RF TECHNICAL NOTE

Retuning Philips YK1350 Klystron for Operation At the Nominal APS Operating Frequency

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I. Introduction

The Philips YK1350 klystron selected for retuning, s/n 73201.35, was originally part of the CWDD project and was absorbed into the APS klystron inventory at the conclusion of CWDD activities. The klystron was later installed in the 350-MHz RF Test Stand klystron garage in Building 420 and used in the test and commissioning of the Diversified Technologies (DTI) series-switch/anode modulator tank. The accumulated operating time of the klystron is estimated at less than 1,000 hours, so it has the potential to perform as a reliable rf power source at APS for many years.

The klystron was originally factory tuned for efficient operation at 352.21MHz. Initial attempts to operate it at the nominal APS operating frequency of 351.93 MHz indicated that the klystron was not useable as an operational spare for the APS booster and storage ring rf systems due to low rf gain. It was decided that one or more of the klystron cavities would need to be retuned for the klystron to operate properly at the APS frequency. A plan was set forth to perform this re-tuning during the week of October 6-10, 2008.

II. Operation at Original Frequency

The klystron was successfully operated at full power on 11/15/06, producing approximately 1MW CW output power into the test stand 1MW rf load. Data from that operation is shown below:

Operating frequency = 352.21MHz
Cathode voltage = 88.1kV
Beam current = 16.4A
RF input = 83 watts
RF output at klystron output (EPICS) = 956.9kW
RF power into load after transmission losses = 922.20kW
Operating efficiency = 66.22%
RF gain = 40.61dB

This data indicated that the klystron was healthy and operating at rated specifications. There were no vacuum events, gun arcs, or other instabilities noted, which was remarkable for a klystron that has been in storage for approximately 15 years.

III. Operation at APS Frequency Before Retuning

After the test run at 352.21MHz was completed, the rf drive frequency was changed to 351.93 MHz and the klystron was again operated into the 1MW rf test load. Due to poor efficiency, beam current was limited to 12.5A to stay within the 1MW dissipation limit of the collector. Data from that operation is shown below:

Operating frequency = 351.93MHz
Cathode voltage = 88kV
Beam current = 12.5A
RF input = 110 watts
RF output at klystron output (EPICS) ≈ 350.9kW
RF power into load after transmission losses ≈ 320kW
Operating efficiency = 31.6%
RF gain = less than 40dB

This test revealed that the rf gain of the klystron was significantly reduced at 351.93MHz, which severely limited operating efficiency because the 200-watt driver amplifier reached maximum output power before the klystron reached saturation. It was clear at this point that the inability to saturate the klystron with rf drive and the resulting loss of efficiency would make the klystron unusable in the APS rf systems.

IV. Retuning Process

The first step in the retuning process was to determine the resonant frequency of the klystron cavities prior to any changes. The Philips klystron design does not include coupling loops in each cavity, so a low-power rf sweep response of the klystron with beam power applied was utilized to determine the cavity frequencies. This test was performed on 8/14/07, and the results are shown in Figure 1 below.

