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Test Results on the SSC Low Energy Booster RF Cavity

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Abstract

A tunable, high-accelerating-gradient cavity has been designed for use in the rf system of the Low Energy Booster (LEB) at the Superconducting Super Collider (SSC). Details of the cavity design are discussed along with low level, swept frequency, and high power test results.

I. INTRODUCTION

The LEB is designed to accelerate a 100 - 500 mAdc proton beam from 1.2 GeV/c momentum up to 12 GeV/c. The resultant change in proton velocity requires the rf frequency to vary from 47.5 MHz to 59.8 MHz over the 50 ms accelerating ramp. The rf is also required to deliver a peak ring voltage of 765 kV. Lattice space, higher order mode impedance, and cost considerations all push toward achieving this voltage with the minimum number of cavities.

The cavity approach chosen is a λ/4 coaxial design [Friedrichs 91] with the inductive portion of the cavity being a ferrite loaded tuner (cavity R/Q ≈ 37 Ω). The design goal is to be able to run with as few as 6 cavities (127.5 kV per cavity). This high voltage operation, along with the wide tuning requirement, results in high stored energy and the potential for increased rf losses in the ferrite. Perpendicular magnetic biasing of the ferrite is used to help minimize these losses [Smythe 83, Smythe 85, Poirier 93].

Different ferrite cooling options (beryllium oxide disks, liquid bath, and water cooled substrates have been considered. Test results on the BeO cooled option have been reported earlier [Coleman 93]. This paper details results using a liquid cooled tuner.

Figure # shows a diagram of the cavity. The tetrode amplifier (150 kW) is capacitively coupled into the cavity. The applied magnetic field, provided by the magnet yoke, biases the ferrite to different permeabilities (μ) and hence tunes the cavity.

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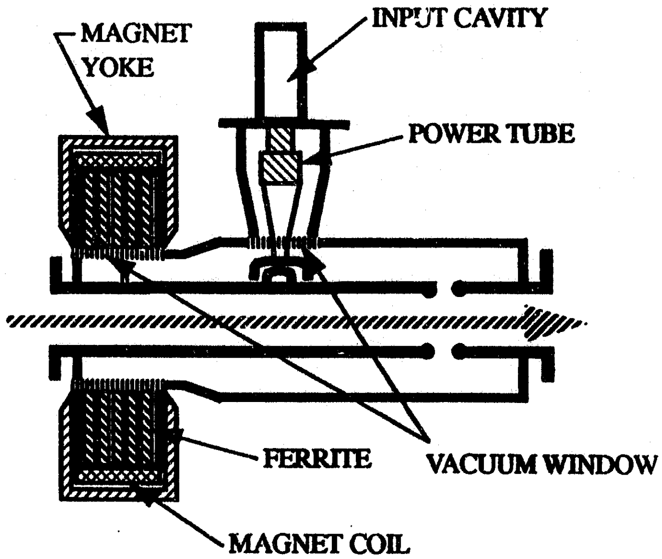

Figure 1. LEB prototype cavity.

In the liquid cooled tuner design, the toroidal rings of ferrite are separated by 5 mm to allow flow of a cooling fluid directly over the ferrite surfaces. The liquid is pumped into the bottom of the tuner housing and out at the top allowing the fluid to flow in the same direction as that of natural convection.

Two fluids have been investigated: Fluorinert™ (FC77), and water (H_2O). Use of the dielectric fluid FC77 has the advantages of high dielectric strength, low rf loss and an inert chemical nature. The disadvantage is that under extreme conditions this fluid could be broken down to toxic compounds which might represent an environmental and personnel safety concern.

The use of water as the coolant has the advantages of extremely good heat transfer and is inherently non-toxic. Water has its disadvantages as well. If a copper tuner shell is used, free oxygen in the water will oxidize the copper surfaces. This oxidation can result in reduced thermal conductivity and it may eventually have an affect on the cavity Q. Another disadvantage is that water has relatively high rf losses [Friedrichs 91]. To reduce these losses, special efforts are made to prevent large volumes of water from being exposed to high electric fields.

