BNL-101448-2014-TECH
RHIC/RF- 29;BNL-101448-2013-IR

Frequency budget for the PoP cavity

A. Ratti

July 1995

Collider Accelerator Department
Brookhaven National Laboratory

U.S. Department of Energy
USDOE Office of Science (SC)

DISCLAIMER

RHIC/RF-29

RHIC Project
BROOKHAVEN NATIONAL LABORATORY

RHIC/RF Technical Note No. 29

FREQUENCY BUDGET FOR THE PoP CAVITY

A. Ratti

July 1995

Frequency budget for the PoP cavity

Alessandro Ratti

1.0 Introduction

The computer code superfish has been used in conjunction with measurements, to obtain a frequency budget for the PoP cavity. The goal of the exercise is to have a valid prediction of the natural resonant frequency of the final accelerating cavity to be build for RHIC. An estimation of the frequency shift due to the power coupling window is also included and compared with measurements.

2.0 Cavity measurements.

Using small probes to minimize the loading from the 50 Ω ports of the network analyzer, S parameters measurements were done to find the cavity resonance in various conditions. Particular care was spend on the power window, since it represents a substantial reentrance in the cavity and therefore effects the resonance in a non negligible way. Fig. 1 shows the cavity resonant frequencies (in reflection, S11) for the following cases:

a. Cavity with Power Amplifier	f = 26.617 MHz
b. Cavity w/o Power Amplifier	f = 26.622 MHz
c. Cavity w/o Power Window	f = 26.611 MHz
d. Cavity with Window Closed	f = 26.628 MHz

Fig. 2 shows the case when the reentrant part of the window was closed to conserve the circular symmetry (the same configuration that is calculated by superfish). In this case, the measured resonant frequency is 26.641 MHz. In Fig 3 is the reflected cavity shunt impedance as it is seen at the tube anode in the power amplifier.

The power coupling loop was subsequently increased in size and all the above measurements repeated. From the results shown in Fig. 4 the resonant frequencies are:

a. Cavity with P.A. @ P.A.	f = 26.632 MHz
b. Cavity w/o Power Amplifier	f = 26.000 MHz
c. Cavity with P. A. @ cavity	f = 26.624 MHz

Fig. 5 shows the reflected cavity shunt impedance as it is seen at the tube anode in the power amplifier.

3.0 Effect of the diagnostic ports

The frequency shift due to the many (twenty-six 4-1/2" Conflat and ten 2-3/4" Conflat) small ports are not a particular concern, since they are small and will not be present in the final cavity (the only ports that might be in the cavity are those used for mode dampers of fixed tuners where the effect of the device itself is much more relevant then the one of the port itself). Nevertheless it is possible to estimate the frequency shift induced by the ports with a very simple, rough approximation. Since all the ports are in the external tank, where the electric field is not very strong, they will directly effect the cavity inductance, by increasing the effective path length, and therefore change the cavity resonance.

The total cavity volume can be estimated to be $V_t = 0.893\ m^3$. The 4-1/2" Conflat flanges create an extra volume of $7.917\ 10^{-5}\ m^3$ each, or $2.0584\ m^3$ total, whereas the smaller 2-3/4" are responsible for $1.924\ 10^{-5}\ m^3$ each and $0.1924\ 10^{-3}\ m^3$ total. From this, knowing that:

$$\frac{df}{f} = -\frac{1}{2} \times \frac{dV}{V}$$

it is possible to estimate the frequency shift $\Delta f = -\ 33.438$ kHz. This means that the resonant frequency of the PoP cavity is expected to be 33.438 kHz below the theoretical computed value. Caution: this is an upper estimate of the frequency shift. In reality the ports are at various locations in the cavity tank where the magnetic field can vary by a factor of 3. The effects of the ports are consequently not the same, whereas this method assumes that they all effect the cavity inductance at its most sensitive place. A more accurate calculation can be used to have a better estimate of the effect, by considering that the frequency shift varies with the square of the electric and magnetic fields affected by each port.