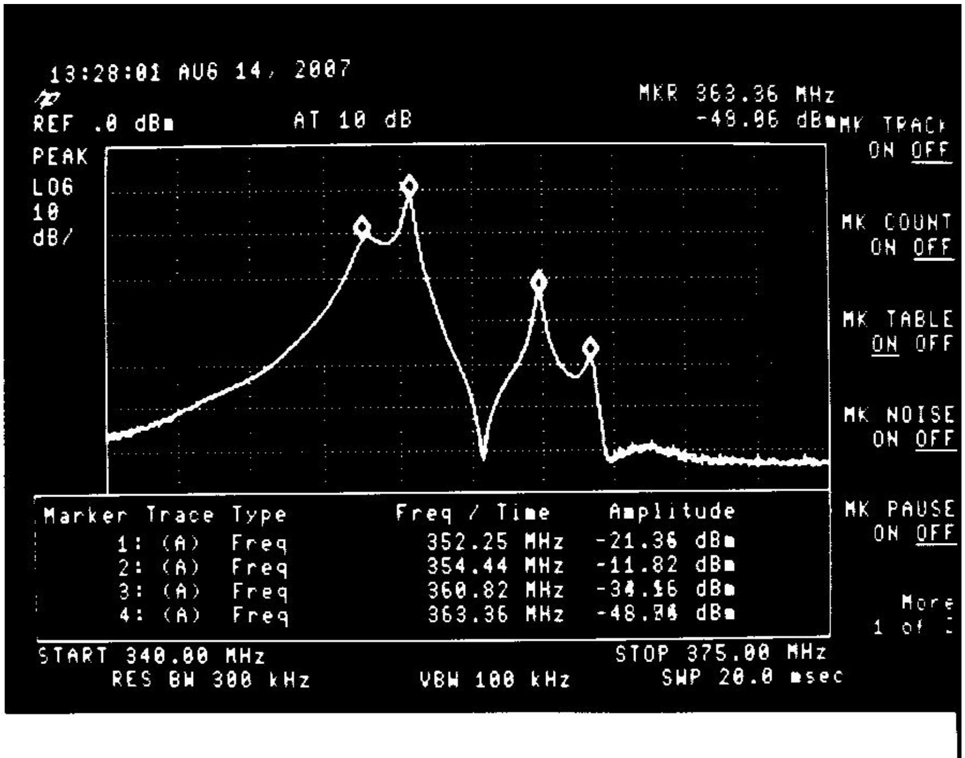

Figure 1 – Low-power rf sweep of klystron with 70kV/4A beam.

The individual cavity resonant peaks can be clearly seen in the sweep response. Left to right, the resonant peaks in Figure 1 represent C1, C2, C4, and C5. The 3rd cavity is not seen as it is tuned to the approximate second harmonic of the fundamental (approximately 699 MHz), and the output cavity is not visible as a discrete peak due to the fact that it has relatively low Q.

Reviewing test data on this klystron taken at CERN during the original acceptance tests in 1990 suggested that only the input cavity of the klystron needed to be re-tuned to recover rf gain and improve performance at 351.93MHz. Operating bandwidth factory test data indicated that the klystron rf output decreased by only 0.13dB when the operating frequency was decreased from 352.21MHz to 351.93MHz, but the rf drive power required to saturate the klystron increased dramatically at the lower frequency. At 352.21MHz, 74 watts of rf drive power was sufficient to saturate the klystron at full power, but that the saturation rf drive level increased to greater than 135 watts at 351.93MHz. This loss of rf gain was confirmed during initial operation of the klystron on the APS rf test stand, and strongly suggested that the first step in retuning would be to lower the resonant frequency of C1 by 280kHz to approximately 351.97MHz.

The first step in the retuning process was to remove the side covers on the klystron in order to access the cavity tuning adjustment points. A photo of the klystron with the side covers removed is shown in Figure 2.