In order to allow adequate tuning speeds, the tuner shell is slotted to allow the bias fields to penetrate to the ferrite quickly. Bare stainless steal (as opposed to copper plated stainless) is used for the shell material. Bare stainless was chosen for two reasons. First, its lower conductivity (a factor of 100 below copper at these rf frequencies [Walling 93]) results in a lower Q cavity. It is felt that accurate control (tuning, rf amplitude and phase) is one of the toughest challenges for this rapid cycling rf system. Lowering the Q makes control of the cavity easier. However, the price to pay is increased amplifier power and more heat load to the cooling system. The second reason for choosing stainless was to avoid the copper oxidation problem described earlier when water is used as the coolant fluid. If tests determine that it would be desirable, the tuner shell can always be copper plated at a latter date.

Once slots have been cut in the tuner shell, it is necessary to find some way to contain the coolant fluid yet not inhibit the bias flux penetration. Figure # shows the cover that is used for this purpose. A nonconducting composite material (similar to G-10) is epoxied to the outside of both halves of the stainless shell. It is designed in such a way as to allow disassembly and reassembly of the tuner. This composite cover also acts to restore some shell strength that was lost by slotting.

Figure 2. Slotted tuner housing with composite covering.

A. FC77 and H2O configurations tested

One of the most important regions in the cavity design is that of the geometry around the tuner window. The tuner was designed to allow testing of both FC77 and water with minimal changes to the hardware. Figure # shows the tuner geometry while operating with FC77. An alumina (Al_2O_3) window acts as the vacuum barrier and Rexolite^{TM} is used as a mechanical spacer at the inner radius of the ferrite rings.

Figure 3. FC77 cooled tuner geometry.

To run with water, the rexolite spacer was initially used to confine the water in the region of the ferrite (thus eliminated high energy densities in large volumes of water). Water leaking past this barrier proved to be a problem and only limited data was taken in that configuration. As an alternative, the Rexolite spacer was modified, and water was allowed down to the radius of the vacuum window. The use of the modified Rexolite spacer reduced the energy density in most of the water, however high losses are still present near the radius of the vacuum window.

II. LOW LEVEL TESTS

A. Tuning range

Figure # shows the tuning curves for the FC77 and H_20

Figure 4. Cavity tuning with bias current.

operation. Measured and calculated (using a SUPERFISH model) results agree well. The tuning range of the two configurations differ primarily due to the high dielectric constant of the water (76 for H_2O vs. 1.86 for FC77) significantly changes the impedance of the tuner

B. Cavity Q

The following table summarizes the cavity Q's.

@ 57 MHz	dry cavity	FC77	H_2O
measured	1980	1770	1290
calculated	2380	2240	1660

Use of the bare stainless tuner housing results in relatively low Q's. The presence of the water in high electric field regions is seen to cause a significant drop in Q. If this low Q proved to be unacceptable (due to power constraints), the tuner housing could be copper plated.

C. Tuner response

. The rapid cycling nature of the LEB requires the rf cavity to be tuned over a 50 ms time frame. This is the primary reason for slotting the tuner. The slots allow rapid penetration of the bias flux that is used to adjust the resonant frequency. This quick penetration is also useful when quick corrections are needed (such as rapid changes in beam loading).

Figure # characterizes the frequency response of the tuner. The tuner bias current was first adjusted to a dc level. A small signal amplitude modulation of the current was then applied and the resultant change in resonant frequency monitored. Shown in the plot is the measured response along with the calculated response using MAFIA [Walling]. The 3dB bandwidth is ~ 2 kHz which is considered more than adequate for this application.

D. Swept frequency operation

Initial results of swept frequency operation have been obtained. A digital signal generator (DSG) was used to drive a voltage controlled oscilator (VCO) with the LEB frequency program. Another DSG was used to drive the tuner bias supply with a current program (feed-forward signal) that would result in the cavity resonance approximately following the drive frequency. The phase across the tetrode amplifier was then used as an error signal that was added to the feed-forward signal that drove the bias supply.

Figure # shows the envelope of the rf gap voltage during a 50 ms ramp. Overlaid on this is the frequency program driving the VCO. The gap voltage is seen to stay approximately constant (19 kV) over the entire sweep. It is felt that the performance during the first 15 ms of the sweep can be improved by damping of a spurious tetrode mode and proper adjustment of the feedback gain in this portion of the sweep

Figure 5. Tuner frequency response.