4.0 Computer model and loading from the power window

Table 1 is the input file for Superfish that reflects the configuration of the PoP cavity being tested in the rf test stand in building 1005. The very fine meshing of 5 mm was used to ensure the maximum possible accuracy in the frequency result. The fundamental frequency is found to be 26.557 MHz, to be compared with the measured value of 26.641 MHz.

```
$_POP4CMA.DAT NO DISK, GAP=3.96CM - AR's Oct 6 1994
$reg nreg=2, dx=0.5, xmax=215., ymax=46.0, npoint=29 $
$po x=0.0, y=0.0 $
```

```
$po x=0.0, y=8.91 $
$po x=12.81, y=8.91 $
$po nt=2, x0=14.81, y0=8.91, r=2.0, theta=270. $
$po nt=2, x0=14.81, y0=8.91, r=2.0, theta=0. $
$po nt=2, x0=14.81, y0=8.91, r=2.0, theta=90. $
$po x=11.53, y=10.91 $
$po x=11.53, y=14.91 $
$po x=51.75, y=14.91 $
$po nt=2, x0=51.75, y0=16.91, r=2.0, theta=0. $
$po nt=2, x0=51.75, y0=16.91, r=2.0, theta=90. $
$po x=22.00, y=18.91 $
$po x=22.00, y=42.0 $
$po x=55.00, y=42.0 $
$po x=212.00, y=42.0 $
$po x=212.00, y=25.92 $
$po x=173.00, y=25.92 $
$po x=173.00, y=26.35 $
$po x=170.25, y=26.35 $
$po nt=2, x0=170.25, y0=26.10, r=0.25, theta=180. $
$po x=170.0, y=14.91 $
$po nt=2, x0=166.0, y0=14.91, r=4.0, theta=270. $
$po x=22.81, y=10.91 $
$po nt=2, x0=22.81, y0=8.91, r=2.0, theta=180. $
$po nt=2, x0=22.81, y0=8.91, r=2.0, theta=270. $
$po nt=2, x0=22.81, y0=8.91, r=2.0, theta=0. $
$po x=40.0, y=8.91 $
$po x=40.0, y=0.0 $
$po x=0.0, y=0.0 $
$reg npoint=1 $
$po x=212.00, y=42.0 $
```

Table 1. - Superfish input file for modeling the PoP cavity as tested.

Looking at the effects of the power window, from the SFO1 output listing it is possible to see that in the segment corresponding to the location of the window, the df/dr frequency perturbation would be -3.9 kHz/mm. A similar case was run with a 4 cm reentrance to see the effect of the radius change on the frequency sensitivity, and it was found to be -3.5 kHz/mm. From this sensitivity, it is possible to linearly scale the result to the subtended angle of the actual window (about 48 degrees over 360), and estimate the frequency shift in our case for an average radius increase of about 4 cm. The frequency shift is:

$$\frac{df}{dz} \times fractional\text{–}angle \times depth = -3.7\frac{kHz}{mm} \times \frac{48deg}{360deg} \times 40mm = -19.73kHz$$

The measured difference as it has been shown is -13 kHz (Fig 1.d and Fig. 2). Note: the measurements of Fig. 1 are done on reflection, whereas all other measurements are in transmission between two ports. The effect of the loading of the instrument is neglected, since the coupling for all probes is very small.

The frequency shift due to the power window opening is also verified in Superfish by looking at the resonant frequencies of the two cases studied (PoP cavity and a cavity with a 4 cm step in the outer conductor, in place of the window) and linearly scaling for the azimuthal fraction occupied by the window:

$$(26.475MHz - 26.623MHz) \times \frac{48}{360} = -19.73kHz$$

in expectable agreement with the previous approximation.

5.0 Loading of the cavity from the amplifier coupling through the drive loop

Knowing the output impedance of the amplifier and the desired coupling coefficient, it is possible to calculate the expected frequency shift of the cavity due to the loading of the amplifier.

The PoP cavity can be modeled as an RLC tank circuit, knowing R/Q = 67.5, Q = 12600 and f = 26.623 MHz, with the following parameters:

R = 850 kΩ

C = 88.61 pf

L = 403.7 nH

(The parallel RLC circuit is chosen for ease of use, whereas a series configuration is typically adopted to represent the drive loop/cavity system more directly [1]).

The coupling coefficient n can be calculated from an S11 reflection measurement with a vector Network Analyzer, using a probe between the anode of the tube and the ground cylinder around it. This was done in the cases of loops of two different sizes respectively shown in Fig. 3 and 5.

