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THE MULTIPACTORING - FREE RF CAVITY OF THE DAΦNE ACCUMULATOR

R. Boni, B. Spataro

Abstract

The performance of the RF cavity resonators may be limited by the resonant electron discharges or multipactoring. This phenomenon can take place in under vacuum RF devices, it makes difficult the cavity conditioning, causes RF losses and prevents to reach the operating voltage range.

The RF cavity of the DAΦNE Φ-Factory Accumulator Ring [1], is designed to operate at 73.65 MHz with a maximum accelerating voltage of 250 kV peak and consists of a reentrant λ/4 coaxial resonator.

The shape has been carefully studied to achieve a multipactoring- free cavity. The simulation of discharge trajectories due to resonant electrons in cavity resonators having rotational symmetry has been carried out for this RF cavity with the computer code Newtraj [2]. Numerous code outputs are presented and discussed in this paper. The cavity power tests have been performed successfully; theoretical and experimental results, together with the design criteria, are presented.

Introduction

The DAΦNE accumulator RF cavity is a so-called "single-ended" structure and has been chosen to have a resonator of compact size, making the manufacturing easier and cheaper even though the cavity shunt impedance is about half than a double ended structure. However, the available tetrode RF power is large enough to feed the resonator. The cavity is also designed to operate in ultra high vacuum (UHV) and is made of oxygen free high conductivity (OFHC) copper which guarantees good thermal and electrical conductivities.

Multipactoring (MP) is a phenomenon of resonant electron discharge which can occur in RF under vacuum devices . It acts as a barrier and is known to be responsible of field limitations [3,4,5,6].

The electrons, field-emitted from the metallic surface, are accelerated and deflected by the electromagnetic (em) field of the cavity and can impact the cavity inner surface on the same or on different points generating emission of secondary electrons.

In the first case the particle transit time is an integer number of RF cycles while in the second one is an odd-integral multiple of half RF cycles.

If some kinematics and physical conditions (i.e. impact angle and energy, level and phase of the RF field) are fulfilled, the mechanism efficiency is greater than unity and the process leads to a resonant multiplication of the electrons emitted by the walls which increases the RF cavity losses, preventing further increases in field with RF power.

Depending on the electron trajectory, one can speak of one point or two point MP respectively. In such cases, the operation of the cavity resonator can be fully inhibited.

The authors have experienced the operation of the 51 MHz accelerating cavity of the ADONE e+/e- storage ring. The cavity, made in Aluminium, was so heavily affected by MP that high peak power RF pulses with fast rise time, were required from the RF source to overcome the barrier. This caused serious problems to the RF equipment [7], and the continuous wave operation was very much unreliable, as well. Coating the cavity end plates with graphite reduced temporarily the problem but it was necessary to realize a new resonator [8]. The one point MP at the high level operation vanished, by making the rounded shape at the end- plates of the re-entrant resonator. The two points MP at the low level, was still detected between capacitive plates, even though this barrier has been overcome applying low power pulsed RF with steep rise time. In order to realize a fully reliable and MP free coaxial resonator and to make easy the conditioning operation, a proper shape profile was proposed for the DAΦNE accumulator ring.

The cavity electromagnetic project and the MP design criteria have been given in an early paper [9].The MP simulations are presented here in greater details and also we report the results of the power test made on the real resonator which fulfill successfully the expected behaviour.

Multipactoring simulations

In addition to the problem of compactness, special care was dedicated to study the best cavity profile and the most suitable material in order to keep MP unlikely.

Besides the kinematic conditions, the cavity shape and the surface secondary emission (SE) coefficient play an important role in setting up the conditions for a resonant discharge. It is possible to reduce or even to avoid the MP by properly shaping the cavity internal surface or by coating it with Titanium or its compound TiN which have SE < 1.

Given the good results obtained in the design and at the high level operation of the 51 MHz ADONE cavity [8], we followed the same design criteria for the DAΦNE accumulator one: an important goal was to reduce the probability of resonant electron loading emission from the internal surfaces, fully in the operation voltage range.

Newtraj is a post-processor of the code Oscar2D [10] and can simulate the electron trajectories, finding out the regions of the cavity surface with the highest probability of electron emission per particle impact.

The equations of the electron motion in the RF field are solved with the following initial conditions: extraction energy and angle of the particle, phase of the electric field. The code does not consider phenomena related to the ionization of the cavity residual gas.

Newtraj computes the probability that electron emission occurs at each particle collision on the cavity internal surface, due to secondary electrons and to back-scattering process as well. The initial conditions and the relative energy distribution of the re-emitted particles are important parameters of the code calculations. A detailed description can be found by the code author in ref. [2,8]. The SE yield can be found in the technical literature (see for example Ref. [6]) as a function of the particle collision energy. Copper and Aluminium have a maximum SE coefficient of 1.25 and 2.3 respectively for an impact energy range between 100 and 1600 eV. Therefore MP is commonly less severe and the cavity RF conditioning is easier if Copper is used in place of Aluminium.

For each collision, the extraction energy of each secondary electron is assumed to be constant at some eV for the primary electrons according to the emission energy values. Different values of extraction energies are assumed by the code in case of back-scattered electrons. The particle motion is followed until a new impact occurs and the iteration process stops if one of the following conditions is fulfilled: the secondary yield is less than unity; the RF phase between the two last hits is below ten degrees; the electron finds the wrong sign of the field, the electron leaves the cavity through the beam tube; the number of impacts on the surfaces exceeds forty; and for a given value of RF cycles.

The cavity shape design

It is known that to reduce or eliminate the MP, it is recommended to have a curved profile for the resonator surfaces or to use asymmetric cavities, in order to make less symmetric the resonant electron discharges which will become more unstable for the secondaries production [3,6].

In Fig. 1 the cavity shape chosen after careful investigations shows the field flux lines and the relative dimensions are presented, and in Table 1 the relevant RF parameters are given.

