time is just 1/2 of the RF period (or 3/2 , 5/2 ...) the effect is amplified by resonance and an increasing electron shower travels backwards and forewards between electrodes.

A.J. Hatch [2] shows in a very practical graph how to find multipactor distances in Al-cavities (Fig. 2). It may be seen that there is only a small zone for the multipactor. No problems arise below 50 eV (line a) for all distances. For small distances (b) all voltages are safe. Multipactor occurs for a given distance only if the voltage level passes into the hatched zone (c).

The multipactor is reported to be more intense in the middle (m) due to the highest secondary emission coefficient of 2.3 at 300 eV. Above 3000 eV the secondary emission coefficient drops below 1 and MP gets weak. In the MP ranges with acceleration by 3/2, 5/2, 7/2 and more RF cycles (d), MP intensity diminishes as well for more dispersion of the electrons [3].

For copper the start level is at 200 eV, stop at 2000 eV and has its maximum of 1.3 at 600 eV [4].

While A.J. Hatch assumes, in his theory, plane parallel electrodes pairs, U. Klein [5] has made a computer code to calculate two points and also monomode MP where the electron path needs no second electrode but turns back to the same electrode in a curved path (for supraconducting cavities in the GHz range).

Attention should be paid to the fact, that if high RF-power is fed into the cavity, MP may turn it into a destructive arc. To find dangerous power levels at critical distances, the graph of A.J. Hatch is redrawn for our Cu cavity for 114 MHz, considering the voltage ratio between window, damper and gap for the power feeding the cavity (Fig. 3).

If MP is used in a controlled way, surfaces are cleaned and multipactor intensity diminishes (= conditioning).

### *2.1 Influence of multipactor to the RF*

The cavity feels the MP as a loading, local heating and detuning if one of the multipactor levels are approached. Bombardments of the surfaces provoke a rise in pressure which in turn cleans and conditions the surfaces (reduces the secondary emission coefficient, frees gas layers on the surface). At the beginning of a conditioning of the cavity the RF level and the vacuum is very unstable. After a certain time the intensity of the MP is reduced and the power level can be increased to a next "hard limit ", where the slightest RF increase rises the pressure abruptly (1% more RF produces a 10 times worse vacuum).

Due to : a) different distances in the cavity, dampers, window,
b) different materials (OF-copper, plated copper, Al, ceramic),
c) locally different pressure from outgassing or micro leaks,
d) locally different voltages.

the observed effects are not always pure multipactor but mixtures of different phenomena such as outgassing, local glow discharges, X-rays. At certain RF levels, a rise in RF may suddenly improve the vacuum.

The mentioned loading from MP may also be used for self protection, provided that the pressure rise cuts rapidly the power. If the RF is loosely coupled to the cavity, the loading reduces the Q-factor of the cavity and therefore also the power coupled to it. Detuning may have as well a protective effect for the cavity, because it reduces the voltage at the gap, but it may increase the voltage at the ceramic RF passage by reflection and force the amplifier to self oscillations (cable resonances).

## 3. HISTORY OF UNSUCCESSFUL STARTING PERIODS

### *3.1 Copper plating the ceramic of the RF window*

In the beginning it was thought that outgassing has to be activated by pushing power (approximately 5 kW CW) into the cavity and allowing vacuum rises up to $10^{-5}$ mbar. Protection for worse vacuum levels and overcurrent in the amplifier was done via relays taking more than 0.1 second to switch off. Another bad behaviour was the tendency of the final stage to self oscillation at full power (50 kW) from insufficient neutralization together with cable resonances. This created high voltage at the window as well as high current in the loop, evaporating copper to the ceramic. The window could be repaired afterwards by sand blasting.

(weak points: self oscillation, high pressure levels, too slow protection, no reflection limit).

### *3.2 Cracking of the ceramic of the RF window*

A hair-crack causing a big vacuum leak was provoked by an arc along the ceramic. The discharges started from a sharp overlapping metallization where the ceramic is brazed to the coaxial conductors (same experience at DESY [9]).

A thick layer of soldering material was evaporated in parts of the ceramic (hiding the crack). All started with a power rise, too rapidly, at the beginning of the conditioning period.

(weak points: overlapping metallization, uncovered brazing, too slow protection for pressure rise and reflection, human fault: being impatient).

### *3.3 Vapour plating of the copper layer inside the cavit,*

When power was increased (provoking outgassing) the stainless steel parts of the gap-shorting-switch (in open position) became white hot, covering the copper surface with a thin layer of stainless steel. Until we found the inside of the cavity "illuminated as by a 60 Watt lamp" this was wrongly considered as multipactor. Direct light observation was difficult due to emission of X-rays working with hundreds of kV's.