Figure 6. Swept frequency operation.

III. HIGH VOLTAGE TESTS

A Multipactoring performance

The LEB voltage program calls for very low cavity voltages at the beginning and end of the ramp (~50 kV total ring voltage). As one drops the voltage in a cavity, multipactoring may occur inhibiting operation of the cavity. For this cavity, typically 1 day of conditioning was required to reach 10 - 20 kV minimal voltages on the gap. It is anticipated that to reach the required minimal ring voltages that counter-phasing of the cavities would be employed.

B. Maximum gap voltages

The table below summarizes the maximum gap voltages achieved.

Config	V_{gap} (kV)	V_{tuner} (kV)	Limit
FC77	100	38	no failure
H_2O	100	38	arc at 130 kV at rexolite-ceramic gap

These data were taken for fixed frequency operation. The voltages were present for long pulse-widths (> 10 ms) and elevated tuner temperatures (~35° C).

While operating with FC77 in the tuner, the voltage was not pushed past 100 kV. With water, the cavity was operated up to 130 kV, but arcing occurred after 1 hour of operation. The location of the arc corresponded to a region of high loss in the water. It is felt improved flow of water in this region would improve the voltage performance.

C. Nonlinear effects

Ferrites in high fields are known to exhibit nonlinear effects [Shapiro93, Friedrichs93, Hulsey 92]. When the amplitude of the rf magnetic field becomes appreciable (> 2%) compared to the bias field, the effective operating μ changes. This then results in a shift of the resonant frequency complicating the control of the cavity.

Figure # displays measurements of this effect for this cavity. The detuning is seen to increase with gap voltage. Note also that at high frequencies (high bias field) the effects are reduced.

Figure 7. Cavity detuning due to ferrite nonlinearity.

IV. HIGH POWER TESTS

In order to simplify measurements and interpretation of data, the high power performance of the cavity was characterized under fixed frequency conditions. The operating frequency was chosen to be 57 MHz which represents a power weighted average frequency. The duty factor was adjusted to achieve the desired average power for a given gap voltage. If the cavity is operated at a fixed voltage V_o, an 11% duty factor (df) would result in the same average power dissipation as an LEB cycle which peaks at V_o.

The resonant frequency of the cavity was seen to vary with tuner temperature (57 MHz/°C for FC77 and 41 MHz/°C for H_2O). This is due to the saturation magnetization of the ferrite and the dielectric permittivity of the water being functions of temperature [Friedrichs 93].

The cavity was operated at voltages form 20 kV up to 130 kV. Average total power into the cavity ranged from 4 to 20 kW. Most thermal runs lasted for 1 - 2 hours allowing the cavity to come to thermal equilibrium. One 70 kV, 11% df, FC77 run lasted for 24 hours.

Power being deposited in the tuner was monitored with calorimetry of the cooling fluid. Measurements indicated that the use of water results in much more power being deposited in the tuner. However, the data also indicated that water is a much more efficient coolant (i.e. less temperature rise per watt deposited in tuner). An ~ 11° temperature rise is observed for 130 kV, 11% df, H_2O operation. The tuner arced after 1 hour at this operating point. This operating point corresponds to the design goal. Although the tuner experienced an arc at this point, satisfactory cooling (11° temperature rise) was demonstrated.

V. SUMMARY

The primary problem encountered while testing was that of tuner coolant leaks. The combination of liquid cooling and a slotted tuner, made for a difficult mechanical problem. Iterations on the tuner design need to be made in order to solve this problem.

Initial swept frequency operation of the cavity was quite encouraging. With minor modifications to the equipment, it is felt that swept frequency operation will be completely satisfactory.

The cavity has been operated at high voltages and powers. The liquid cooling of the tuner is adequate for handling powers associated with the LEB program. The cavity has demonstrated 100 kV gap voltages and with improved circulation of the tuner coolant, higher voltages should be possible.

The measurement data obtained on this cavity point to this cavity design as being a viable one for a high-gradient accelerating cavity for use in rapid cycling, low energy proton synchrotrons.

