DAΦNE TECHNICAL NOTE

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Note: **RF-4**

RF CAVITY DESIGN FOR THE DAΦNE ACCUMULATOR

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INTRODUCTION

This note deals with the electromagnetic (e.m.) design of the accumulator RF cavity. We will discuss the criteria of the choice of the resonator geometry, carefully directed to avoid the resonant electron loading (multipacting), and the possibility of damping some of the most troublesome parasitic modes to keep at a minimum the beam cavity interaction.

The main features of the Radiofrequency System (RFS) for the DAΦNE accumulator can be found in Ref. 1. The RF frequency is exactly one fifth of the main ring one to synchronize the injection of any desired bucket of DAΦNE[2] while a gap voltage of 200 kV is required to have large energy acceptance.

CAVITY DESIGN CRITERIA

Given the low operating frequency of about 73 MHz, a reentrant coaxial resonator is more suitable to reduce the cavity size. We have chosen a single ended structure that, in spite of a lower shunt impedance compared with a double ended cavity, is more compact and therefore makes mechanics and vacuum simpler and less expensive. The cavity will be made of copper which has better electrical and thermal conductivity to reduce the RF losses and keep the cooling easier.

Multipacting (MP) is a well known process which can plague the operation of the accelerating cavities in high vacuum conditions. The process can be inhibited by coating the internal cavity surfaces with elements (Ti) or compounds (TiN) having a secondary yield coefficient lower than unity or by properly shaping the cavity to overcome the problem. Encouraged by the successful results obtained in designing and operating the 51 MHz Adone cavity[3], we have designed the accumulator cavity in order to reduce the probability of resonant electron emission from the internal surfaces; this work was accomplished with the support of the computer code Newtraj[4] which simulates the resonant discharge phenomena in resonators and predicts areas of strong emission probability under certain conditions of the cavity e.m. fields.

Fig. 1 shows the cavity shape chosen after careful investigations. The curved profile given to the external resonator surfaces reduces the probability of "one point MP" in those regions and the rounded shape of the internal electrode should avoid the "two points MP" which usually takes place there at low RF voltages. Newtraj code simulations confirm the previous considerations but predict a possible MP level in correspondence of the magnetic field region for a gap accelerating voltage of about 190 kV. Fig. 2 shows a code output with a resonant trajectory, at 190 kV, found by the code. RF conditioning has however proved to be often successful in such cases. Furthermore, the tuner and main coupler break the symmetry of the structure keeping MP less probable. In any case, the possibility of coating the interested area must be foreseen.