No Q deterioration was observed after this undesired plating. On the contrary the conditioning seemed to be easier.

(weak points: bad thermal and electrical conductor of the shorting bar, no cooling.).

### *3.4 Heating of parts of the damper*

The higher mode damper is a notch filter consisting of a small cavity tuned to block the passage of the cavity resonance frequency to the external resistance (50 Ω, 1 kW). Above 114,5 MHz parasitics are passed to the resistance and damped (Fig.1b).

A small sleeve on the inner conductor of this damper-cavity, made out of aluminium was heating up strongly and vapour plating the opposite copper surface.

The damper cavity is flanged on the main cavity and is part of the main vacuum system, therefore this heating effect was at first considered as MP in the main cavity.

Certainly, there is some low level MP, but we came closer to the origin of the trouble when we found the external resistor burned. With a discharge across the blocking resonant circuit, an important part of the RF power was coupled to the 1 kW load resistor and burned it. Dismantling the damper showed the Al-plating.

Now, all Al surfaces are made out of copper or copper-plated and a better heat transfer to cooled surfaces is assured.

(weak points: bad heat conductance of adjustment sleeve.)

### *3.5 Bad behaviour in the PS ring.*

After installation the cavity could not be brought to the desired 400 kV for our first beam tests although this level had been reached in our test place days before the transport.

We found that the voltage behaviour was changing with the machine cycle and it was finally traced back to the stray field of the big bending magnets touching both sides of the cavity. A synchronization of our RF pulses to the intervals without magnetic field re-established our high voltage and a day later the voltage could be pushed to the desired value with a field in the nearby magnets of 1.8 kG (for $e^+$ and $e^-$). With the stray field from the high field for protons (up to 12 kG) the cavity could not be conditioned.

(weak points: too short time to condition outside, no flushing with $N_2$, cavity kept under air at transport time).

## 4. IMPROVEMENTS FOR SAFE CONDITIONING

### *4.1 Electronic Protections*

The slow acting relay-interlocks have been replaced by pin switches cutting the RF input, driven from comparators sensing the vacuum and reflected power.

### *4.2 Interventions in the Amplifier*

The self oscillation of the final stage of the RF amplifier has been eliminated by revising the neutralization and damping the resonance peaks appearing in the anode circuit from the cable resonances. Adjusting the cable length to entire numbers of half wave-length move these cable resonance peaks symmetrically away from the cavity resonance.

The low level drive system has also been reviewed to avoid driving the amplifier at its parasitic resonances.

### *4.3 Changes at the RF window.*

The presently used SPS window with its overlapping metallisation at the ceramic disc is now protected by metal rings at the inner and outer conductor (Fig. 1c). The field-strength at the sharp edges is reduced and the solder made invisible to electron bombardments. With our repaired window ( removing the overlapping metallization) and a copper-plating of the solder we also improved the MP behavior (even without rings).

A new window (Fig. 1d) is under test, where the distances are reduced and optimized for our frequency. The $Al_2 O_3$ disk, not metallized, is screwed between flanges using Al- wire joints (later, C-joint will be used). First result on a line resonator showed no bad MP behavior with up to 2 times our nominal voltages. Glow discharge surface cleaning (at 0.1 to 1 mbar $N_2$) removed the start up voltage limits in minutes.

### *4.4 Eliminating vacuum leaks causing local discharges*

Some flanges and diamond Al-joints suffered by heating with slow cycling RF power. Local heating, up to 60 degrees was observed at approximately 10 kW average power into the cavity. The reason is the bad heat conductance of the stainless steel body of the cavity and accessories.

Additional cooling at these flanges (nose cones, short, tuners) and copper-plating of remaining stainless steel surfaces under RF-currents cured the situation.

A leak from a joint under stress from accidentally fast movements of the shorting arm, could be eliminated by an electronic protection system limiting arm accelerations.

Nevertheless, some of the Al-diamond-joints should be replaced in the future by the more elastic C- shaped joints.

## 5. SLOW AND SAFE CONDITIONING

In the following steps, a typical conditioning cycle is shown (after having learned from the above mentioned difficulties).

The RF power is increased just below the chosen pressure limit (5E-7 mbar), above this level a PIN switch cuts the RF. When the vacuum improved 2 to 5 times, the RF was increased manually for stable working conditions. The power levels mentioned in the list are "hard limits" like the burning voltage in a glow lamp and could not be punched through by very short pulses.