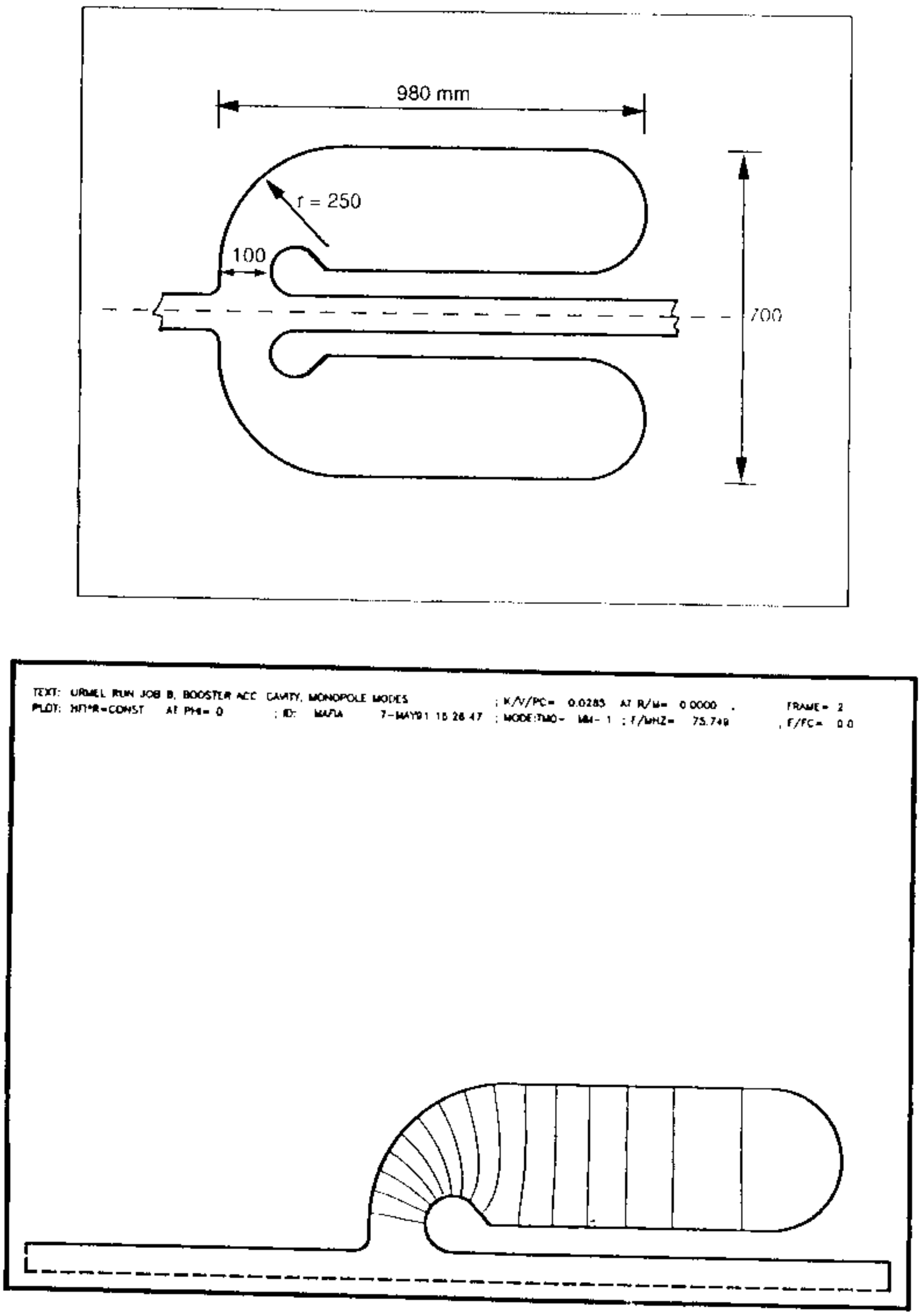

Fig. 1 - RF cavity shape.

Table 1 - The RF Cavity Main Parameters.

Operating frequency	73.65 MHz
RF peak voltage	200 kV
Cavity quality factor	20500
Cavity shunt impedance	1.62 MΩ
Generator-cavity coupling	1.2
Cavity wasted power	12.3 kW
Cavity type	Copper. λ/4 coaxial reentrant

The curved profile given to the external resonator surfaces avoids the one point MP in those region and the rounded shape of the internal electrode avoids the two points MP which usually takes place there at low voltages.

a) Two points multipactoring.

The study of the two flat electrodes configuration, has been presented by A. Hatch [6]. He computes the theoretical MP zones by using the parameter F∗d, where F is the operating frequency in MHz and d is the electrode gap. In the case of the DAΦNE accumulator cavity, the parameter value of 736.5 MHz∗cm, corresponding to F = 73.65 MHz and d = 10 cm, would lead to MP in 3/2 RF cycle for a gap voltage between 400 V and 1 kV.

A similar behaviour could be found also on the axial apertures of the accelerating cavities working on the fundamental mode TM_{010}.

The presence on the gap of the electric field, both radial E_r and longitudinal E_z, and of the magnetic field H_ϕ, where ϕ,r,z are the cylindrical coordinates, could lead to the two points MP configuration, when the counteraction of the radial electric force and of the magnetic force is compensated, determining the resonant discharges, as it has been obtained in the bunching cavities system of linear accelerators and klystrons.

Many numeric simulations were necessary to find the optimum gap shape of the RF cavity of the DAΦNE accumulator. The asymmetric shape, with respect to the central transverse plane in the gap region of the cavity resonator, due to the unlike curved surfaces of the electrode and that of the external profile, makes it easier to lose the kinematic and physical conditions, as the flight time and the secondaries yield, to avoid the production of stable trajectories on the surfaces, between the same two points.

In order to have some rough ideas about the possible areas of the resonant discharges, we plotted on the same picture many trajectories in the supposed zones of discharge, for the same initial point, the different gap voltage, the different RF phases and initial slopes. This procedure characterizes the concentration of the trajectories in the cavity; afterwards we investigated in detail the possible peculiar spots.

We calculated the trajectories varying the gap voltage from 400 V to 3 kV with steps of 100 V, the RF phase from -60° to 180° in steps of 20° degrees, the initial slope angle from -90° to 90° in steps of 10° degree, for many initial positions of the starting point.

The results showed that the curved surfaces avoid stable trajectories, between the two same points configuration, as predicted [3,11].

In Figs. 2÷7 typical trajectories for some values the voltage gap, RF phase, starting point etc. are presented.

Figure 2 shows clearly the trajectories confinement in the beam tube and does not show concentrated spots in the cavity resonator.

In Fig. 3 the electron hits the opposite bottom surface, from which the emission angle of the secondary particle is towards the cavity, and afterwards is pushed down in the beam tube by the transverse radial electric force.

In Fig. 4 the electron does not hit the opposite rounded surface of the electrode, and is slightly deflected up by the magnetic force. When the field changes of sign, the electron is deflected down in the beam tube, by the transverse radial electric force.

In Fig. 5 the transverse forces, electric and magnetic, deflect up the electron until it hits the external curved surface, and afterwards drifts in the cavity resonator.

In Fig. 6 the particle hits the external curved wall, thesecondary yield is deflected up by the transverse forces, electrical and magnetic, hitting again the same surface and afterwards drifts in the cavity resonator.

In Fig. 7 the electron oscillates between different points of the opposite surfaces without finding the resonant discharges, and afterwards is pushed down in the beam tube by the transverse radial electric force.