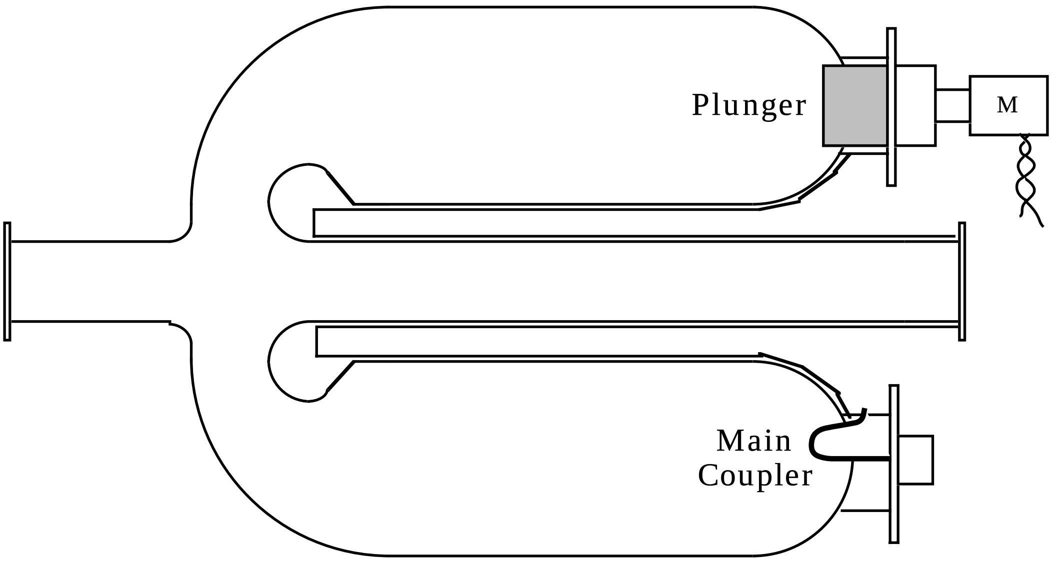

Fig.1 - Profile of the Accumulator Cavity.

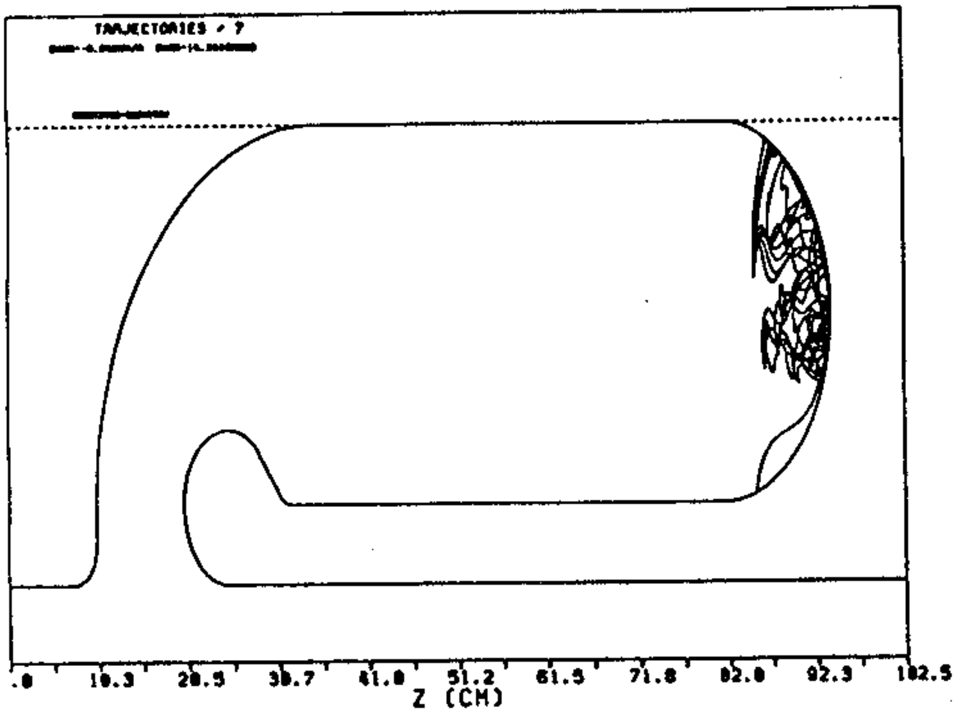

Fig. 2 - Resonant trajectory for V_c ≈ 190 kV (cavity not to scale).

The main RF cavity parameters, as computed by the Oscar2D code[5], are listed in Table I.

TABLE I

Resonant Frequency (without tuning)	F_o	= 73.510 MHz
Harmonic number	n	= 8
Unloaded Quality Factor	Q_o	= 22,000
Transit Time Factor	T	= 0.99
Effective Shunt Impedance (RT^2)	R_c	=1.7MΩ ($V^2/2P$)
Max Cavity Gap Voltage	V_c	= 200 kVp
Max Surface Electric Field (@ 200 kV_p) (see point A in fig.1)	E_s	= 3.9 MV/m
Max Axial Electric Field (@ 200 kV_p)	E_a	= 1.48 MV/m
Cavity Length	L	= 900 mm
Cavity Diameter	D	= 700 mm
Cavity Gap	g	= 100 mm
Beam synchrotron power (*)	P_b	≈ 1 kW

(*) The parasitic losses due to the changes of the vacuum chamber cross section (i.e. kickers, bellows, etc) have still to be carefully calculated but a rough estimate gives a value of about 20 keV[6] that would increases to 3.6 kW the total beam power. Here the factor β has to be kept to 1.2. The RF voltage should not require to be increased.