It was only after hours or days that hard levels could be increased slowly. Some of these levels appeared for a short time again, when the conditioned cavity was idle for some days. Weak MP levels may be observed as small spikes in the rise and fall time when pulsing. With an optical window and TV installed, we could never see light from multipactoring.

## 5.1 Timetable of a typical RUN - IN in the test place

| time day | action , observations | mode | power kW | vac. mbar |
|---|---|---|---|---|
| | | | | |
| 0 | cavity manually cleaned with alcohol, at air | | 0 | 760 |
| | start pumping with turbo pump | | | |
| 1 | rough vac. level reached | | | 1E-6 |
| 2 | baking out ion pumps at 300 deg. | | | |
| | baking out cavity at 150 deg. | | | 1E-5 |
| 5 | cooling down, ion pumps on | | | |
| 6 | leak tests | | | |
| | vac ok for low level RF start limit | | | 3E-7 |
| 7 | **start with network analys. as driver, sweep freq.** | FM 0.1MHz | <0.1 | |
| | limit for vac protection set to 5E-7 | | | 5E-7 |
| | vac.and RF unstable : damping and detuning | | | |
| | frequent switch off by vac. protection | | | |
| | resonance curve at netw. analys. deformed | | | |
| 8 | improvement in shape of res. and vac. | | | 1E-7 |
| | little more power ( 1%)rise pressure 10 times | | 0.1 | 5E-7 |
| | vac improves, still deformation of res. curve | | | 2E-7 |
| 9 | more power | | 0.2 | 5E-7 |
| 10 | vac improves | | | 2E-7 |
| | more power | | 0.3 | 5E-7 |
| | vac improves | | | 2E-7 |
| 12 | power increased, vacuum improves | | 0.7 | 1E-7 |
| | power increased | | 1.0 | 5E-7 |
| | vac improves, more stable resonance curve | | | 2E-7 |
| 13 | **changed to pulsed RF, automatic cav. tuning** | pulsed 1% | 1 | 1E-7 |
| | | pulsed 10% | 1 | 3E-7 |
| | | pulsed 50% | 1 | 5E-7 |
| | vac improves with power increase | | | 2E-7 |
| | more power, vac becomes better | pulsed 10% | 2 | 1E-7 |
| | more power, vac improves slowly, damper hot | | 5 | 5E-7 |
| | more power , vac improves slowly | | 7 | 5E-7 |
| | more power, vac improves slowly | | 10 | 5E-7 |
| 14 | check for sufficient cooling, check for hot spots | pulsed 50% | 10 | 5E-7 |
| 15 | more power, shorter pulses | pulsed 20% | 12 | 5E-7 |
| | vac improves | | | 2E-7 |
| | more power, vac improves slowly | | 14 | 5E-7 |
| | more power, vac improves slowly | | 19 | 5E-7 |
| 16 | more power, vac improves slowly | | 25 | 5E-7 |
| 17 | dampers less hot than at low power, tuners hot | | 25 | 2E-7 |
| 18 | **desired level reached (>500kV at gap)** | | 25 | 1E-7 |
| 25 | higher level possible with shorter pulses | | 37 | 8E-8 |
| | (limitations by cooling in damper and tuner) | | | |
| 35 | vacuum improves and is not changed by RF | | 40 | 3E-8 |

Concluding from this first conditioning period (see table above and Fig. 4), it took us one week for vacuum preparation, one for low power conditioning and another one from 2 to 25 kW. For power below 1 kW we used FM, while above we changed to pulsed mode, constant frequency.

Insufficient cooling did not yet permit to run on CW (which is not required for operation).

Once conditioned in the lab, transporting (under vacuum) to the ring, installing and pumping, conditioning time took only a few hours to reach 25 kW.

This slow procedure could be made faster by replacing our manual stepping by computer control, but up to now each "hard limit level" showed a different behaviour and needed to be handled with "personal care".

On the other hand, "rushing" took us a longer time - counting repair and pumping.

Nevertheless, with the presently installed protection systems and improvements on the cavity, the real conditioning time from signal level to full power should become less than a week, without any danger.

### *5.2 Comparison of conditioning levels with calculated MP levels*

No clear relation was found with the "hard levels" (sudden rise of pressure or reflection when increasing RF = dotted lines in Fig. 3) measured and the predicted MP ranges from theory, due to overlapping ranges in components (damper, window) and the cavity itself. There are also other outgassing effects, ionisations, stronger MP due to contaminated surfaces and MP at the ceramic of the window, difficult to predict.