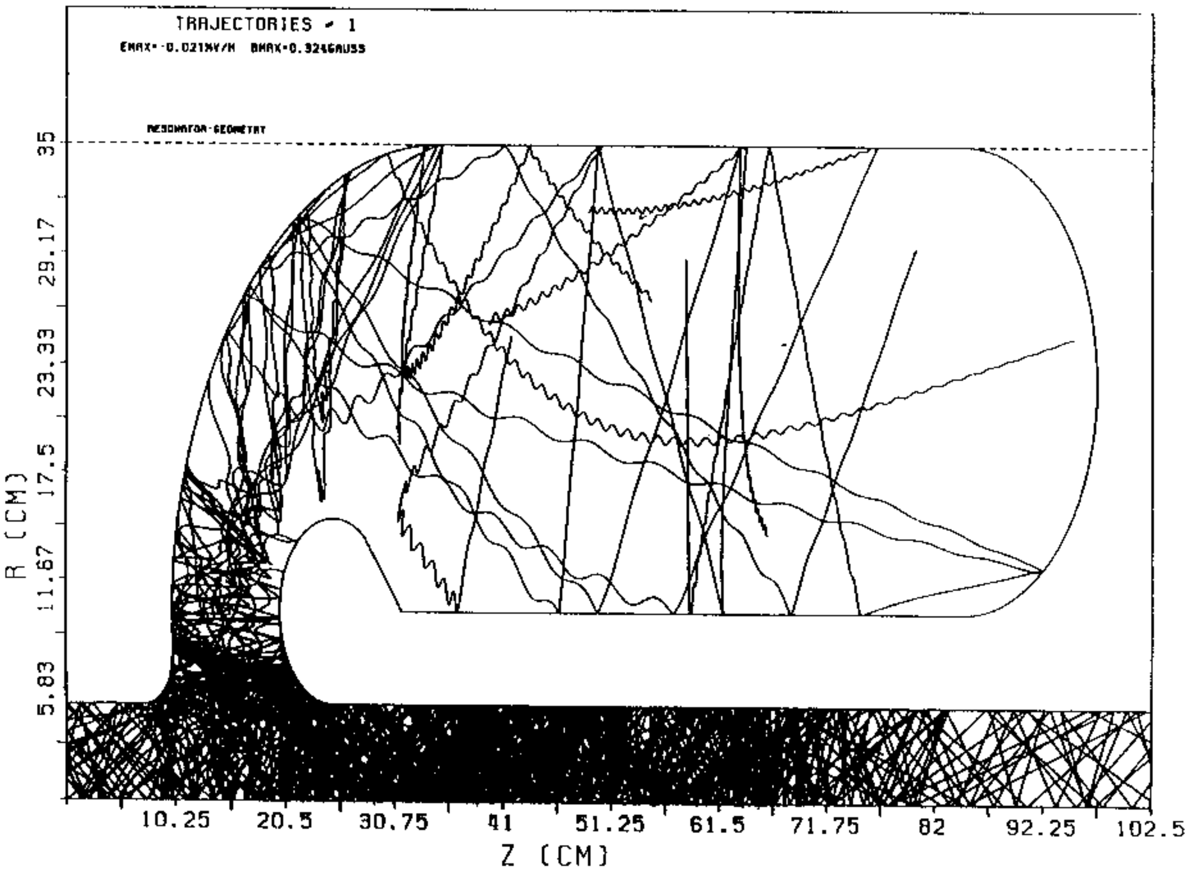

Fig. 2 - The electron starts the trajectories at r = 6.5 cm and z = 15 cm (in the central part of the gap), varying the RF phases from 0° to 180° in steps of 45°, the initial angles from -90° to 90° in steps of 10°, and keeping the gap voltage at 1 kV.

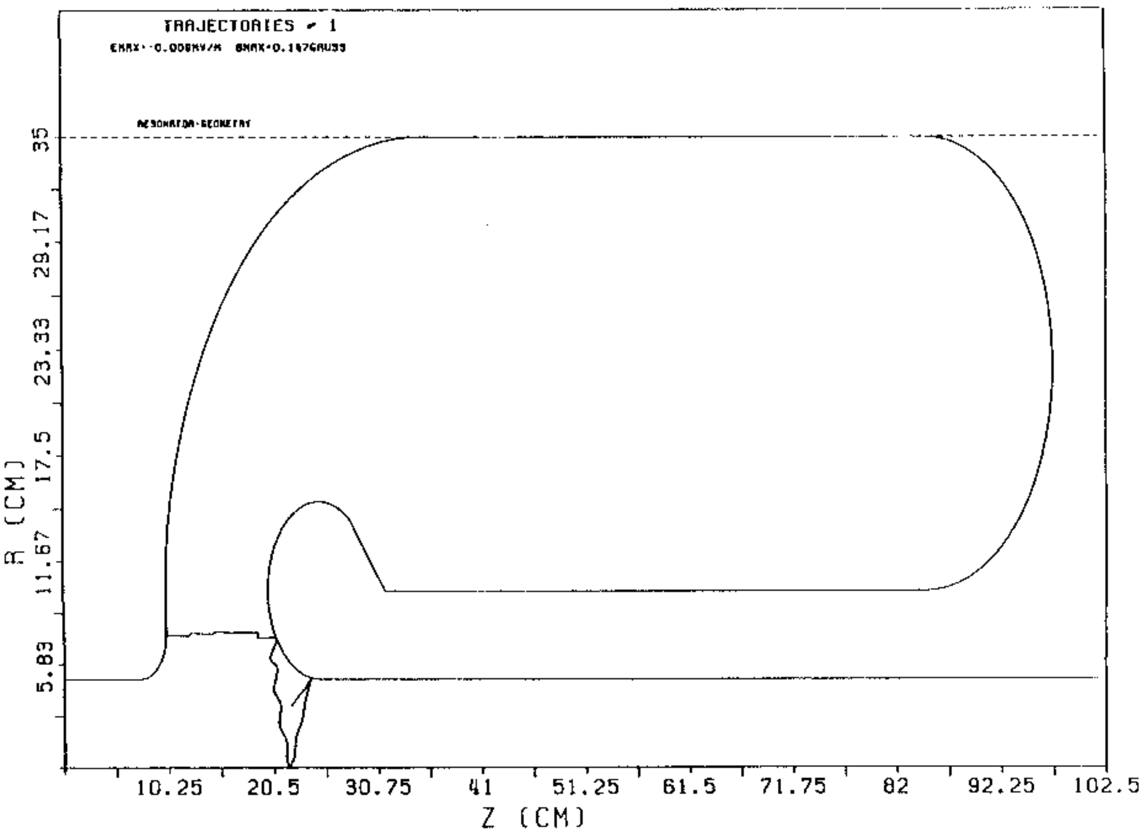

Fig. 3 - The electron starts the trajectory at r = 7.5 cm on the external curved wall, with the RF phase -20°, gap voltage 500 V and initial angle 90°.

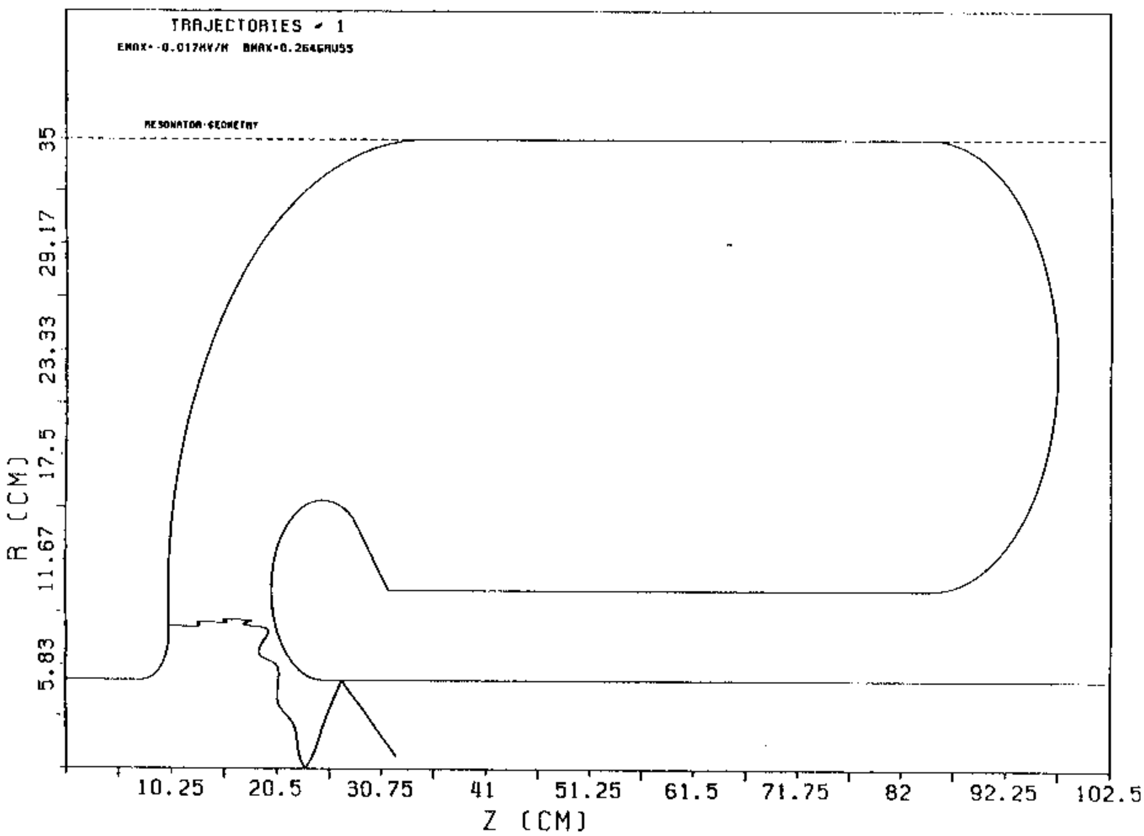

Fig. 4 - The electron starts the trajectory at r = 8 cm on the external curved wall, with RF phase -20°, gap voltage 900 V and initial angle 90°.