In practice, a reduction of about 30% in Q_0 and R_c has to be considered in the real cavity, mainly due to the presence of tuner, main coupler, RF probes and to the surface heating when the resonator is RF powered.

Then we estimate:

Power wasted in the cavity walls (with $R_c \approx 1.2$ MΩ)	P_c	$= 16.5$ kW (@ 200 kV_p)
Cavity-generator coupling	β	≈ 1
3 dB RFS bandwidth	B_w	≈ 10 kHz

The value of the maximum surface electric field reported in Table I, is well below those given in Ref. 7 as the experimental discharge fields due to surface electron emission in ultra high vacuum resonators. In our case we have a security margin of about 3. Anyway great care will be required in surface finishing and RF conditioning.

CAVITY TUNING

The cavity resonant frequency will be fairly sensitive to temperature, so it is necessary to provide for tuning to operate at different temperature conditions. Moderate detuning will also be necessary to provide Robinson stability and to compensate for the beam loading though it is small, being the beam power a few hundreds of watts.

In the proposed cavity the best tuning method is to introduce a cylindrical plunger in a region of intense magnetic field as illustrated in Fig. 1.

The change in resonant frequency due to a small metal plunger in a region of only magnetic field is given by:

$$\frac{\delta F}{F_0} = \frac{\mu_0 H^2}{4U} \cdot (\delta v)$$

where ∂v is the perturbing volume, U is the energy stored in the cavity and H is the peak value of the magnetic field.

For our cavity, Oscar2D code gives an average magnetic field of about 2108 A/m in that region and a total stored energy U = 0.546 joules at 200 kV_p gap voltage; therefore we get :

$$\frac{\delta F}{F_0} = 2.56 \cdot (\delta v) \qquad \text{with } (\delta v) \text{ in } m^3$$

The effect of the temperature variation in the resonant frequency of a coaxial resonator is roughly given by:

$$\frac{\delta F}{F_0} = \frac{1}{2}\left(\frac{\delta L}{L} - \frac{\delta L}{g}\right) = \frac{1}{2} c\, L \delta T \left(\frac{1}{L} - \frac{1}{g}\right)$$

$$with \quad c = \frac{1}{L}\frac{\delta L}{\delta T} = 1.6 \cdot 10^{-5} per \quad ℃ \quad (copper\ thermal\ expansion coefficient)$$

L = 0.9 m cavity length

g = 0.1 m gap length

∂T = temperature variation

Considering a cavity temperature variation of $5^{o}C$ when the cavity is turned on and before the cooling system compensation, we get:

$$\partial F = -23 \text{ kHz}$$

This frequency shift can be compensated by inserting a plunger into the magnetic field region of the resonator for a volume of $1.22{\cdot}10^{-4}$ m^3. The tuner available in our laboratory, whose diameter is 116 mm, should then protrude 1.2 cm into the cavity and therefore it can be used.

Also, the detuning needed to provide Robinson stability and compensate for the moderate beam loading is a few kHz's and the tuning correction would be small:

$$(\delta v) = \frac{1}{2.56} \cdot \left(\frac{-5kHz}{73.65\,MHz}\right) = -2.65 \cdot 10^{-5} m^3$$

to achieve Robinson stability at the bandwidth limit, and:

$$\frac{\delta F}{F_0} = -\frac{P_b}{2Q_0 P_C} \tan\left(\frac{\pi}{2} - \Phi_S\right)$$

$$\delta F = -F_0 \cdot \frac{1kW}{2 \cdot 15{,}400 \cdot 16.5kW} \cdot \tan\left(88^0\right) \approx 5.3kHz$$

$$(\delta v) = 2.8 \cdot 10^{-5} m^3$$

to compensate for the beam loading. Φ_S is the beam synchronous phase.