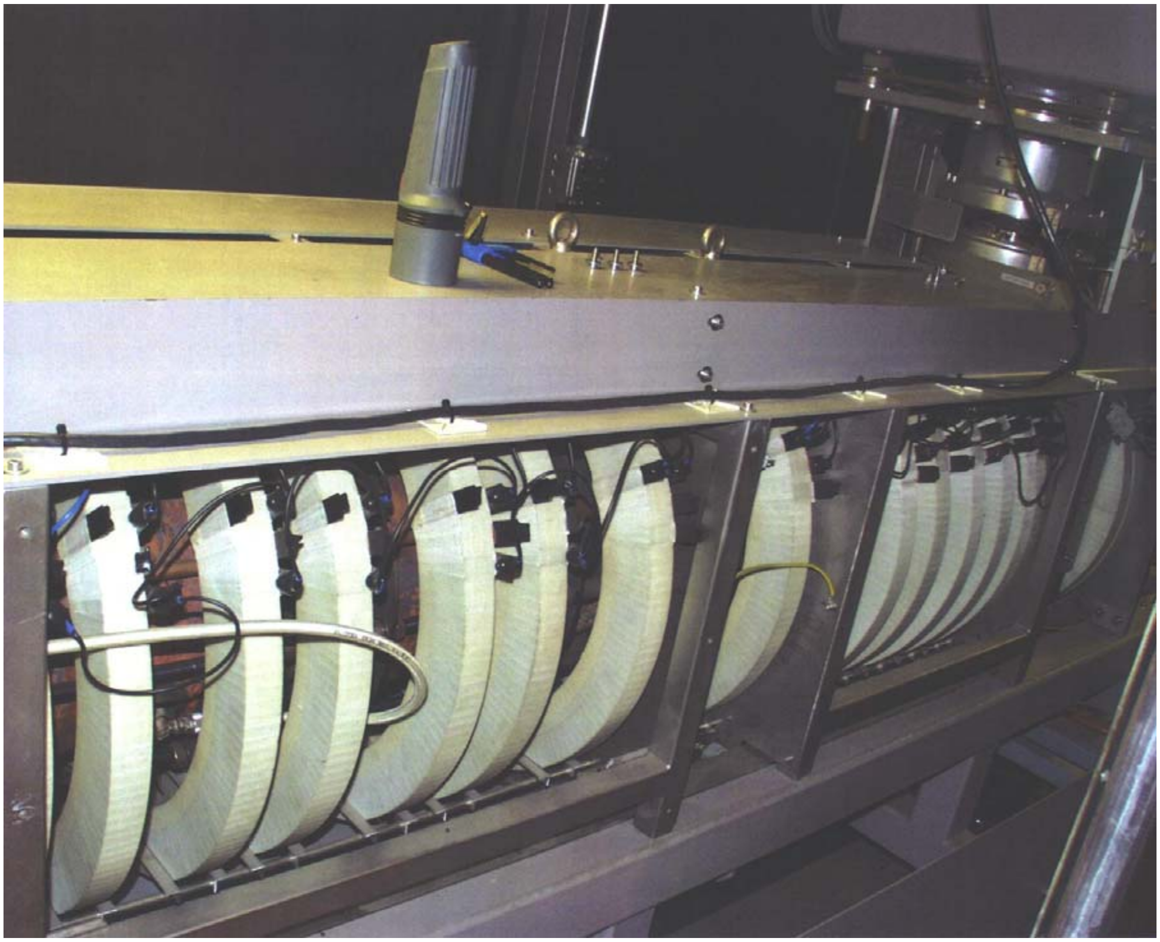

Figure 2 – Photo of klystron with side covers removed, revealing the focus magnet coils, drift tubes, cavities, and the rf input cable connected to the input cavity coupling loop.

Although it was not specifically stated in the Philips klystron manual, it was suspected that the side panels were serving as a return path for focus field flux, so it was planned to re-attach the panels before operating the klystron.

The klystron cavities are designed with field enhancement nosecones that are actually extensions of the drift tubes. This arrangement makes the capacitance developed between the cavity nosecones the dominate effect on cavity resonant frequency. The cavities are designed with one flexible side wall, which is connected to the drift tube on one side of a disc bellows. This arrangement allows the flexible wall of the cavity and the nosecone connected to it to move in and out independent of the other nosecone, thereby adjusting cavity resonant frequency by varying the capacitance between the nosecones. The flexible wall of the cavity is held in place with six threaded rods that are locked in place by locknuts on either side of the rigid drift tube plate. Figure 3 shows the tuning assembly for C2, which was easier to photograph for the purpose of this document. The approximate tuning rate on the cavities is 1.5-2MHz per “nut-turn” on the 350-MHz cavities, and 3.5-4MHz per “nut-turn” on the second-harmonic cavity (C3). These figures were determined on the EEV K3513 klystron, which is very similar in design to the Philips klystron. Using these values, a 280-kHz change in frequency would require only one-sixth of a “nut-turn”, or one “nut-face”. The natural tendency of the cavity is to drift lower in frequency when the tension is released from the flexible wall, so a frequency change of this magnitude could be accomplished by partially loosening the locknut on the cavity-side of the rigid plate while monitoring the cavity frequency.