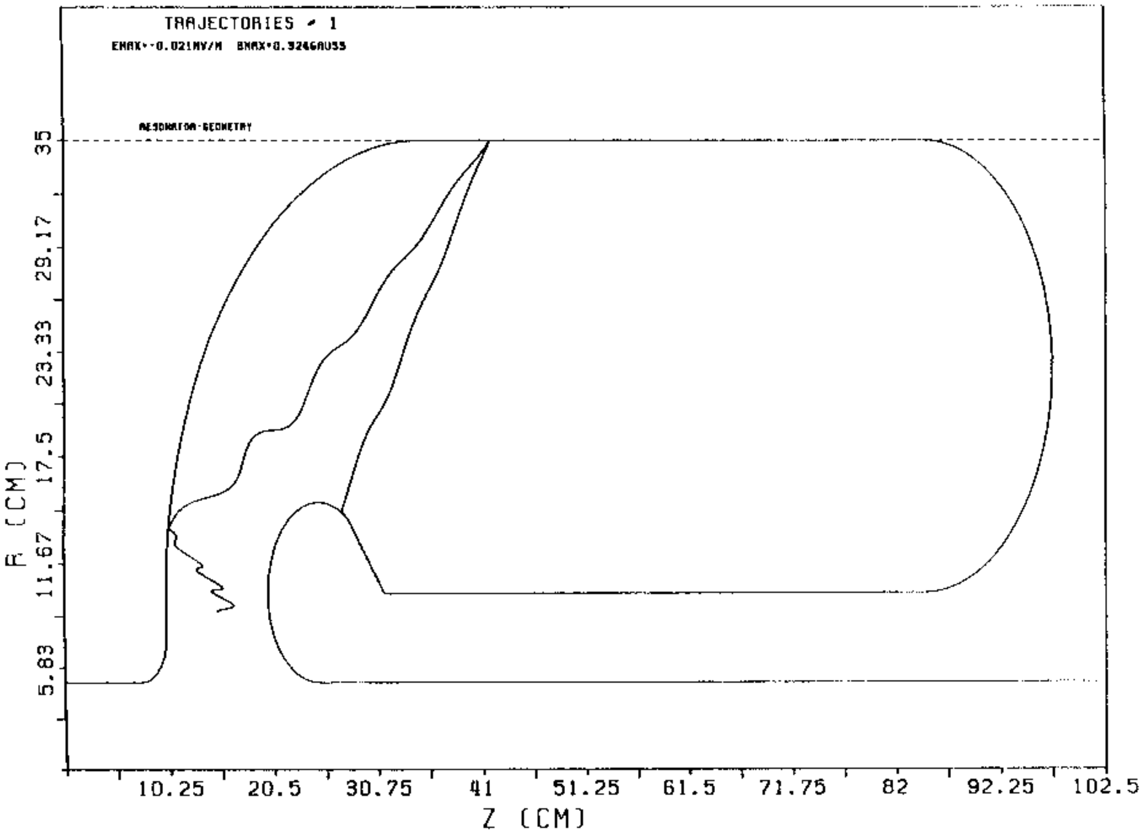

Fig. 5 - The electron starts the trajectory at r = 9 cm and z = 15 cm (the central gap), with RF phase 0°, gap voltage 1 kV and initial angle 180° (towards inside the cavity).

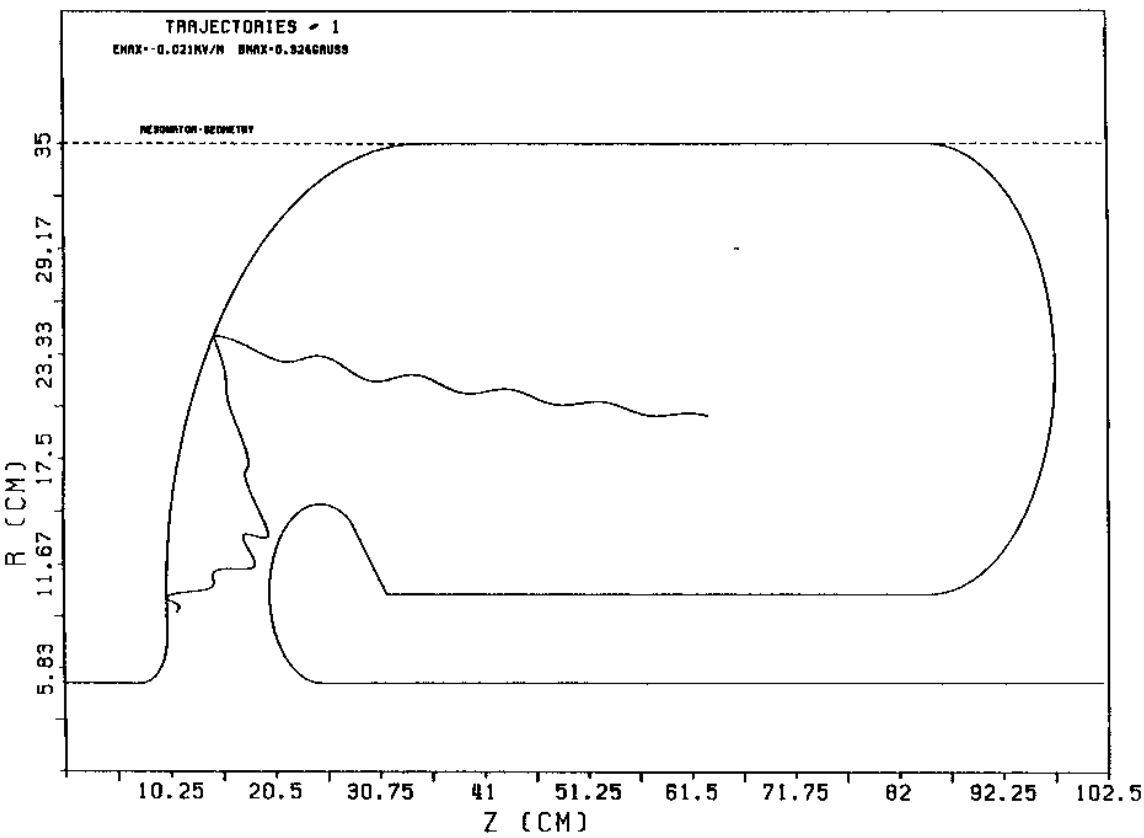

Fig. 6 - The electron starts the trajectory at r = 9 cm and z = 11 cm (inside the gap), with RF phase 45°, gap voltage 1 kV and initial angle 180°.

