DAΦNE TECHNICAL NOTE

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Note: **RF-7**

A COMPENSATING NETWORK TO INCREASE THE DAΦNE RF FEEDBACK GAIN

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INTRODUCTION

The extremely high current foreseen for the operation of DAΦNE calls for some efficient beam loading compensation equipment. In the RF-6 DAΦNE note I have considered a RF Feedback (or Wideband Feedback) scheme for this task. The results for a standard RF Feedback connection showed that the phase margin around the RF working point in the Y-Φ_L plane is much wider in most of operating conditions but it can vanish in some special cases.

There are two ways to avoid Sands instability even in these cases:

1) Improving the RF Feedback performances by adding compensating networks in the return branch of the loop (Phase lead or Phase lag networks, etc...)

2) Considering beam loading compensation schemes other than RF Feedback (RF Feedforward, etc...).

A Phase lead compensated RF Feedback seems to be the most reliable and the easiest way to reach the goal. Furthermore, the RF Feedback complex can be set-up on bench while RF Feedforward cannot be tested without the return signal from a longitudinal beam monitor. This is a good reason to try to preserve the already proposed scheme.

The compensation is accomplished by a dedicated network in the feedback return branch. The resulting new configuration is shown in Fig. 1.

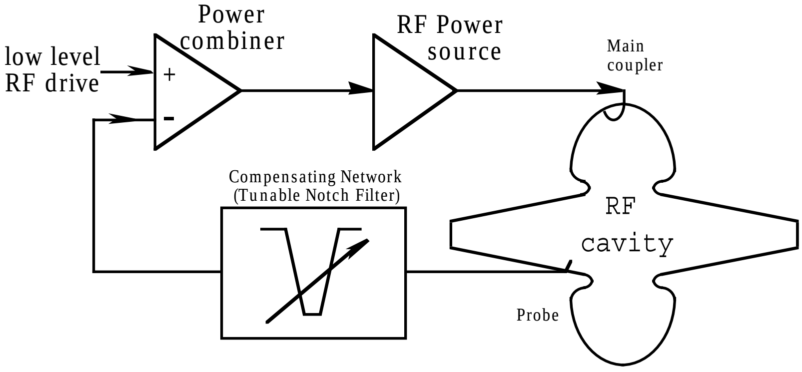

Fig. 1 : Compensated RF Feedback schematic connection.

1) The Compensated RF Feedback

The RF feedback group delay, which limits the maximum loop gain, is essentially due to two contributions T_1 and T_2:

T_1: the physical delay of cables and devices in the loop (which cannot be compensated), $T_1 \approx 100$ nsec ;

T_2: the group delay of the cavities of the RF final stage, $T_2 \approx 300$ nsec.

If one could manage to compensate T_2 an enormous improvement would result. This could be done by canceling out the final stage frequency response by means of notch filters properly designed.

To explain how this compensation works let us assume, for simplicity, that there is only one cavity in the RF final stage (as in the case of a tetrode amplifier). This cavity represents a second pole in the loop transfer function (the first one being due to the main cavity itself). The frequency position of the second pole is the loop cutoff frequency (assuming $\pi/4$ phase margin). To increase the dc loop gain it is worth to get rid of this pole by a pole-zero compensation based on a "phase lead" network.

This network normally introduces a new pole at a controllable higher frequency (typically a decade away).

Such a network could be designed as a standard dc phase lead and connected to the demodulated RF signal. Alternatively one can try to design an RF notch to get compensation directly at the RF frequency.