VI. ACKNOWLEDGMENTS

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Figure 4. LEB prototype cavity. 3

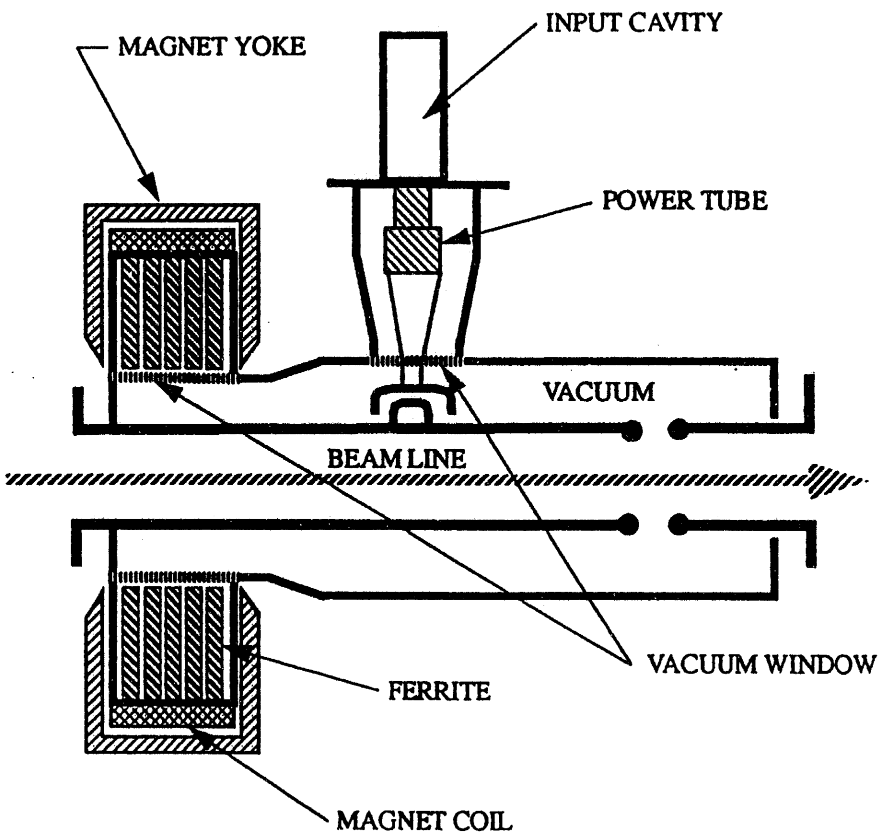