In conclusion, provided efficient cooling is applied, the required frequency correction should be very small and the perturbation of the cavity fields, due to the plunger insertion, should be negligible.

PARASITIC MODE DAMPING

Due to the low frequency of the fundamental accelerating mode, we cannot provide broadband damping of high order cavity modes (HOM) with waveguides which would have too large size.

On the other hand, being the accumulator a single bunch machine, the requirements of HOM damping are less demanding respect to the main ring cavities. Nevertheless, we will investigate the possibility of damping the most troublesome HOM's with dedicated loops or antennas located in correspondence of a peak of either electric or magnetic field.

In table II we report a list of monopole and dipole modes till 1 GHz calculated with the computer code Urmel. In bold, we put in evidence the modes with higher longitudinal impedance (i.e. r/Q). Since the particular cavity shape, only the fundamental mode can be classified as used in technical literature.

TABLE II

Monopoles	Freq. (MHz)	$Q_o \cdot 10^3$	r/Q (Ω) (*)	
TM-010	73.50	22	80	accelerating mode
TM0-MM-2	**245**	**36**	**14.3**	
TM0-MM-3	**426**	**47**	**9.8**	
TM0-MM-4	**577**	**49**	**10.3**	
TM0-MM-5	609	43	0.6	
TM0-MM-6	677	44	1.3	
TM0-MM-7	**725**	**54**	**7.8**	
TM0-MM-8	785	44	2.7	
TM0-MM-9	885	62	1.3	
TM0-MM-10	927	45	0.3	
TM0-MM-11	**1023**	**60**	**5.3**	
TM0-MM-12	1099	51	0.1	
Dipoles	Freq. (MHz)	$Q_o \cdot 10^3$	r/Q' (Ω) (**)	
1-MM-1	**276**	**47**	**20.6**	
1-MM-2	**375**	**49**	**41.6**	
1-MM-3	**510**	**57**	**22.3**	
1-MM-4	644	53	2.9	
1-MM-5	**660**	**59**	**8.2**	
1-MM-6	710	56	0.3	
1-MM-7	727	57	0.2	
1-MM-8	786	62	1.8	
1-MM-9	805	72	0.9	
1-MM-10	834	51	1.0	
1-MM-11	918	90	0.0	
1-MM-12	939	71	0.0	

(*) $$\left(\frac{r}{Q}\right)_n = \frac{1}{2P_nQ_n}\left|\int_0^L E_{nz}(z, r=0)\, e^{j\frac{\omega}{v}z} dz\right|^2 \quad [\Omega]$$

(**) $$\left(\frac{r}{Q}\right)'_n = \frac{1}{(k_n r)^2} \cdot \frac{1}{2P_nQ_n}\left|\int_0^L E_{nz}(z, r)\, e^{j\frac{\omega}{v}z} dz\right|^2 \quad [\Omega]$$

We have also run TBCI code to calculate the loss factor k of the accumulator cavity. The code gives:

$$k \approx 0.14 \text{ V/pC}$$

corresponding to a total loss of about 2 kV for a single bunch of $9 \cdot 10^{10}$ particles.

Figure 3 presents the electric field pattern of the accelerating mode whereas Figures 4 through 8 show the field patterns of some high r/Q parasitic modes. The regions where the electric or magnetic field is maximum or vanishing are marked with an asterisk; in those positions we can put an antenna or a loop to have mode damping. These tests will be carried out on a copper sheet cavity prototype.