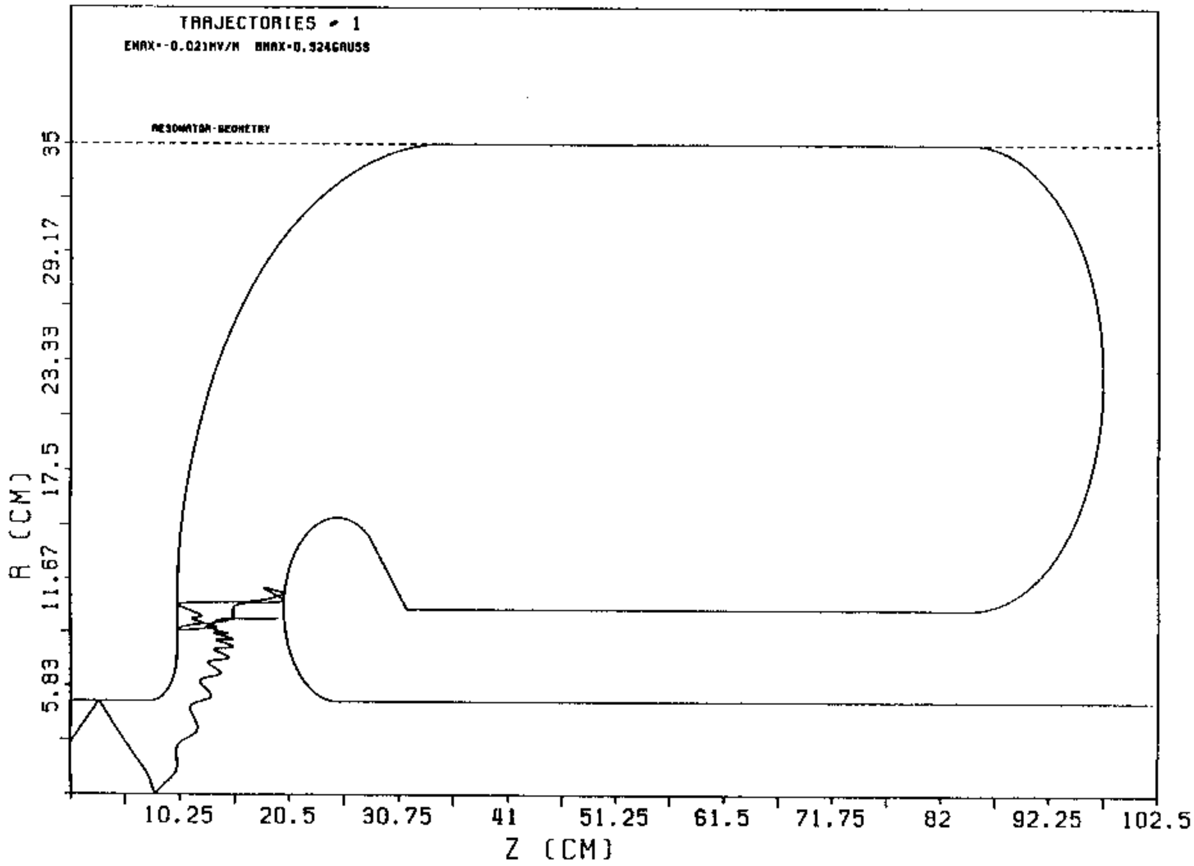

Fig. 7 - The electron starts the trajectory at r = 9.5 cm and z = 19 cm (near the electrode), with RF phase 30°, gap voltage 1 kV and initial angle -90°.

The simulations were repeated following the same procedure, but working on the internal areas of the cavity resonator, for low gap voltages. We found no meaningful regions for resonant discharges, due to the presence of the magnetic field, which drifts the trajectories, as expected.

In general, as the value of the gap voltage increases, the electron, due to effect of the bending magnetic force, tends to drift to the external rounded surfaces areas of the cavity, losing the kinematic conditions for the secondaries production.

In order to show roughly this behaviour, we plotted on the same picture many trajectories starting from the same initial point, for different values of the gap voltage, same RF phases and initial slopes.

In Figs. 8 and 9 the pictures show clearly that the trajectories propagate to the external curved regions in the cavity and do not show peculiar concentrated spots. These results were confirmed by the detailed simulations, as well.

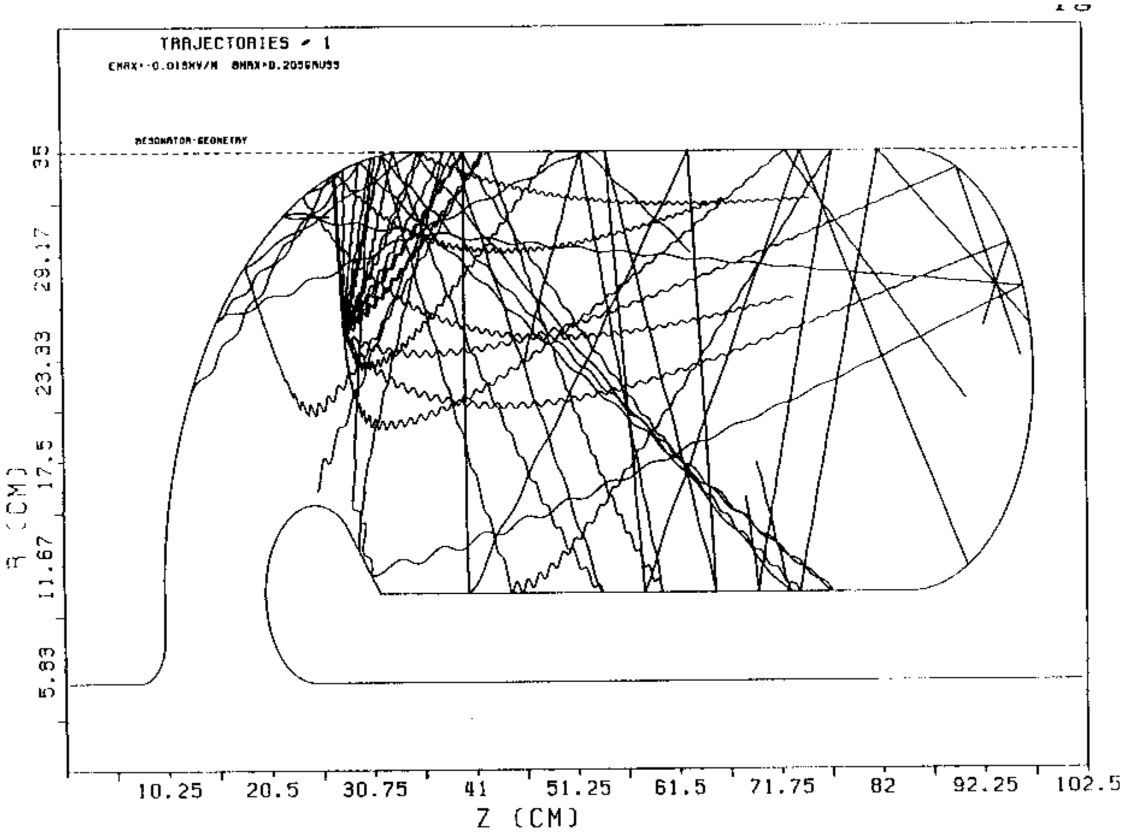

Fig. 8 - The electron starts the trajectories at r = 25 cm and z = 28 cm (in the central part of the gap), varying the RF phases from 0^o to 180^o in steps of 45^o, initial angles from -90^o to 90^o in steps of 10^o, with the gap voltage of 700 V.