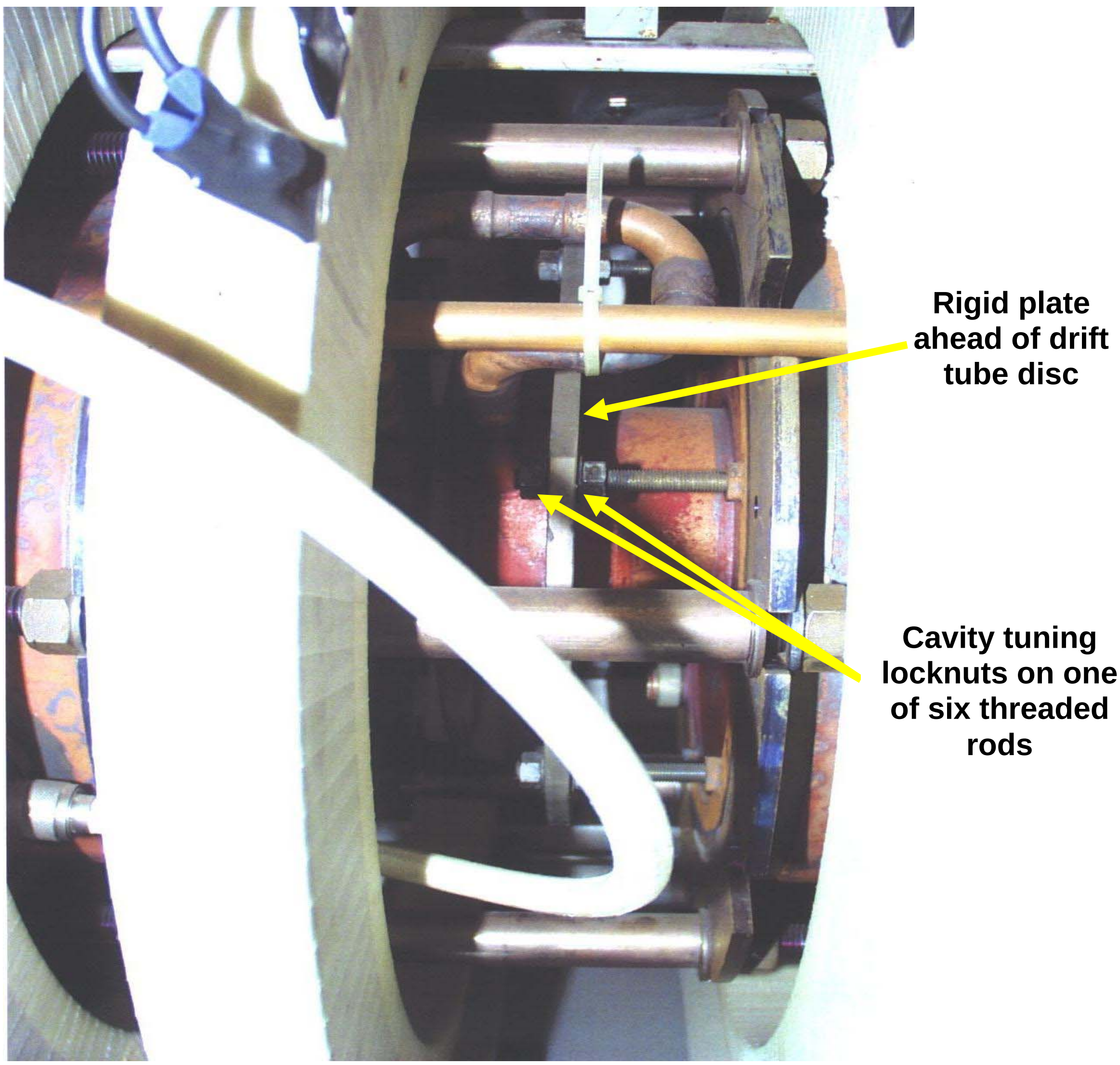

Figure 3 – Cavity tuning adjustment nuts.

Before re-tuning of C1 was attempted, a network analyzer was connected to the klystron rf input connector to monitor the shift of the cavity resonant frequency in real time as the adjustment locknuts were loosened. Figure 4 shows the network analyzer measurement of C1 resonant frequency before the locknuts were loosened. Two locknuts were slightly loosened on opposite sides of the cavity and the resonant frequency was observed to instantly drift down by approximately 500 kHz, which is more than was desired (see figure 5). Due to the difficulty in making such small changes in resonant frequency, the decision was made to operate the klystron with the cavity tuned to this point to verify that we were tuning in the correct direction.