Nevertheless we discovered, that the present window and damper with distances of 20 to 30 mm are in the max. intensity of the MP range. Both components have been destroyed in the conditioning phase (with the slow protection system).

On the other hand, no traces of sparks or colouration have been found inside the cavity, where MP should be weak, due to multiple cycle MP (3/2, 5/2 ...) at the wide distances.

## 6. METHODS TO REDUCE MULTIPACTOR

### *6.1 Experience on other accelerators*

A. Susini reported from GANIL, M. Biet, "Al-surfaces have always to be reconditioned after a spark or a break of the vacuum, but copper stays, once conditioned".

The Titanium layers on our CERN SPS windows (used in PS and DESY) on ceramic and metal take a long time to be conditioned (to re-establish a metallic layer after exposure to air) and are very good afterwards, but we repaired a window by sand blasting, achieved pure $Al_2O_3$ and copper surfaces , and it worked as well.

In Los Alamos [6] they deposit a Ti-Nitrid layer on the Ceramic which seem to be less sensible to contamination by atmosphere.

Painted on carbon layers (Aquadag) diminishes MP at Al-surfaces at SIN [Mr. P. Lanz].

Visiting the old Synchrocyclotron in DUBNA, they told us " We allow a small firework inside the rotary capacitor for the first hours, a thin carbon layer is deposited on the metallic (and ceramic) surfaces from the cracked oil in the vacuum and afterwards it works perfectly" [Mr. E. Rosanov].

There may be a difference between a galvanic layer of copper (PS) and a cavity made of solid OF-copper (SPS), because the SPS cavity takes less time for conditioning (but it has also less surface). (SPS: after a week in the laboratory, 8 hours in the ring [7].)

A clear answer for the best layer (which is copper for RF) could not be found, it seems that the surface quality and surface contamination determine more the time for conditioning.

In the past conditioning was certainly forming a carbon layer on the electrodes by cracking the oil contaminated vacuum. These days it seems to be a real cleaning procedure in an oil-free ultra vacuum.

First results with the new test window (not brazed, but screwed, no TI-layer at the $Al_2O_3$) showed, that cleaning by glow discharge at low RF levels (100 Vp) and at pressures of 1E-1 mbar is very efficient to shorten the time for conditioning.

### *6.2 Intermediate electrodes*

Inserting one or more floating electrodes between the original electrode pair reduces and shifts away the multipactor. The resonance condition for accelerating the electrons is broken [2].

### *6.3 Biasing*

In the CERN SC and other SC's the electrodes especially in the rotary capacitor are biased with a DC voltage (approx. 1 kV) to prevent MP. The DC-voltage accelerates in one half period more, in the next less, disturbing the resonance effect. [8].

The bias-current into the electrode is sensed to switch off RF.

### *6.4 Punch - Through*

The original multipactor graph shows, that for a certain frequency and distance, multipactor occurs only in a short range. If this range may be passed fast enough, so that the vacuum is not effected and no arcing is produced, stable high voltage levels may be obtained (1 kV/µs in [3]; 6 kV/µs in [8]).

This method is used successfully at the TRIUMF Dee resonator in connection with a MWatt RF-amplifier.

In our cavity this is not applicable, due to the slow rise time from the high Q (35000) and the limited RF-power from strong loading in the Punch-through moment.

(For our gap, a punch-through may be considered, but not for the window and damper with their lower voltages and strong MP.)

## 7. FURTHER IMPROVEMENTS IN OUR CAVITY

Al-parts in the cavity such as the shorting arm should be Cu-plated, because the MP range is shorter and the max. sec. em. coeff. is lower and copper has a higher melting temperature in case of an arc. Al-parts in the damper are now Cu-plated.

A glow discharge cleaning is planned to reduce the conditioning time at first run-in in the following way. After reaching 1E-7 mbar, sector valves are closed, pressure is increased by controlled filling with $N_2$ (or Argon) and low power RF is slowly increased up to 100 W sweeping the fequency.

## LIST OF FIGURES AND APPENDIX

**LIST OF REFERENCES**

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[2] A.J. Hatch, Argonne, "Suppression of Multipactor in Particle Acc.", Nuclear Instr. and Methods 41 (1966) 261 - 272.