Figure 7. Liquid containment approach for liquid cooled tuner. 4

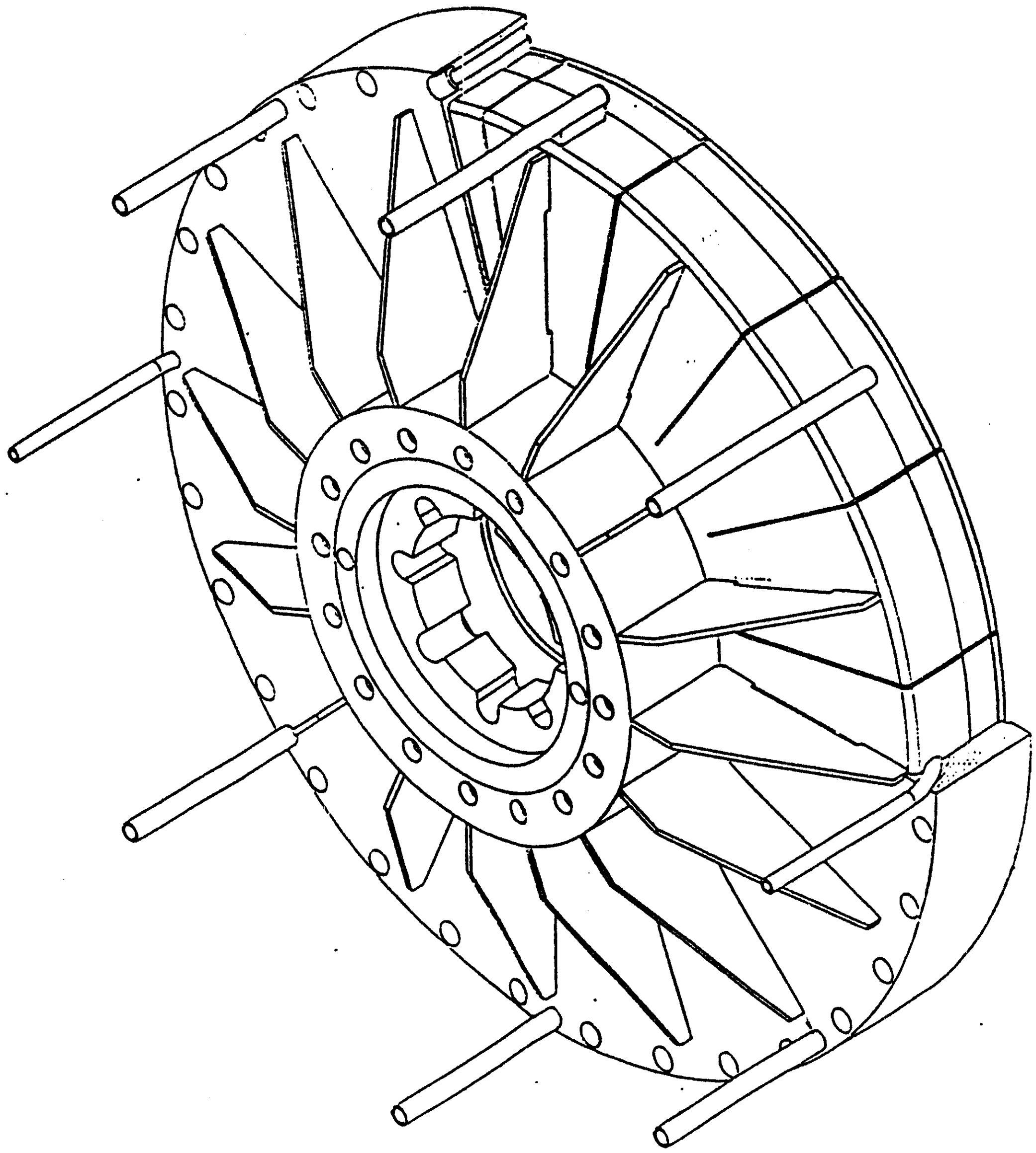


Figure 6. Liquid cooled tuner geometry. 4