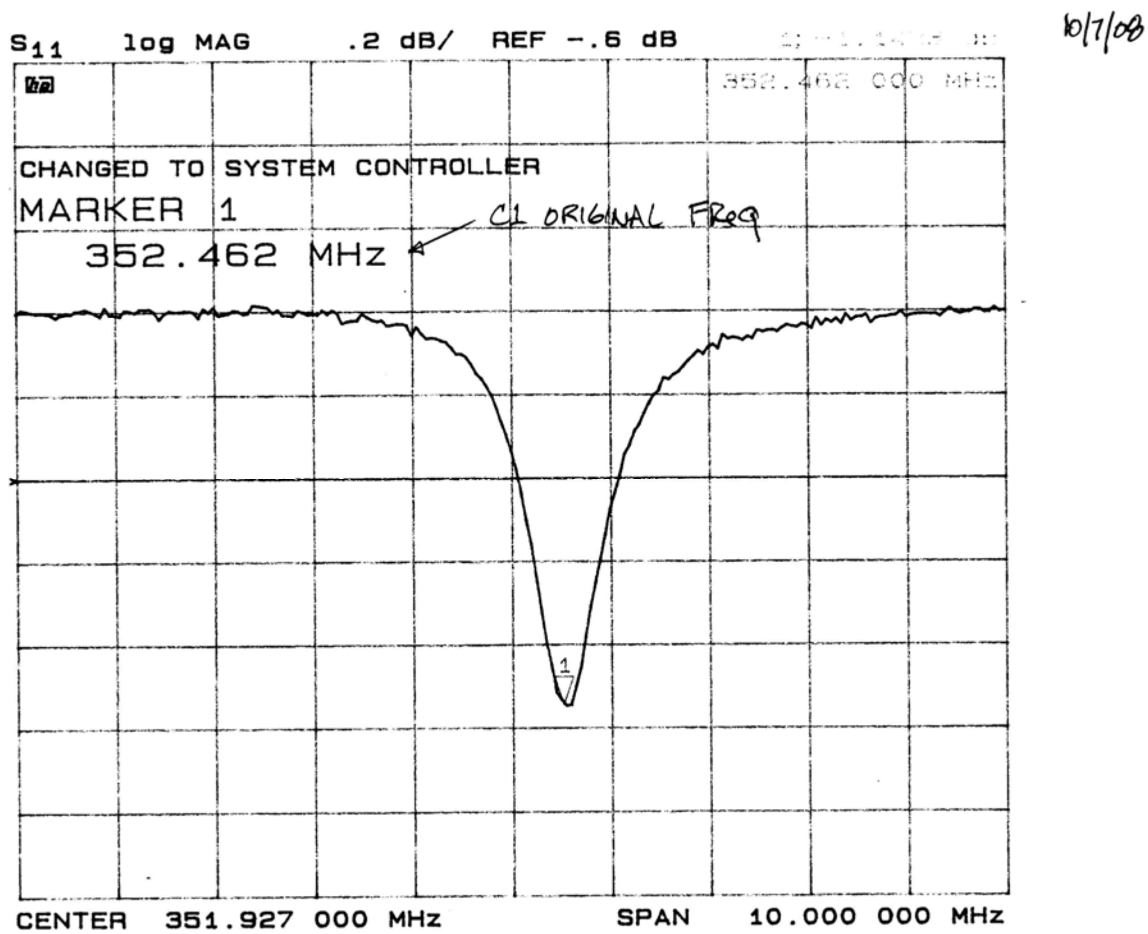

Figure 4 – C1 resonant frequency measurement before tuning.