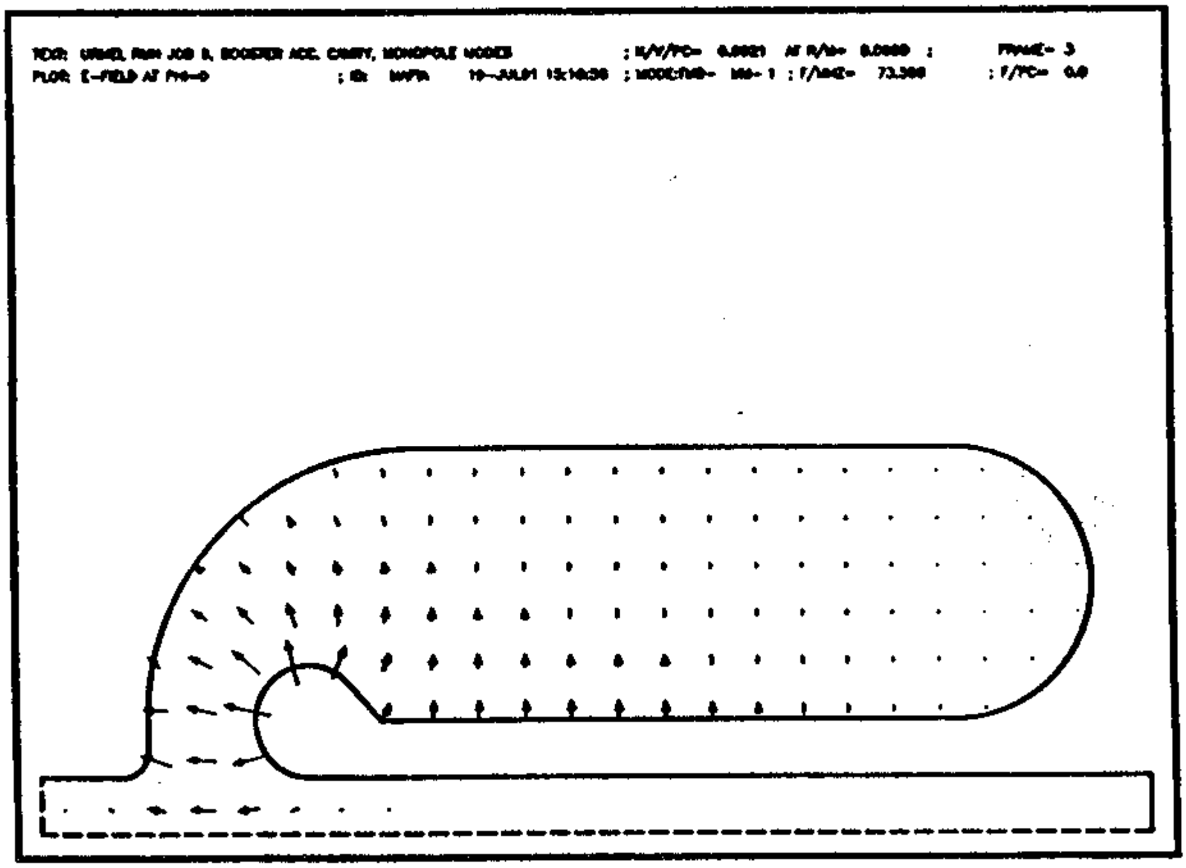

Fig. 3 - Accelerating mode electric field pattern.