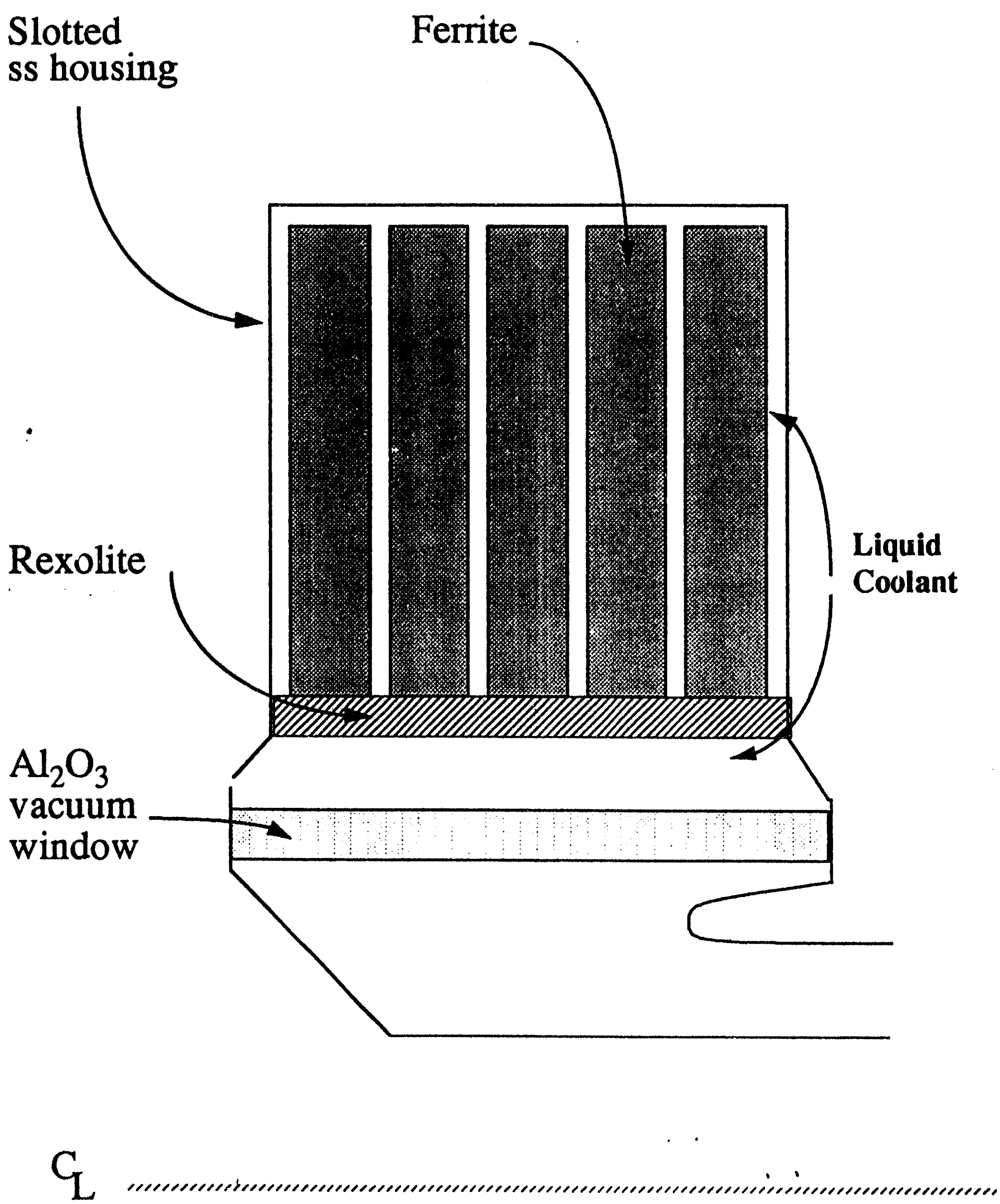


Figure 12. Cavity tuning with bias current (liquid cooled tuner). 9

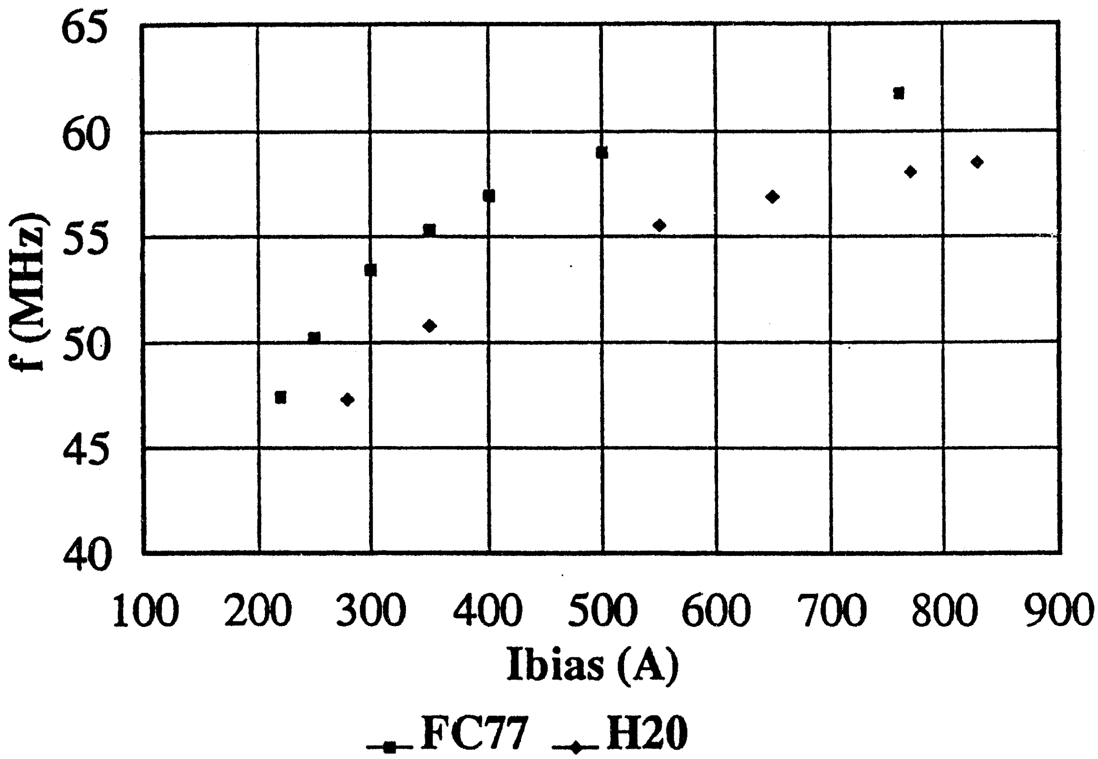