$f_r = 368 \pm 30$ MHz
$\beta = 0.95 \pm 0.05$

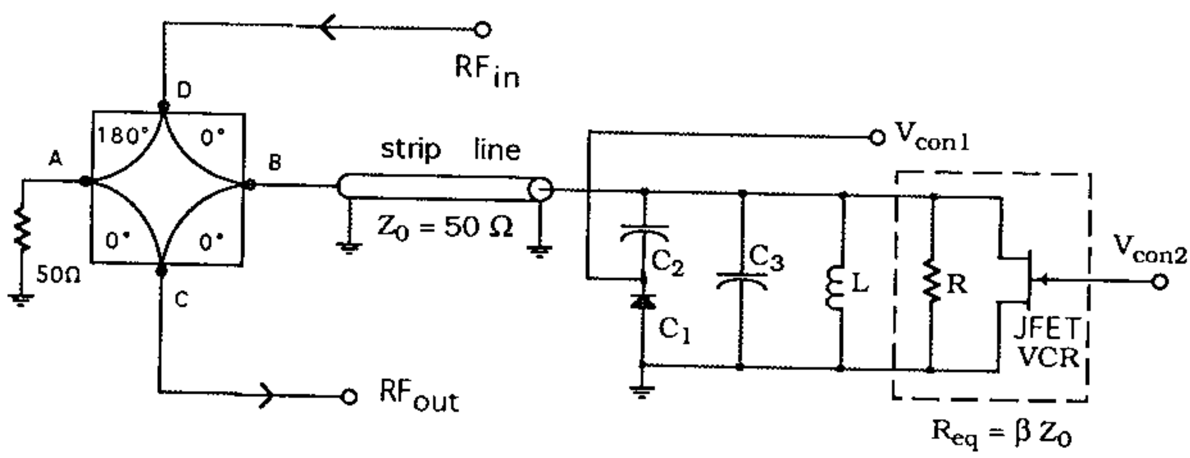

Fig. 2 : Fully Tunable Notch Filter Circuit.

Let us consider the reflected signal from a lumped resonant load. The load impedance is given by:

$$Z(s) = \frac{\beta Z_0 s/(\omega_0 Q_0)}{(s/\omega_0)^2 + s/(\omega_0 Q_0) + 1} \qquad (1)$$

where Z_0 is the impedance of the transmission line and $\beta = R_{eq}/Z_0$ is the ratio of the resistance of the parallel resonant load to the line impedance.

The return transfer function, i.e. the ratio reflected signal to the incident one, is:

$$\rho(s) = \frac{Z(s) - Z_0}{Z(s) + Z_0} = -\frac{(s/\omega_0)^2 + (1-\beta)\, s/(\omega_0 Q_0) + 1}{(s/\omega_0)^2 + (1+\beta)\, s/(\omega_0 Q_0) + 1} \qquad (2)$$

The return signal may be captured with a standard device as a directional coupler, a hybrid junction or a circulator. The resulting circuit is shown in Fig. 2. The return transfer function is given by the ratio of two resonant polynomia. If β is slightly less than 1 the numerator quality factor is much higher than the denominator one. Thus, by properly setting the parameter of the resonant load, it is possible to compensate the frequency response of the final stage cavity by adding a compensating transfer function (the numerator) and a new bandpass response with a much wider bandwidth.

So, in principle it is possible to perfectly compensate T_2. In case of multi-cavity final stages (es: klystron amplifiers) the operation is more complicated because many notches should be inserted. Even in this case the compensation should be possible and the RF feedback should manage only the physical group delay T_1 ($\approx$ 100 nsec).

2) Experimental Simulation of Cavity Compensation

To check the feasibility of this scheme we built the notch circuit with the best care and, inserting a cavity with the characteristics of the final stage cavity mentioned above, we measured the total frequency response (cavity + notch) for the best attainable compensation.

The values of the notch components were computed as follow. Let us assume $T_2 \approx 350$ nsec. This corresponds to a loaded quality factor of the final stage cavity $Q'_L \approx 400$. To best compensate it, referring to eq. 2, we can choose $Q_0 \approx 40$ and $\beta \approx 0.9$ for the resonant load. In this way there is a factor 20 between the pole and zero frequencies of the notch transfer function. The notch resonant frequency is equal to the DAΦNE one (368.25 MHz).

The values of the lumped elements are then:

R=45 Ω C= 384 pF L=483 pH

The very small inductance has been obtained with a strip-line technique. To tune the frequency and the bandwidth of the notch we used a varicap diode as capacitance and a JFET as Voltage Controlled Resistor.

The simple block diagram of the experimental set-up is sketched in Fig. 3.

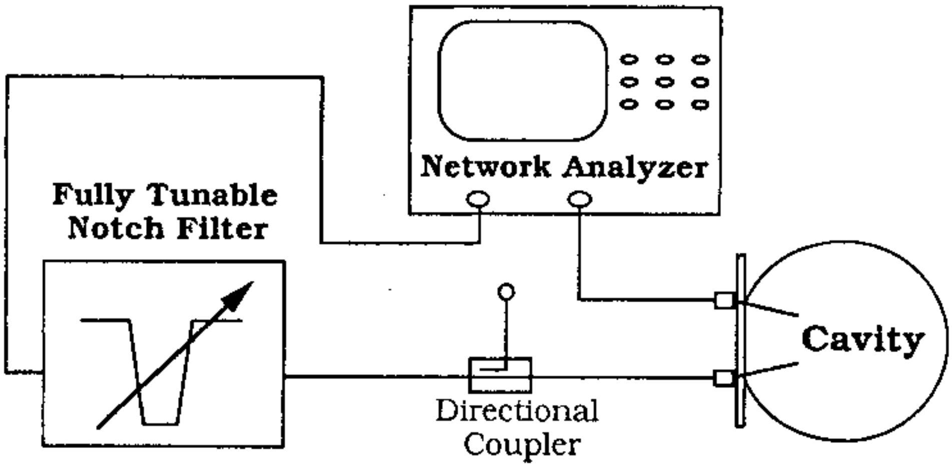

Fig. 3 : Single Cavity Compensation Experimental Set-up.