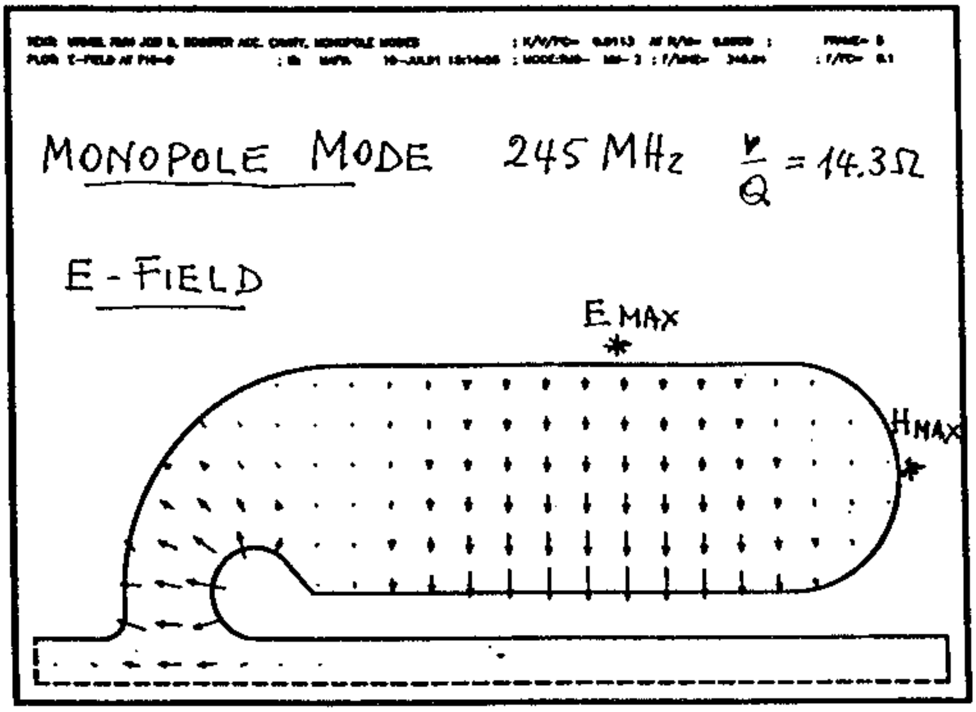
MONOPOLE MODE
245 MHz
r/Q = 14.3Ω
E-FIELD
E MAX
HMAX

Fig. 4

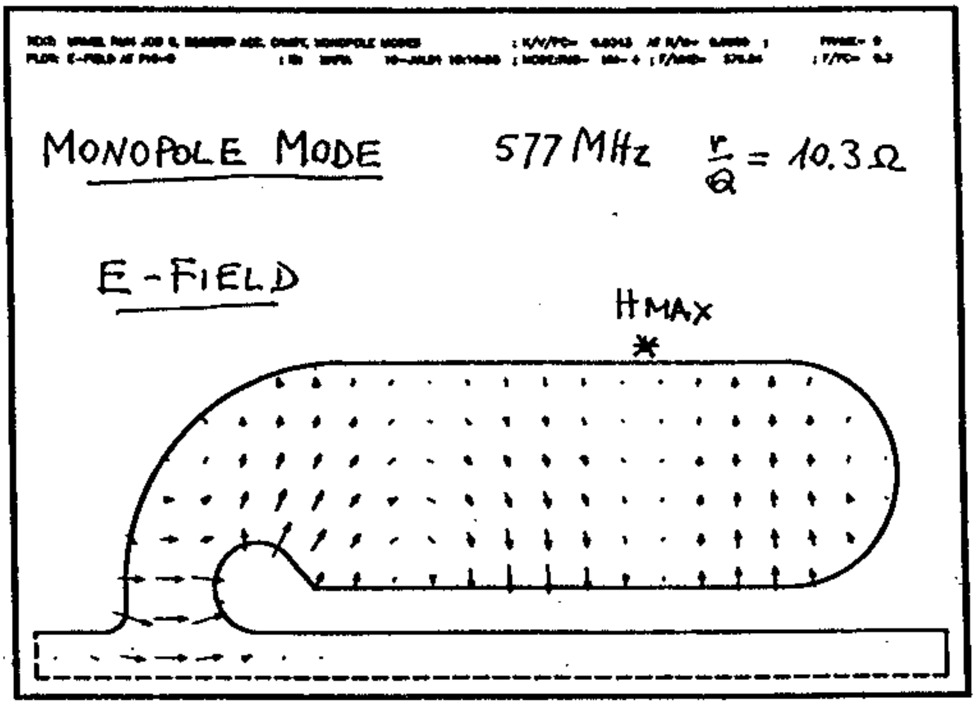
MONOPOLE MODE
577 MHz
r/Q = 10.3Ω
E-FIELD
HMAX