Considering the case of Fig. 3, the reflected cavity shunt impedance measured by the network analyzer is 540 Ω. Knowing from the RLC model the cavity shunt impedance, it is possible to calculate the coupling coefficient:

$$n^2 = \frac{540}{850 \times 10^3} = 6.35 \times 10^{-4}$$

and

$$n = \frac{1}{39.67} = 0.0252$$

The output capacitance of the amplifier can be estimated to about 80 pf, since the tube itself contributes for 60 pf. This is reflected at the gap via the coupling constant. The cavity frequency shift due to the amplifier loading can therefore be calculated with perturbation theory:

$$\frac{df}{f} = -\frac{1}{2}\frac{dC}{C} = -\frac{1}{2} \times \frac{50.8ff}{88.61pf} = -0.573 \times 10^{-3}$$

and at the POP measured frequency, $\Delta f = -7.63$ kHz.

The measured frequency shift from Fig. 1 is -5.39 kHz. The difference can be explained by the instrinsic error in the loop coupling measurement technique. By measuring the reflection coefficient at the drive loop with a network analyzer, the self inductance of the drive loop adds itself in series with the reflected shunt impedance, thus resulting in a higher reading. As a matter of fact, the estimated reflected impedance from harmonic analysis of the anode current in pulsed mode shows a reflected impedance of 384 Ω with a conduction angle of about 106 degrees [2]. In that case, the corresponding calculated cavity frequency shift due to the power amplifier loading would be -5.42 kHz.

When the larger loop is measured, the reflected impedance is 2.4 kΩ. Similarly the calculated cavity frequency shift is -33.93 kHz. From the plots of Fig 5 the measured frequency shift is -32.31 kHz. This is in good agreement, also due to the fact that the higher coupling reflects in a higher impedance, thus reducing the relative errors induced by the loop self inductance.

6.0 Application to the final cavity design

It is now possible to conclude that for a final cavity design, where the desired amplifier coupling is in the order of 1: 25, the expected frequency shift due to amplifier loading is in the order of -19.29 kHz. The final geometry might slightly change this value, especially if the final R/Q - thus the corresponding RLC cavity parameters - will be much different. An additional -19 kHz is to be expected from the power loop opening (almost identical to the existing PoP cavity studied here), for a total combined loading of -38 kHz. An additional minor contribution (~1-2 kHz) is to be expected from the few coupling ports. The effects of mode dampers are studied in a separate note.

7.0 Conclusions

A very accurate description of the PoP cavity geometry was used to write the Superfish input file that best corresponds to what is being measured in the 1005 test area. A very good agreement has been found between the Superfish model and the measurements made on the system. The cavity loading and frequency shift due to the power amplifier and coupling loop has also been calculated and successfully verified with measurements taken on the system.

8.0 Acknowledgments

I would like to express my gratitude to Joe Greco and Jeff Aspenleiter who very diligently provided a constant support, in particular all the accurate measurements of the cavity shape, not to mention the several coupling window assemblies and disassembling that were needed. Also, I would like to thank Slawomir Kwiatowski and Werner Pirkl for many helpful comments, hints and suggestions.