Figure 13. Liquid cooled tuner frequency response. 10

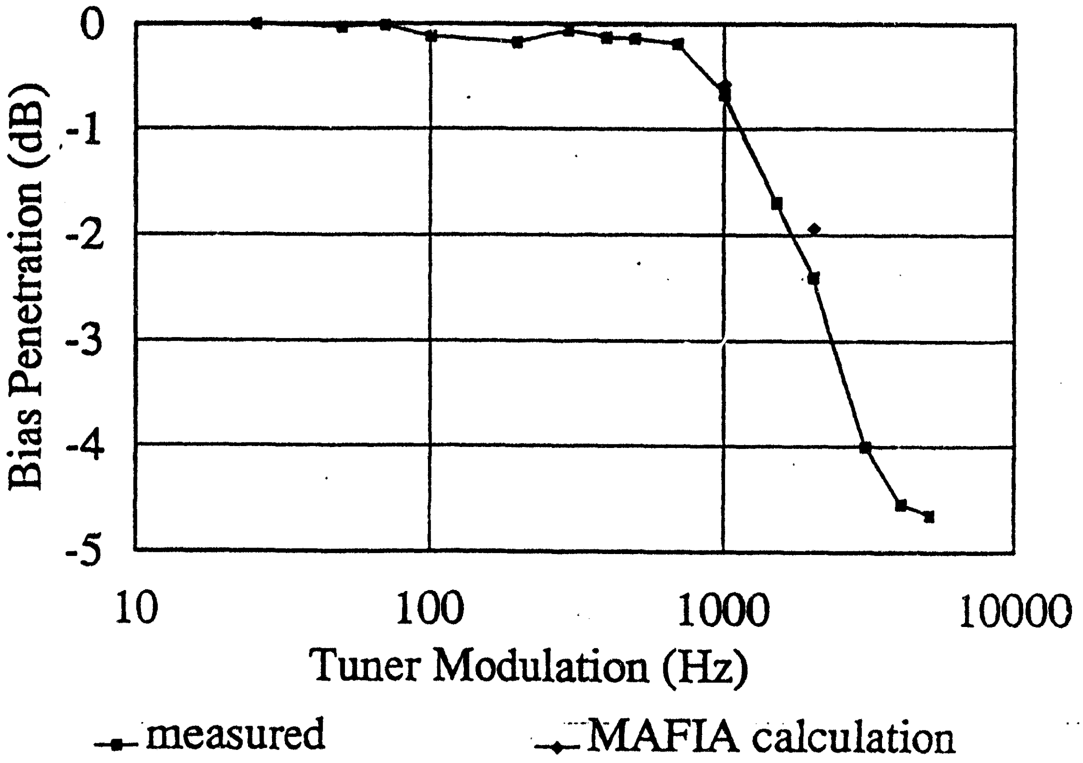


Figure 14. Swept frequency operation

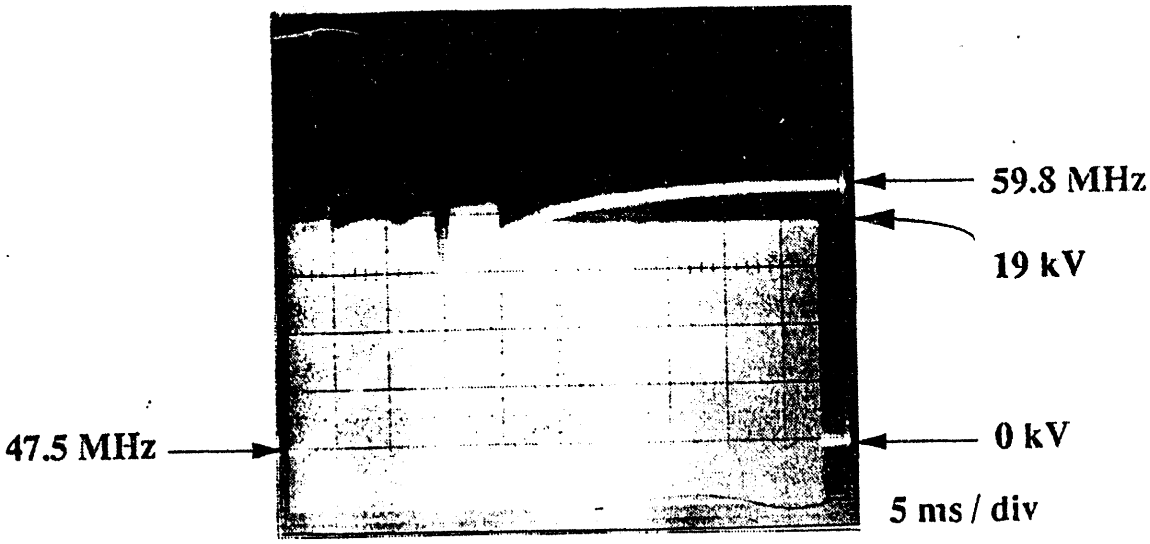