Fig. 5

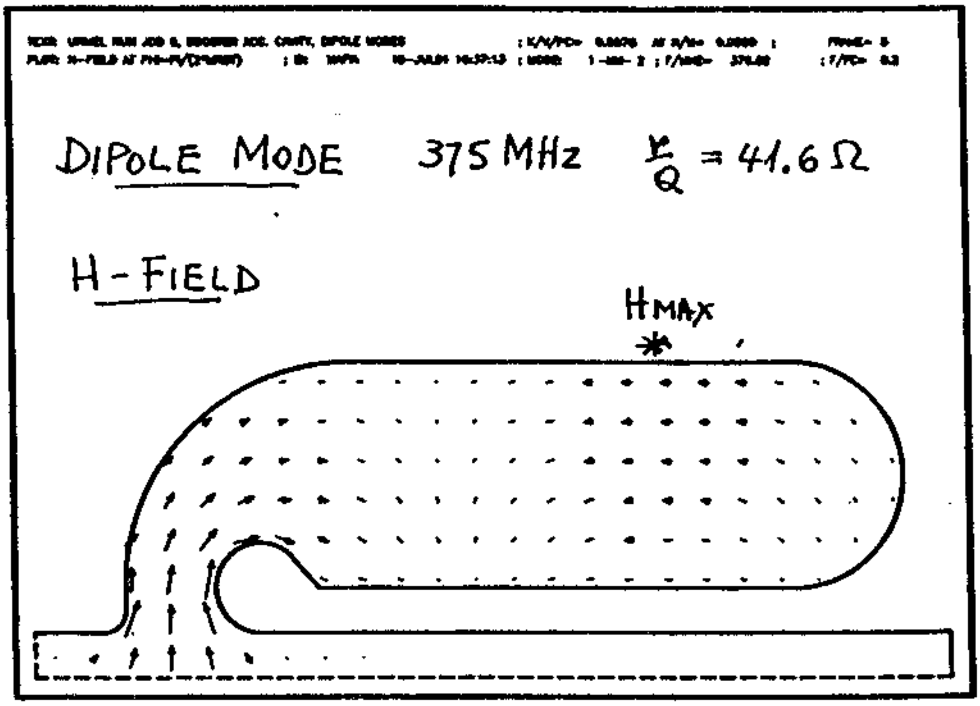
DIPOLE MODE
375 MHz
r/Q = 41.6 Ω
H-FIELD
HMAX

Fig. 6

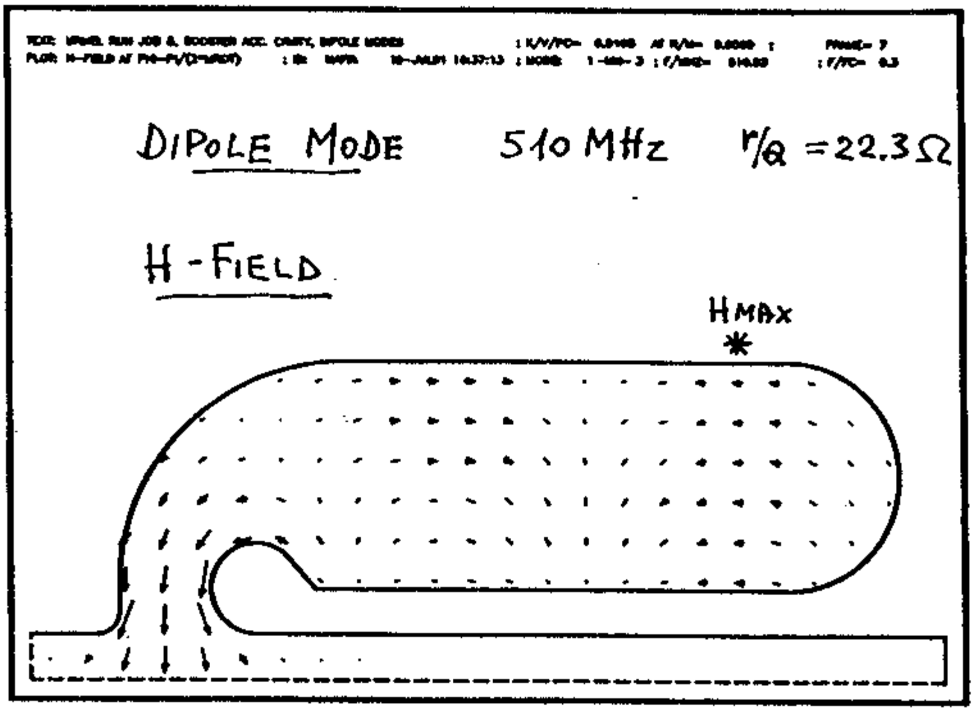
DIPOLE MODE
510 MHz
r/Q = 22.3 Ω
H-FIELD
HMAX