9.0 References

[1] S. Kwiatowski - private communication

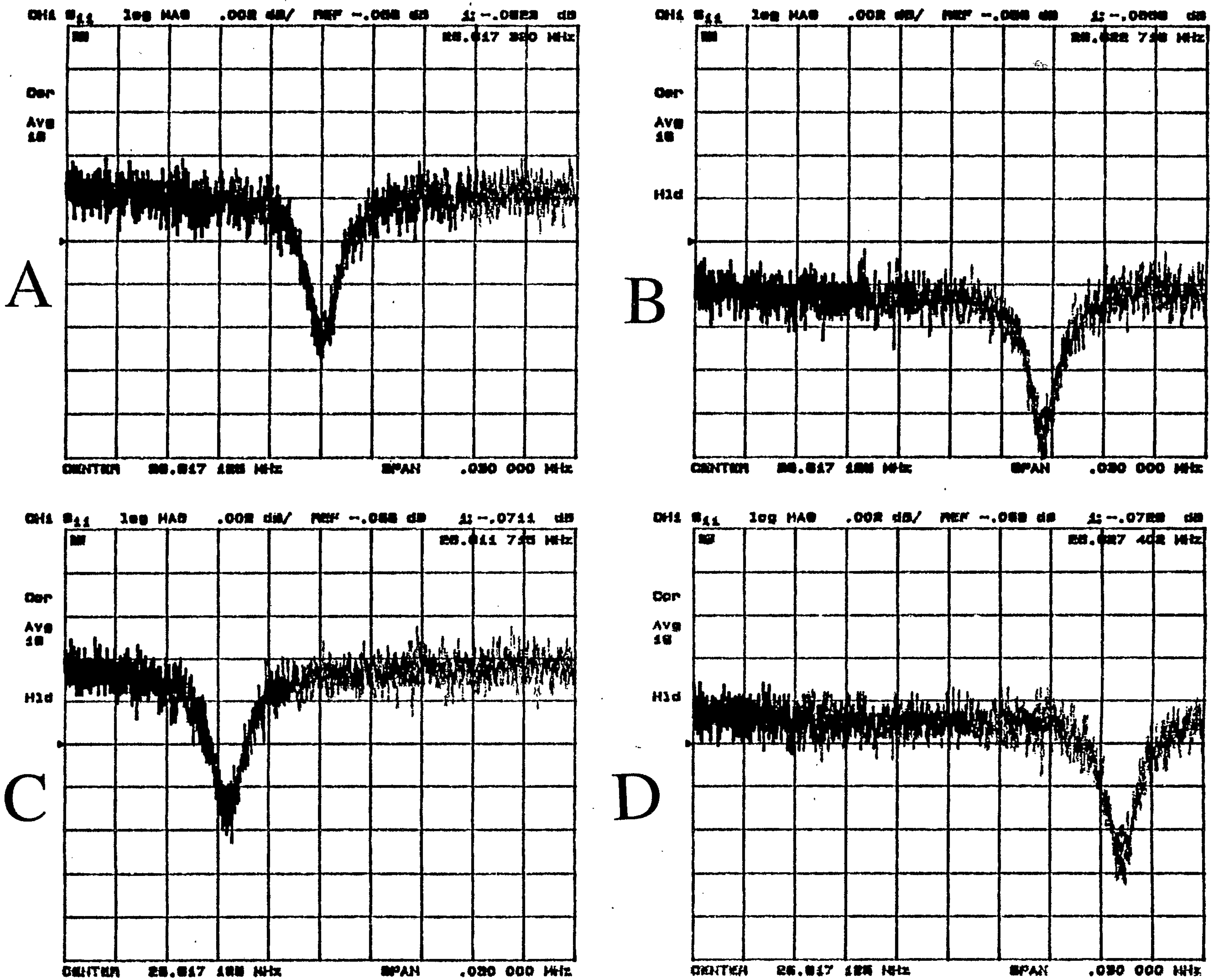
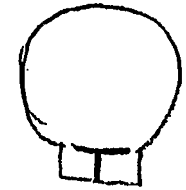


Fig 1 - PoP cavity S11 measurements - a. Cavity with Power Amplifier; b. Cavity w/o Power Amplifier; c. Cavity w/o Power Window; d. Cavity with Window Closed .