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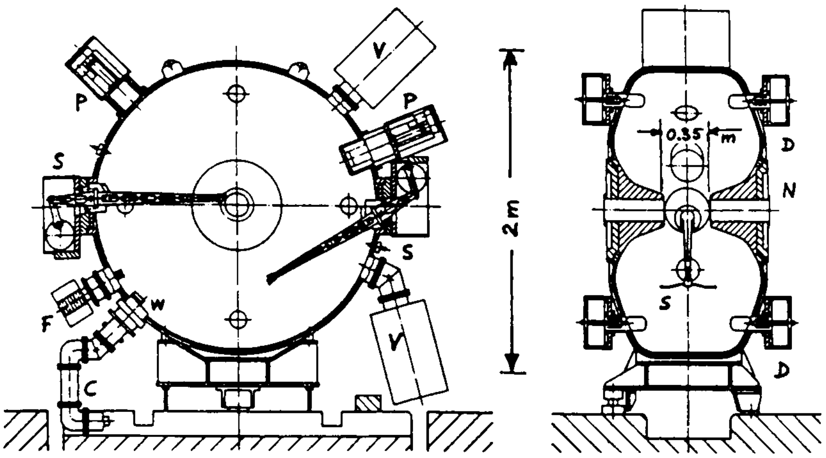



Fig. 1

The 114 MHz cavity

N = nose cone
D = damper
W = RF window
C = cable to amp.
F = ferrite tuner
S = short
P = piston tuner
V = vacuum pump

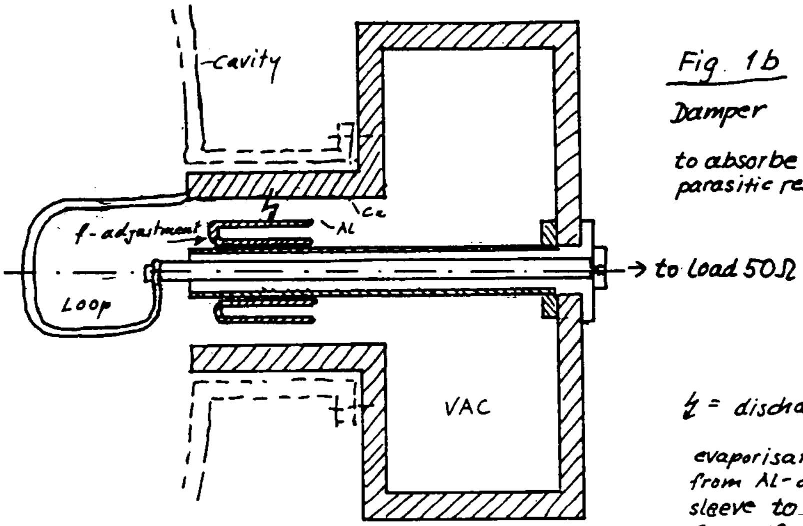



Fig 1b

Damper

to absorbe parasitic resonances

ϟ = discharges

evaporisation from AL-adjustent sleeve to Cu-surface

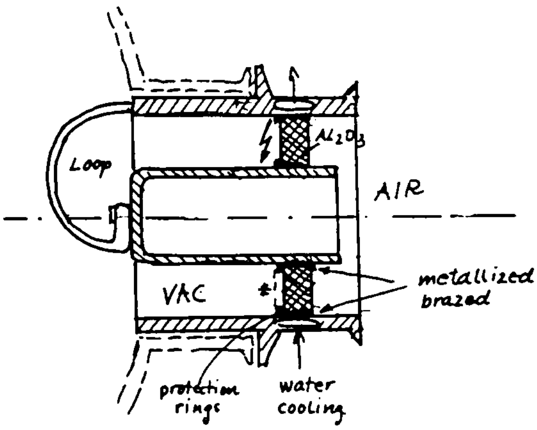



Fig 1c

presently used RF-window (SPS)

* surface with Titan layer

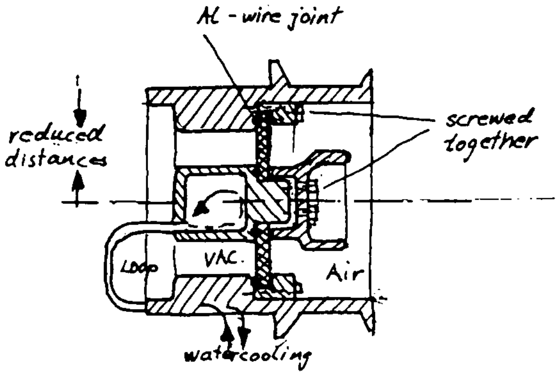



Fig 1.d

new Test RF-Window

(no brazing)

*FIG 2 Original Multipactor-graph of A.J. HATCH[2] with lines for explication of limits and for copper*