We used a heavily loaded pill-box cavity to simulate the final stage response. Then we tuned the notch to smooth as much as possible the overall frequency response. The results are shown in the 4 plots of Fig. 4.

In the first one the amplitude and phase of the cavity transfer function are reported. The loaded quality factor was roughly 300.

In the second plot the notch frequency response (after tuning) is shown. The positive slope of the phase curve and the negative peak of the amplitude curve were adjusted to best cancel out the cavity response.

The third plot is the overall frequency response. It appears clearly that the amplitude is very much smoother while the slope of the phase curve decreases a lot. The quantitative effect is shown in the fourth plot were the overall group delay is compared to the group delay of the cavity alone. The impressive result is that the cavity group delay of 300 nsec is reduced to a rough uniform value of 40 nsec.

3) Computed Performances of a Compensated RF Feedback

To estimate the performances of a Compensated RF Feedback I considered a residual delay of 120 nsec for the overall loop after compensation. Accordingly to eq. 13 of RF-6 the maximum attainable loop gain A in this case is A =28.3 =29 dB for the Z/n=2Ω β=5 case, and A =10.7 =20.5 dB for the Z/n=1Ω β=15 case. These values are substantially larger than those reported in RF-6 Tab. 2. That is why the feedback should work much better after compensation.

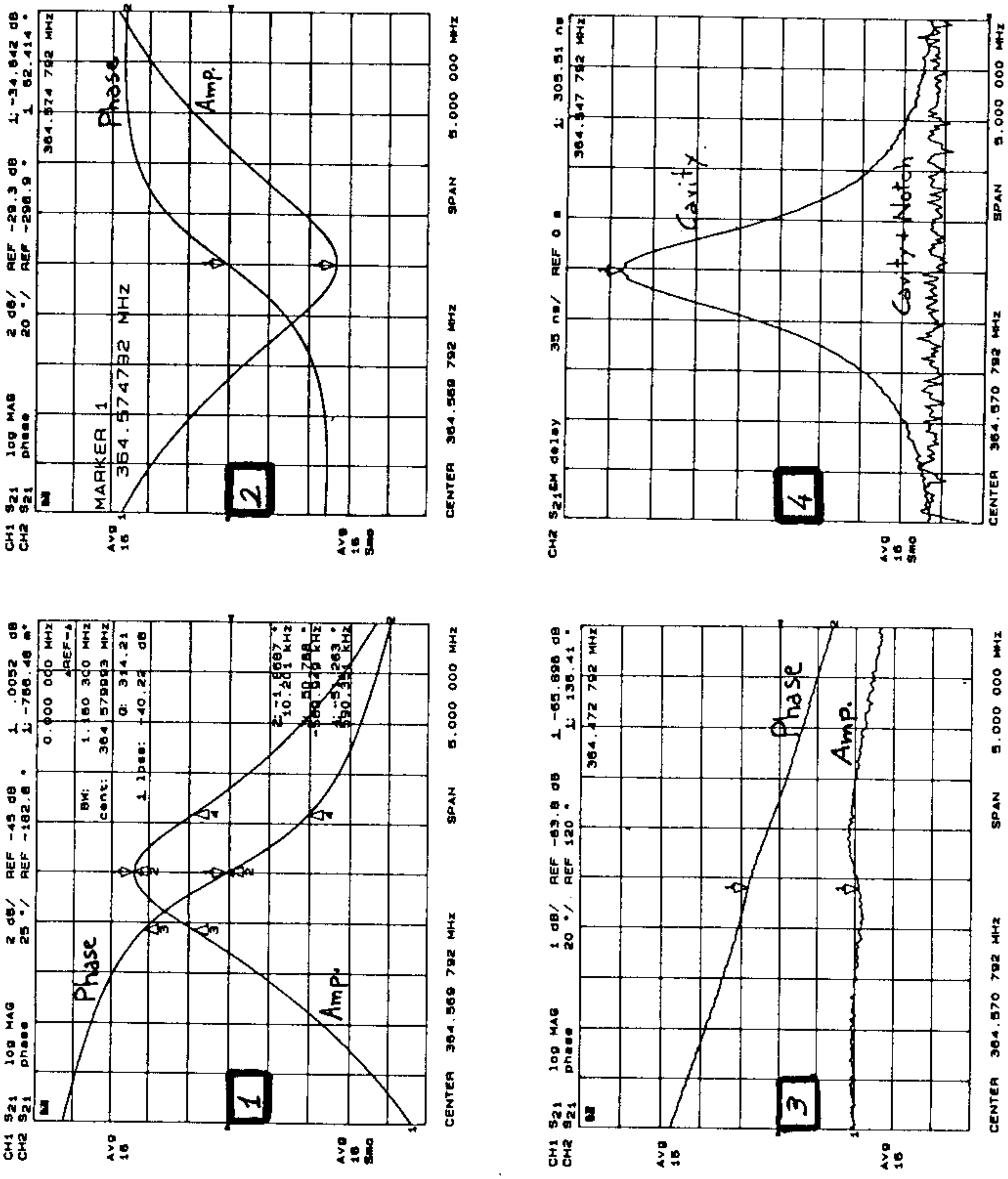

Fig. 4: Experimental Results of Single Cavity Compensation.

The new results are reported in Fig. 5. The limits curves in the Y-ϕ_L plane are shown for the most troublesome cases discussed in RF-6.

The first plot refers to the Z/n=2Ω case for 130 KV accelerating voltage, a value lower than nominal one. In this case the instability threshold is pushed far beyond the power limits by the high gain RF Feedback and the beam is stable for any current up to the limit of 60 bunches foreseen for this case.