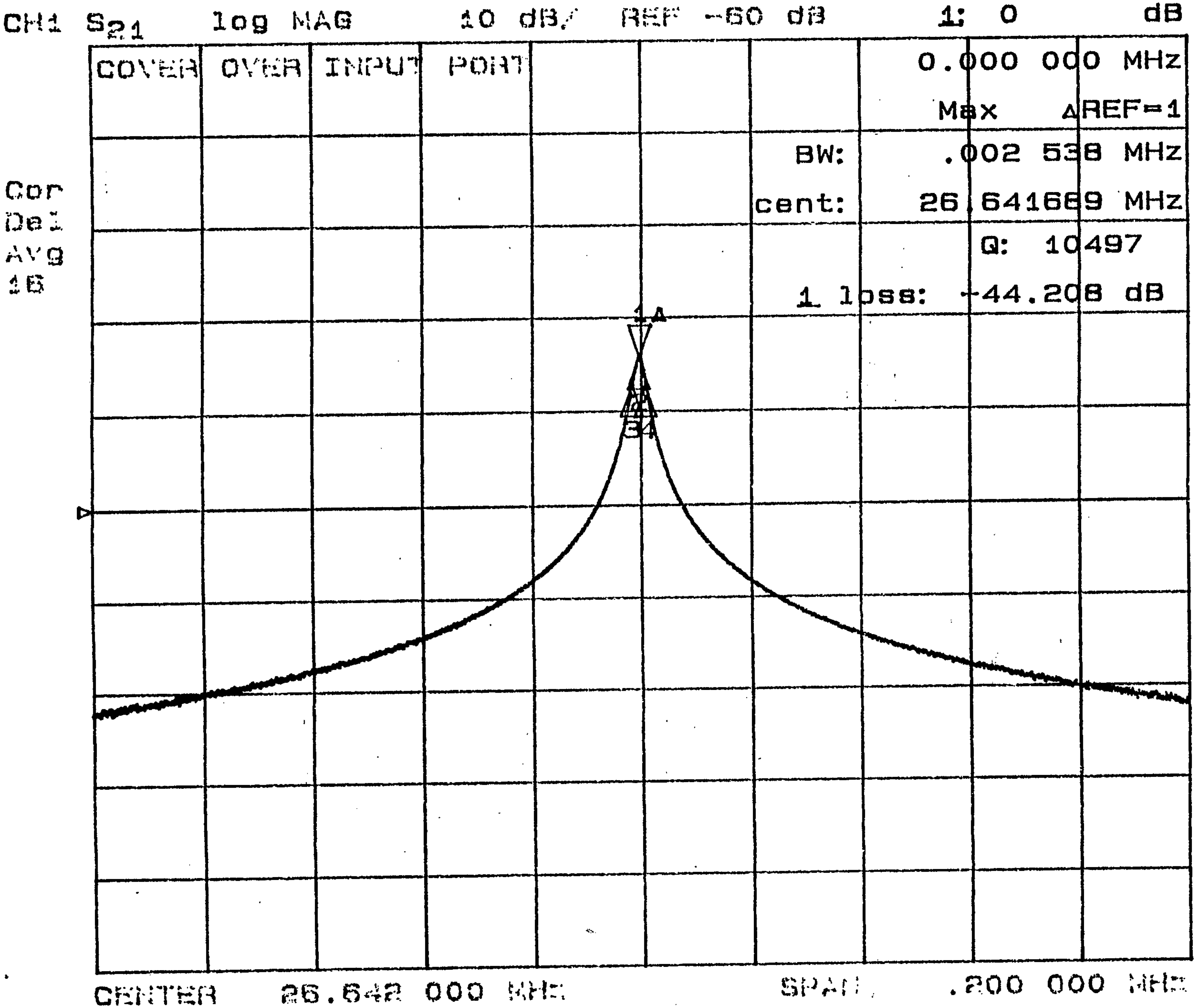


Fig. 2 - PoP cavity S21 measurement with a cover over the input port.

(2)