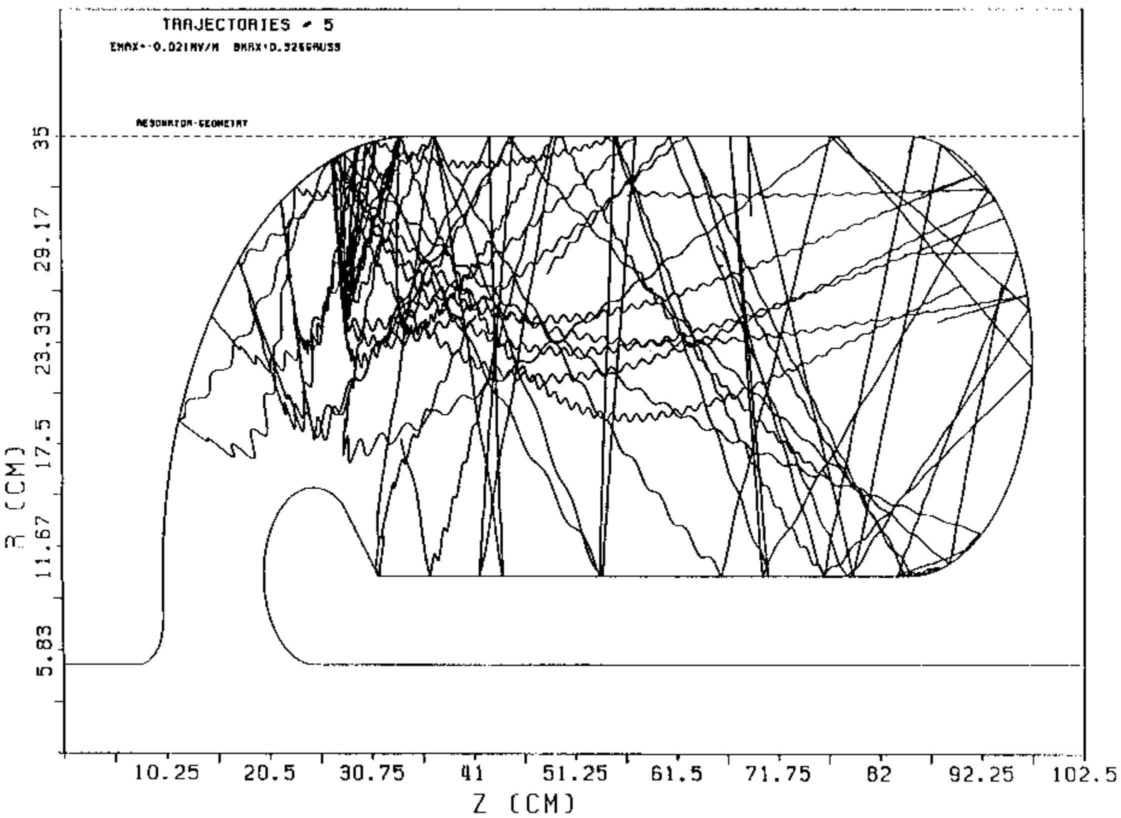

Fig. 9 - The electron starts the trajectories at r = 25 cm and z = 28 cm (in the central part of the gap), varying the RF phases from 0^o to 180^o in steps of 45^o, initial angles from -90^o to 90^o in steps of 10^o, with gap voltage of 1.1 kV.

b) <u>One point multipactoring</u>.

Usually one point multipactoring takes place at high values of the em field and is mainly determined by the magnetic field. Working on the TM_{010} mode, it can occur in the regions of the cavity where the RF fields are $E = (0,E_r,E_z)$, $H = H\phi$ with $E_r >> E_z$. In those areas, the MP levels are proportional to the cyclotron frequency corresponding to a multiple of the RF frequency and the impact energies to the square of the surface field E_r [11].

In order to study the behaviour of the initial external surface shape of the cavity resonator shown in Fig. 1, we carried out the simulations taking into account flat and curved configurations, leaving all the other parts unchanged.

In the case of flat surface, the results showed higher probabilities of resonant discharges, between 10^3 - 10^6, with twenty thousand RF cycles, up to 40 impacts in the areas near the high corner of the investigated surface, corresponding to gap voltages in the 8 kV - 16 kV range and to the order of the levels n = 5,6,7,8. Moreover, in many other simulations, the electron is confined in different surfaces positions for a certain time producing a great number of secondary electrons. In Fig. 10 the high concentration of the trajectories in the corner region is clearly shown.

Figure 10a shows the confinement of the trajectories in the corner area, which produces higher probability of secondaries(of the order 10^4 -10^5) due to the processes related to impact energies in the range of the secondary emission, back-scattered emission, and impact angles on the surfaces [7,8].

We changed the curvature radius of the corner up to 5 cm, but the behaviour in those region was similar as the previous results. In order to avoid these highly probable resonant discharges it was necessary to increase as much as possible the curvature at the corner place. This choice was in accordance with that of other people, which worked on this subject, explained the phenomenological model, proposed curved shape [11,12,13]. Therefore we proposed a curved and rounded surface shape, respectively, at the front and back end of the resonator as shown in Fig. 1. The front end curved part should avoid the two points multipactoring condition especially for some value of the low level field or of some order of one point multipactoring, the rounded end part should avoid discharges at high field values as explained and tested [8].

In the central part the electrons tend to drift to the external parts of the cavity for the effect of the bending magnetic forces losing the kinematic and physical conditions for the secondaries production. We carried out careful simulations to confirm further our assumptions. We found no resonant discharges for any value of the starting coordinates, gap voltage, RF phase and initial angle. We show some typical pictures about the behaviour of the structure.

In Fig. 11 the electron oscillates at the center of the rounded part until it finds the wrong phase of the field, losing the trajectory stability. Afterwards it is pushed away producing a series of oscillations between the internal coaxial and external surface for the effect of the transverse forces, electric an magnetic, and on the same surfaces up and down, mainly, for the bending magnetic force;

In Fig. 12 the electron oscillates at the center of the rounded part increasing the impact energies. When the electric field normal to surface changes sign, due to the zero crossing at the symmetry plane, the electron decreases strongly the impact energies, leading to a secondary production yield less of the unity.

In Fig. 13 the electron oscillates between the internal surfaces until it loses the kinematic condition for production of the secondaries.