Fig. 7

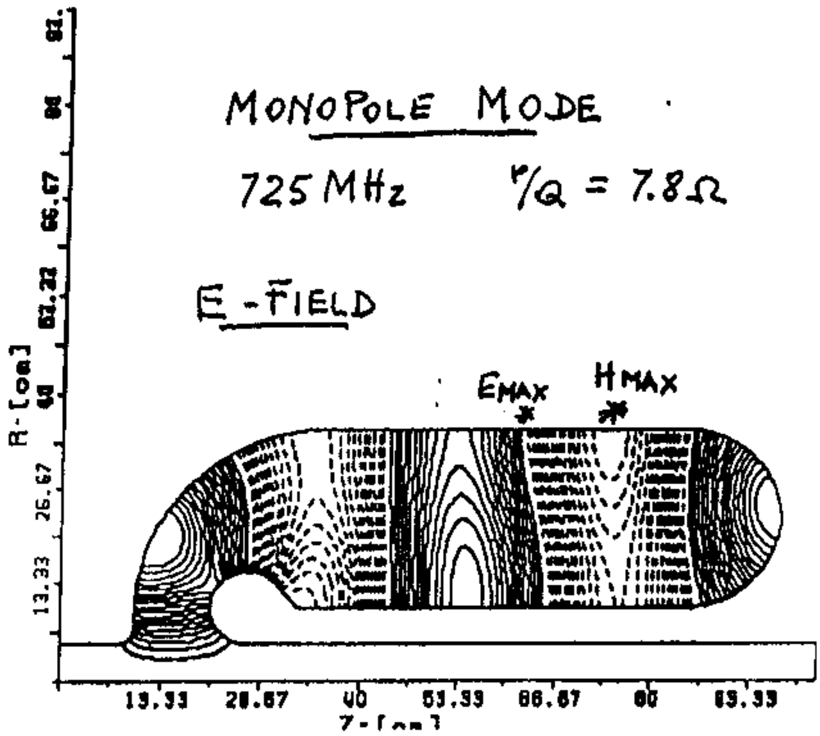

Fig. 8

MAIN COUPLING

A magnetic coupling loop, sketched in Fig.1, will provide the cavity feeding from the RF amplifier.

The coupling ratio between cavity and input RF line, neglecting the beam loading, is given by:

$$\approx \left(\frac{R_C}{Z_0}\right)^{\frac{1}{2}} = \left(\frac{\mathbf{1.2}\,M\Omega}{\mathbf{50}\,\Omega}\right)^{\frac{1}{2}} = \mathbf{155}$$

Then, the projection S of the loop surface on a cavity longitudinal section is approximately:

$$= \frac{V_C}{\omega_0 \cdot \mu_0 H_s \cdot N} = \frac{\mathbf{200}\ kV}{\omega_0 \mu_0 \cdot \mathbf{2108}\,\frac{A}{m} \cdot \mathbf{155}} \approx \mathbf{10.5}\,cm^{\mathbf{2}}$$

where B_S is the average magnetic induction at the loop location in Weber/m^2.

Therefore, with a 20 cm^2 rotating loop, the generator-cavity matching should be easily achieved.

ACKNOWLEDGMENTS

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