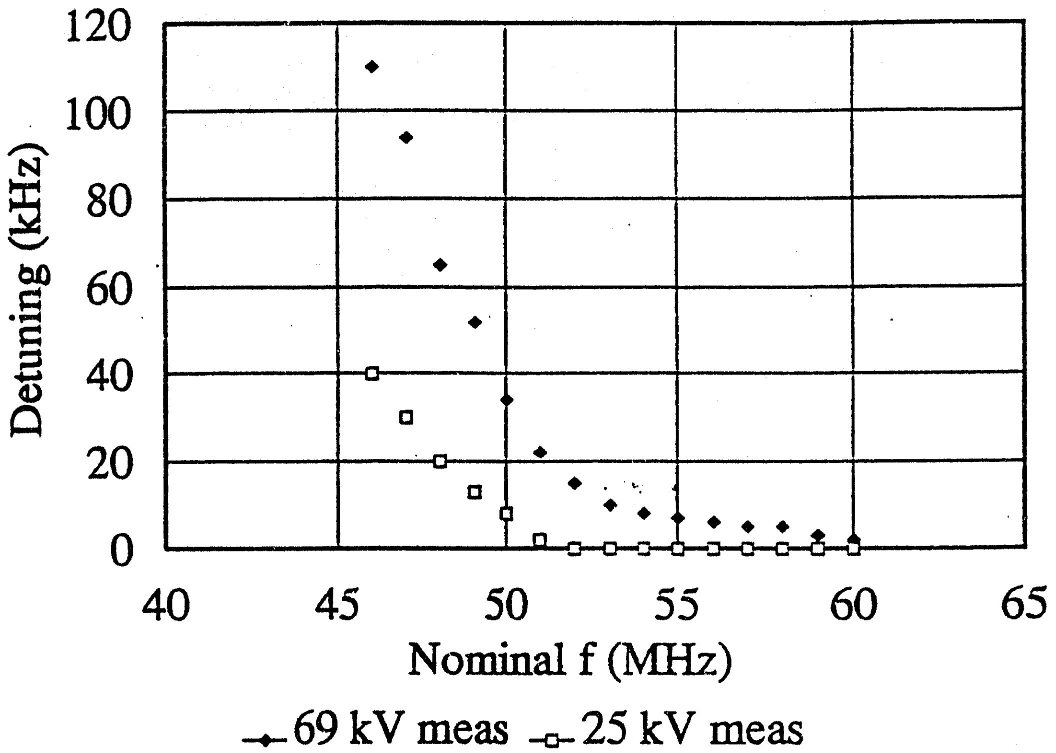


Figure 15. Cavity detuning due to ferrite nonlinearity. 12



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