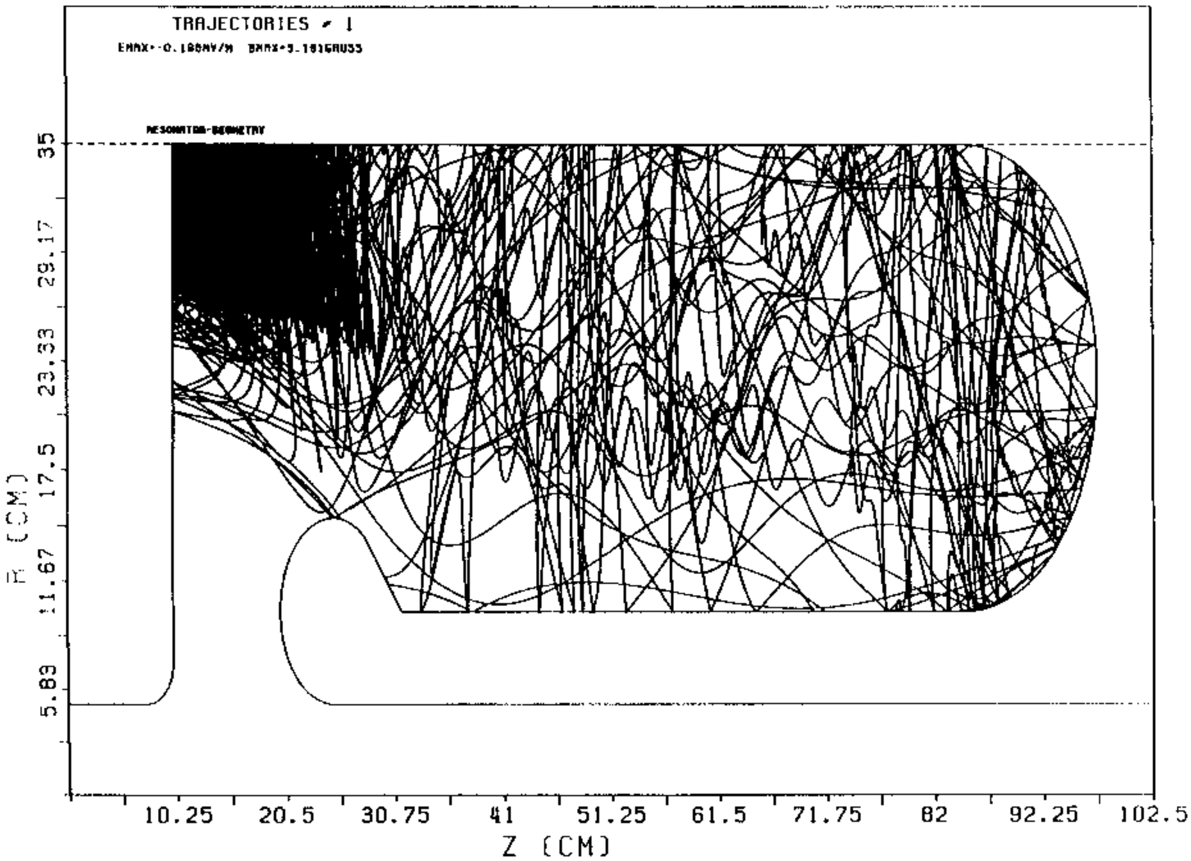

Fig. 10 - Trajectories with gap voltage of 11 kV, the same coordinates of the initial point, r = 34.5 cm and z = 10.5, some RF phases, some starting angle.

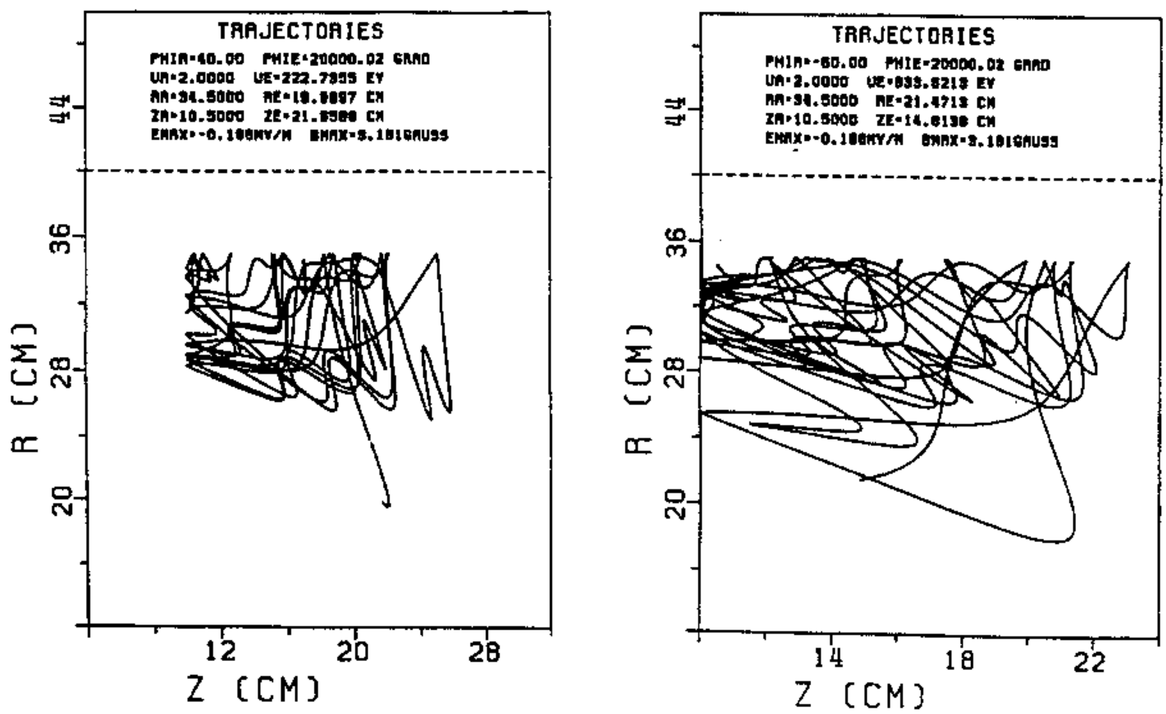

Fig. 10a - Two trajectories having the same coordinates of the initial point, same gap voltage, RF phases 40 and -60 degree, starting angle 45 and 0, as in Fig. 9.

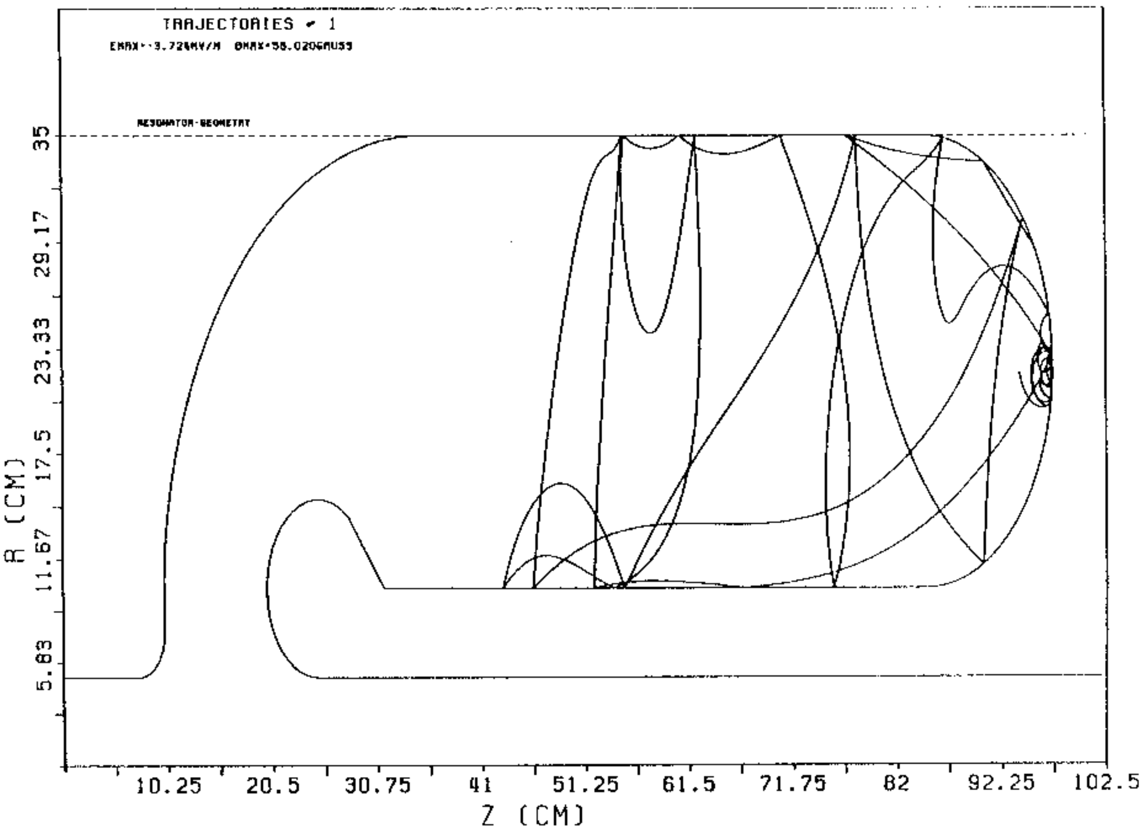

Fig. 11 - The electron starts the trajectory at r = 23 cm and z = 94 cm, with RF phase 0°, gap voltage 190 kV and initial angle 90°.