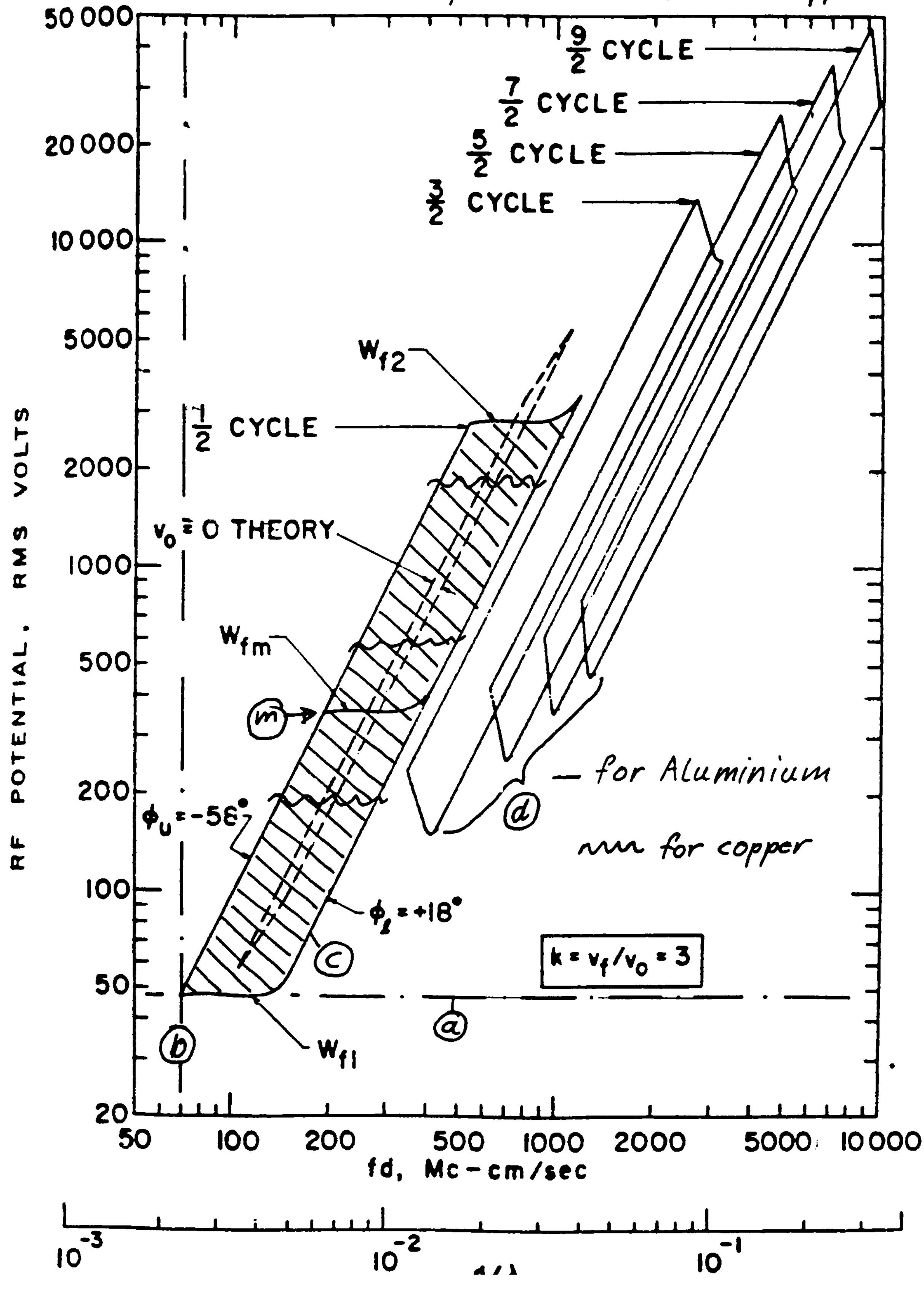


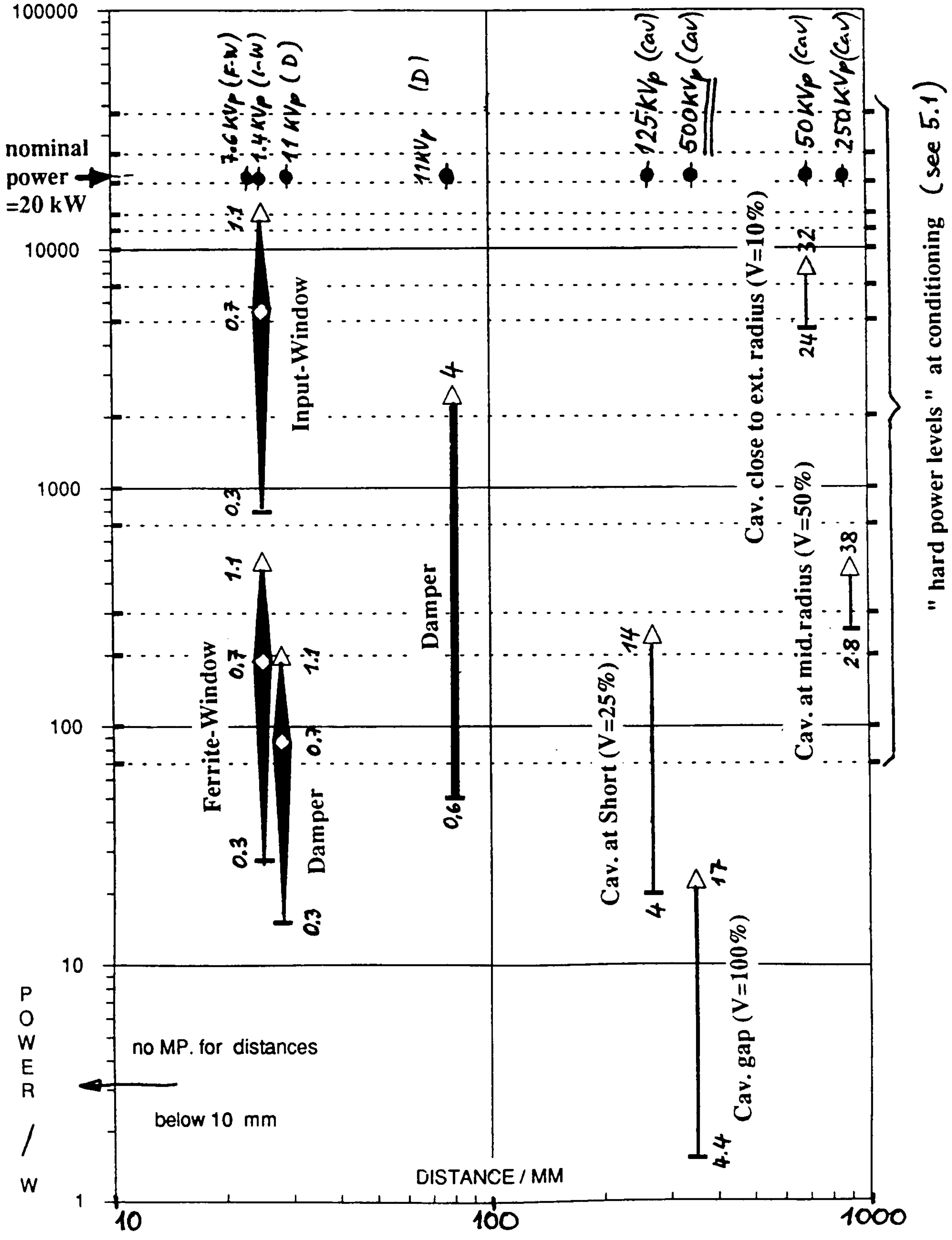
FIG. 3 DANGEROUS POWER LEVELS

excpected start [⊥] and stop [△] of multipactor for the114 MHz cavity with a copper surface depending on distances

( numbers : "kVp" at start. stop and max MP [◇] )

( ⧫ : max voltage at different locations with 20 kW input )