2 Jun 91

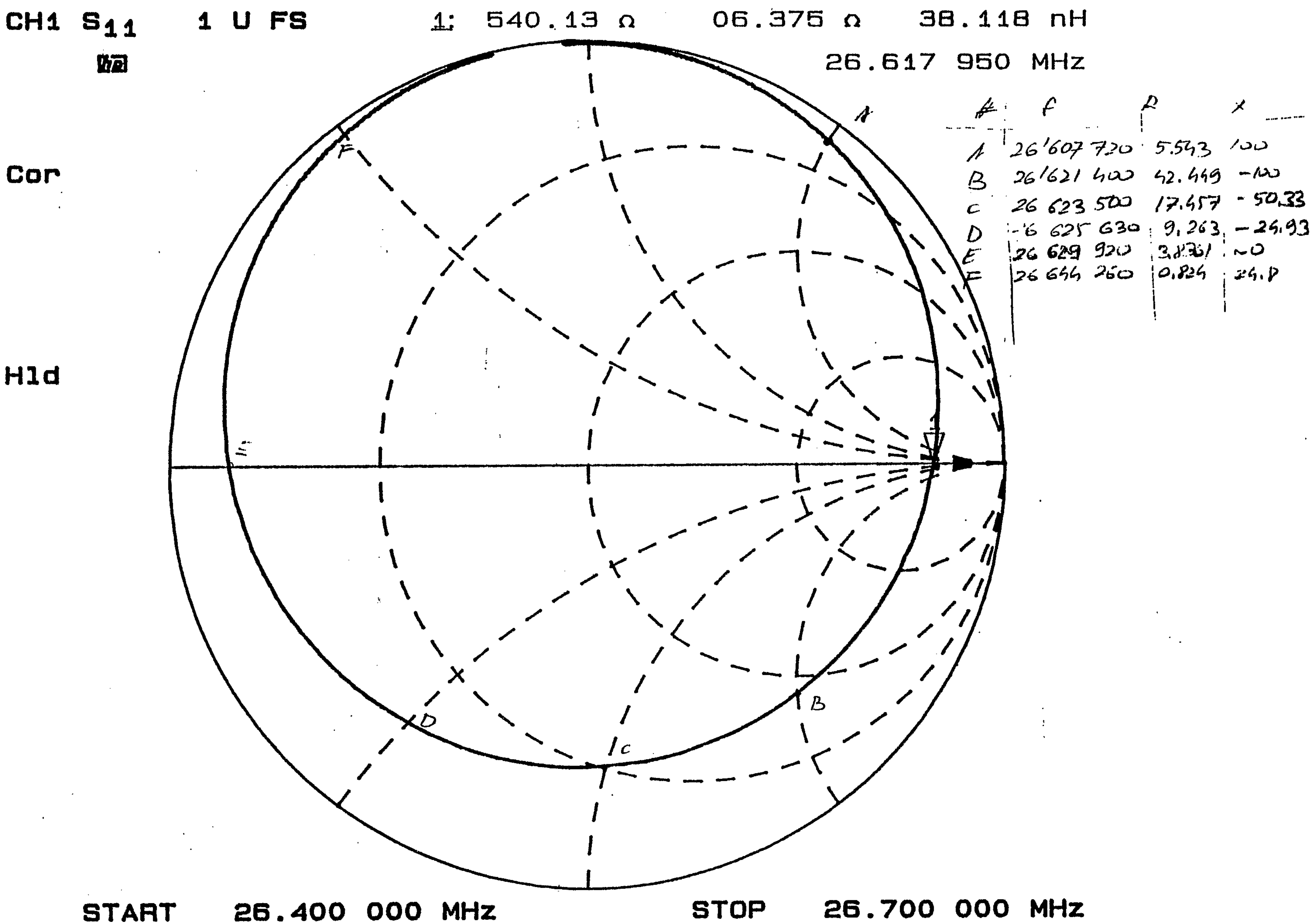


Fig.3 - PoP cavity reflected shunt impedance measured at the tetrode plane (initial loop).