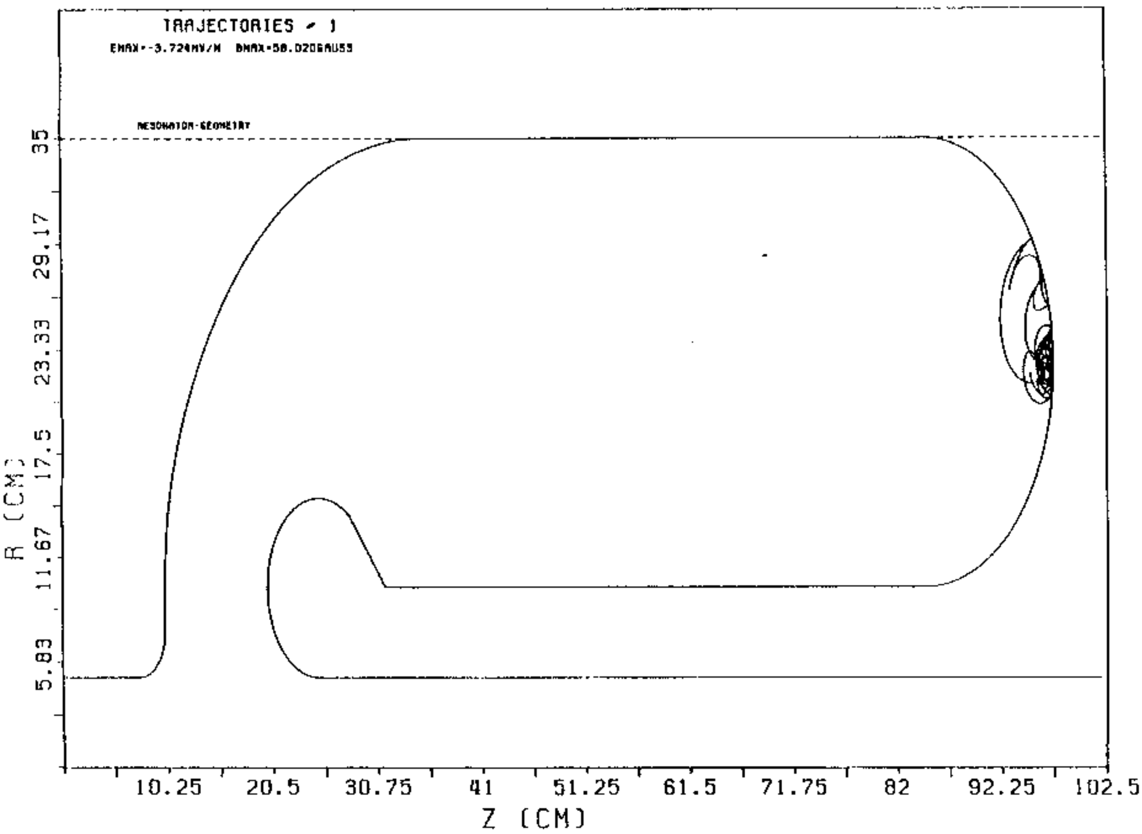

Fig. 12 - The electron starts the trajectory at r = 22 cm and z = 95 cm, with RF phase 0°, gap voltage 190 kV and initial angle 90°.

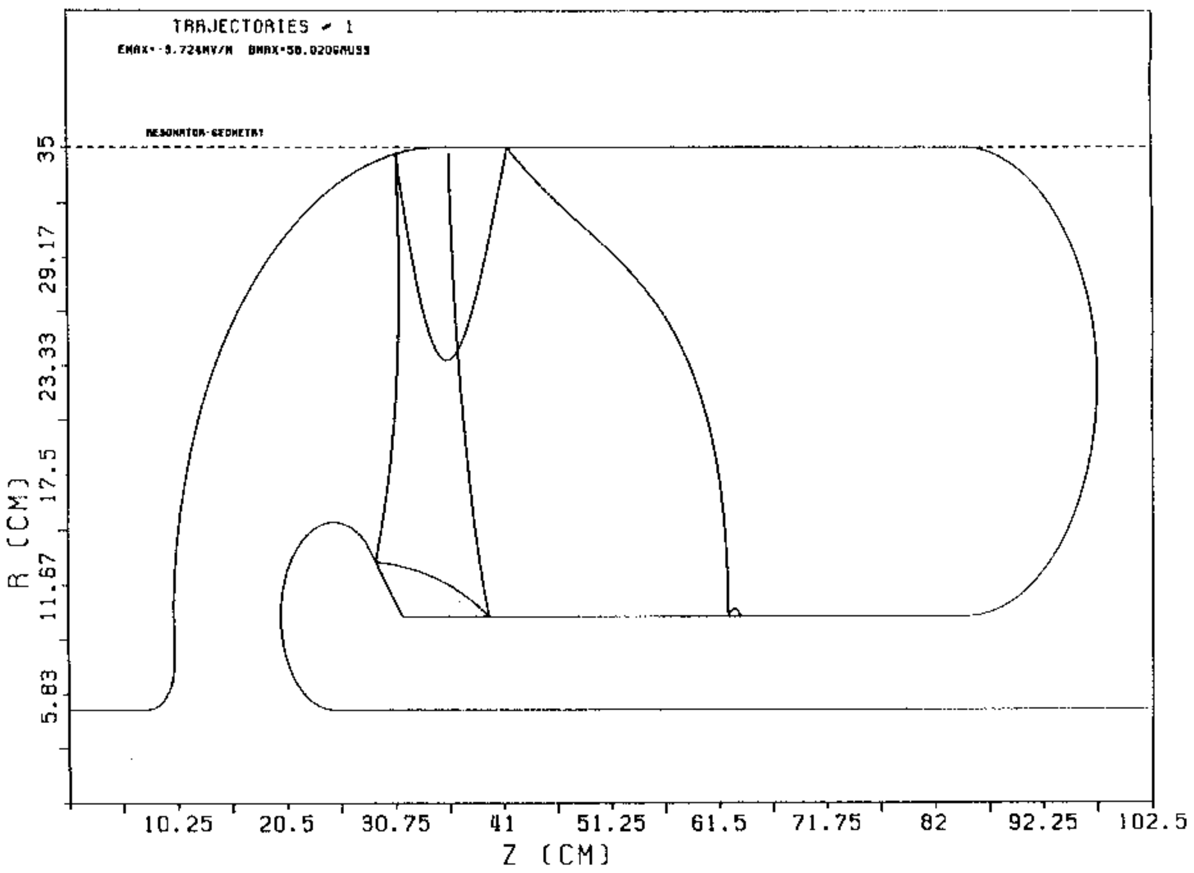

Fig. 13 - The electron starts the trajectory at r = 34.7 cm and z = 36 cm, with RF phase 0°, gap voltage 190 kV and initial angle 0°.

Conclusions

A detailed study of the resonant electron discharge conditions has been carried out on the DAΦNE accumulator cavity with the goal of designing a fully multipactoring-free resonator.

The power tests, performed with a cw tetrode tube amplifier, did not evidence any MP discharges at all the RF input levels up to 20 kW (i.e. 200 KVp).

No RF pulsing is needed to turn the cavity on but the power can be increased very easily in cw up to the desired value: just one full day of RF conditioning was required to feed the nominal power.

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