a thicker line represents stonger Multipactor



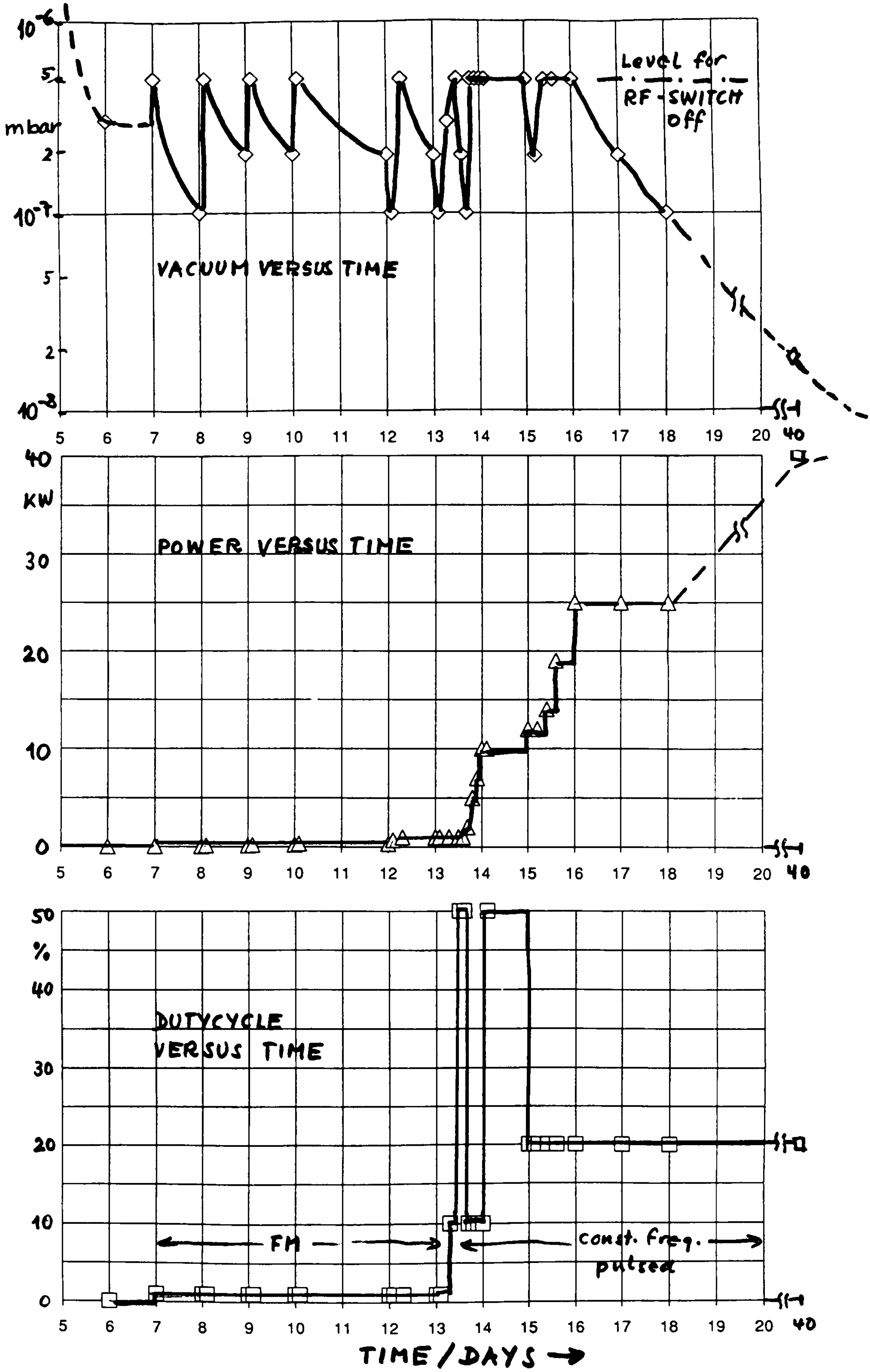



FIG. 4 Typical RUN-IN of the cavity (Test place)

## APPENDIX

### CAVITY DATA

Dimensions

| | |
|---|---|
| external diam. | 1830 mm |
| internal diam. | 1770 mm |
| ext. lenght (in dir. of beam) | 1020 mm |
| distance of gap (nose cones) | 350 mm |

Material

| | |
|---|---|
| cavity shell | stainless steel 18/8 |
| inside galvanic plating | copper layer > 0.1 mm |
| Arm for short | Aluminium<br>(will be Cu-plated later) |
| nose cones | forged oxygen free copper |
| weight | ~ 1600 kg |
| volume | ~ 2 m^3 |
| surface (internal) | ~ 10 m^2 |
| cooling | radialy up and down,<br>inside the double shell<br>by dem. water, 50 l/min |

RF-data

| | |
|---|---|
| resonance freq. | 114.5 12 MHz |
| Quality factor | 35000 (pesimistic value incl. loading by Dampers,short, tuners) |
| R/Q | 180 OHM |
| Rp | 6.25 M OHM |

Voltage in cavity ( with Ampl. 20 kW)

| | |
|---|---|
| at gap | 500 kVp |
| at input-window | 1.4 kVp |
| at ferrite-window | 7.6 kVp |
| at damper | 11 kVp |
| short to wall | 125 kVp |

### AMPLIFIER DATA

| | | | |
|---|---|---|---|
| Power | for operation | 20 kW | |
| | max. continuous | 50 kW | |
| | peak(10ms in 1 sec.) | 200 kW | (needs diff. matching) |

output impedance 50 OHM
connected to cavity over 40 m coax. cable 4 1/2

Amplification 80 dB