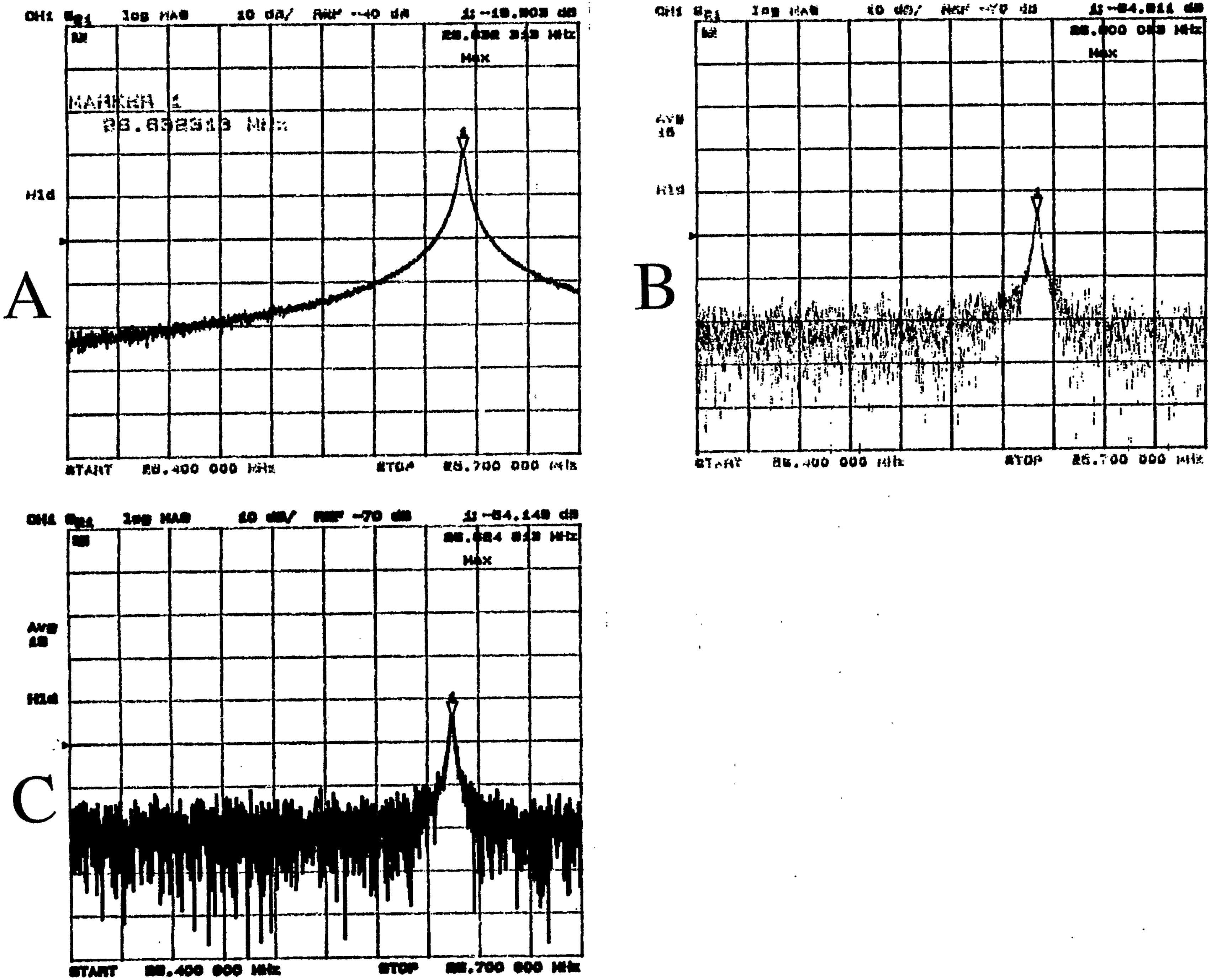


Fig. 4 - PoP cavity S21 measurements (new larger loop) - a. Cavity with Power Amplifier (@ Power Amplifier; b. Cavity w/o Power Amplifier (two probes); c. Cavity with P.A. (two probes).