The second plot refers to Z/n=1Ω case at the nominal accelerating voltage. The Y value, corresponding to 120 bunches, lies now only between power limit curves and is no more affected by Sands instability.

A 120 nsec total time delay RF Feedback seems to allow stable operation for any given set of the RF system parameters.

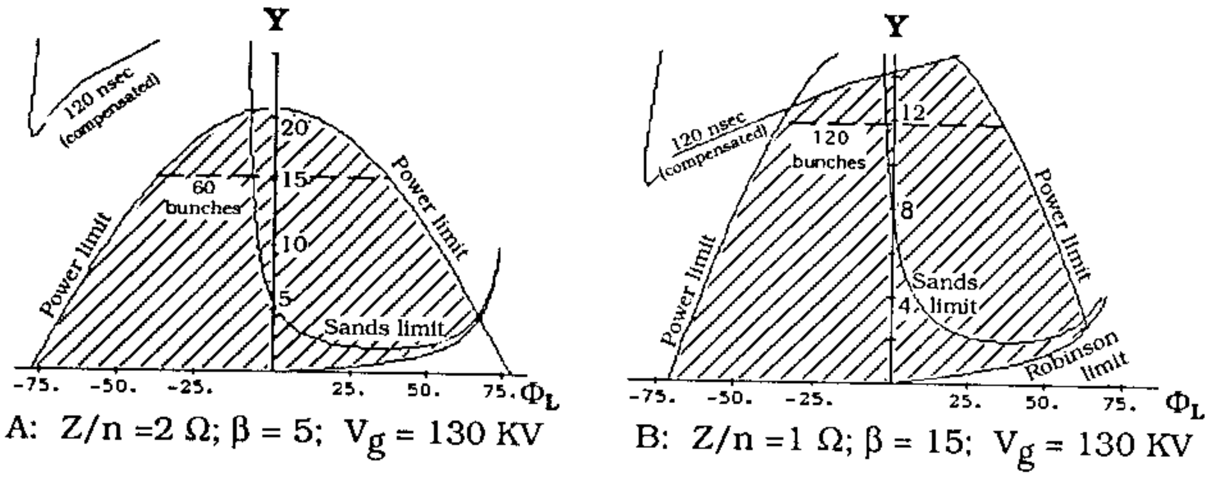

Fig. 5: Working Point Stability Regions for a compensated RF Feedback.

CONCLUSIONS

The compensation by phase advance network seems a promising way to strongly improve the performance of a RF Feedback loop.

Anyway the full cancellation of the final stage frequency response is a challenging task for multi-cavity output stages because one has to insert and tune more than a single notch. Troubles can be expected also by the noise level because a large amplification has to be inserted in the loop to compensate the peak attenuation of the notches.

Many answers about the feasibility of such a scheme can be obtained from experimental tests on real power amplifiers. In fact we are planning an experimental check of these considerations by closing a RF loop around a real power amplifier to measure the loop gain with and without compensation and compare it to the theoretical predictions.

Finally I want to point out that in principle we do not need RF Feedback compensation to reach the day-one target, as shown in RF-6 note. This means that the machine commissioning can start also with a partially compensated loop or even without any compensating networks at all.

ACKNOWLEDGMENTS:

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Special thanks to Dr. D. Boussard from CERN who encouraged me to investigate this way of improving the RF Feedback effectiveness.

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