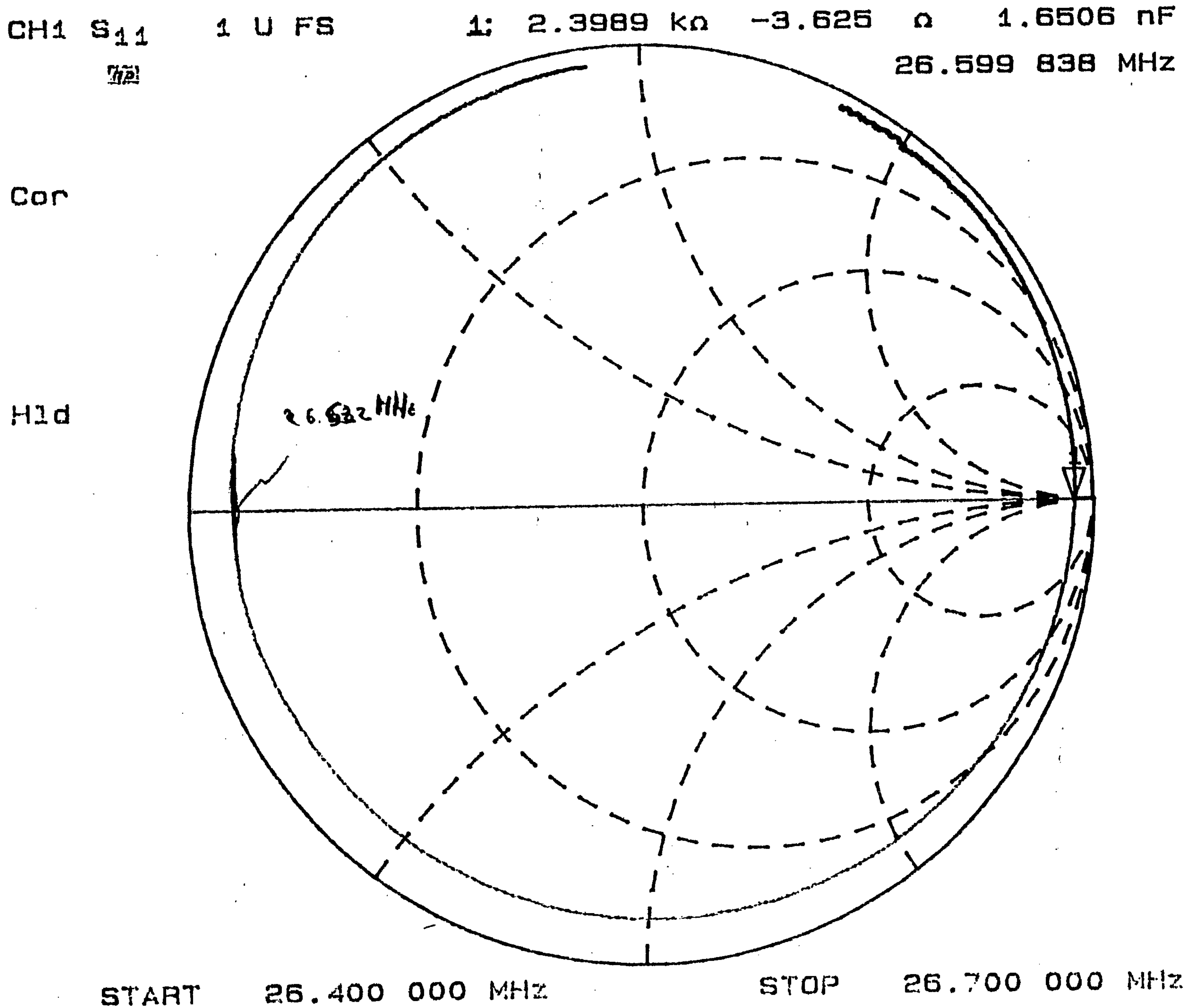


Fig.5 - PoP cavity reflected shunt impedance measured at the tetrode plane (new larger loop).

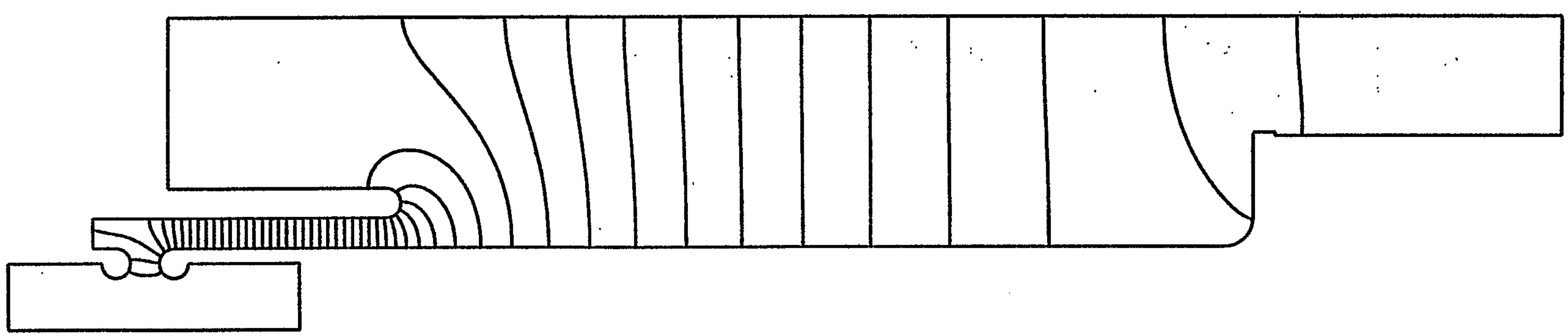


Fig. 6 - Superfish output file corresponding to the input of Table 1.