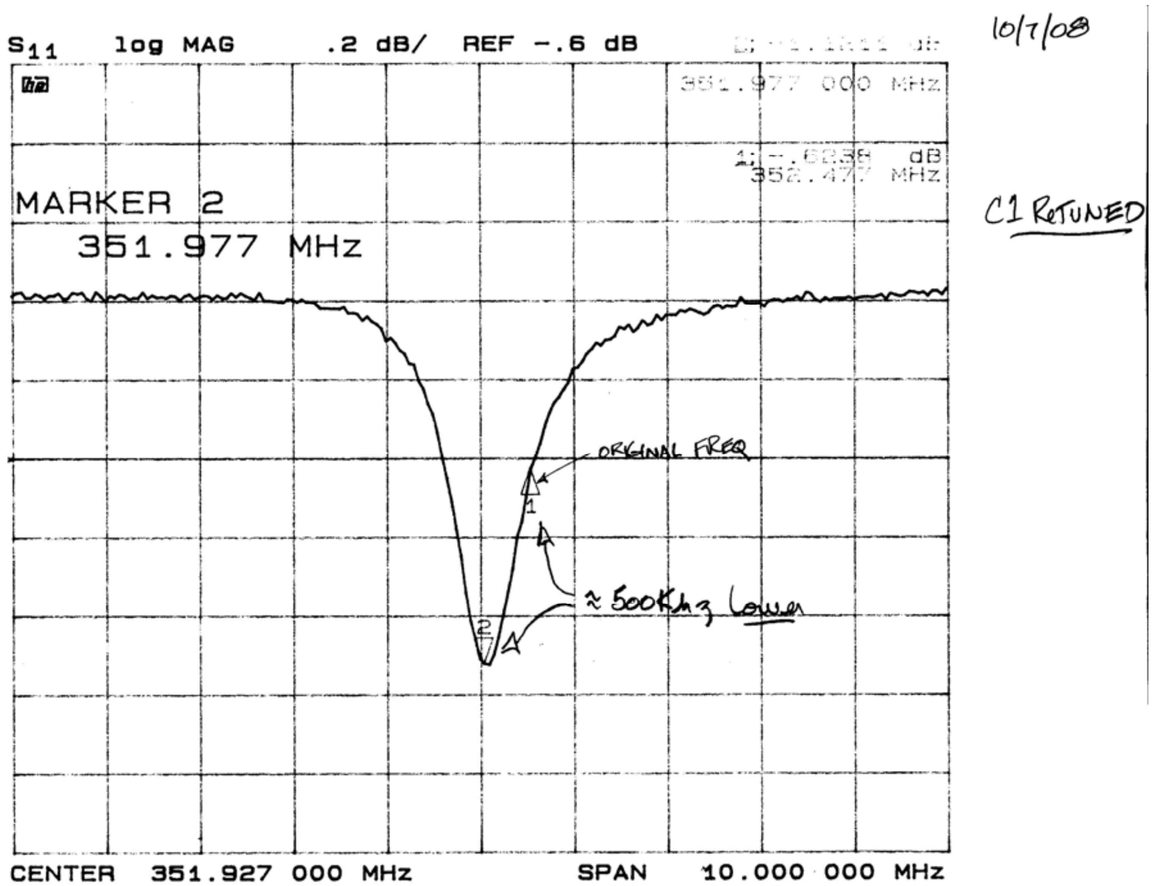

Figure 5 – C1 resonant frequency after tuning, approximately 500kHz below original frequency.

V. Operation after First C1 Retuning

On 10/8/08, the operating frequency was changed to 351.93MHz and operation of the klystron was started at the CERN test data operating point of 70kV/11.75A and 75 watts rf drive. The klystron produced approximately 420kW, which was within approximately 5% of the power level from the CERN data, indicating that C1 was tuned in the proper direction and rf gain was increased. From this point we repeated several other CERN test operating points with similar results. The last operating point was 88kV/1MW rf output, where the klystron produced approximately 950kW with 110 watts of rf drive at over 65% efficiency. The tuning change of C1 had increased the rf gain to approximately 39.3dB, which now made it possible to drive the klystron close enough to saturation to achieve acceptable efficiency. However, it could not be confirmed that the klystron was not fully saturated during this test, as the test stand driver amplifier was running at full output (slightly greater than 200W) to achieve 110 watts at the klystron input jack and therefore may have reached saturation before the klystron. There were no signs of instabilities, and cathode emission was stable with the heater power approximately 100 watts less than was applied during the CERN tests. Performance data at this operating point is shown below.

Cathode voltage = 88kV
Beam current = 15.47A
Mod-anode voltage = 41.86kV
Gun perveance = 1.86μperv
Beam perveance = 0.59μperv
RF drive power = 110 watts fwd/41 watts ref
RF output at klystron (EPICS) = 943kW
RF output at rf load (calorimetric) = 890kW
Efficiency = 65.3%
P collector = 480kW
P body = 7kW
P output cavity = 7kW
Heater power = 19.97A @ 21.4V DC
Focus current = 10.7A

The klystron operated at this output level for approximately seven minutes until the power supply tripped on klystron ion pump current. The ion pump reading quickly returned to normal after the trip, which suggested that the vacuum trip may have been caused by an rf arc in the output cavity.

The high efficiency achieved during the 88kV run suggested that no tuning of cavities C2-C6 would be required for operation at 351.93MHz. However, the rf drive power requirement to reach saturation was still too high for the 200-watt driver amplifiers used at APS, necessitating a second tuning of C1 to bring the cavity frequency closer to the target value of 352.180MHz and thereby optimize rf gain. C1 was subsequently re-tuned approximately 100kHz higher by moving one adjustment locknut by roughly one “nut face”. The results of this change are shown in Figure 6.

After the second tuning of C1, operation of the klystron was resumed. However, a power supply problem developed that prevented us from achieving greater than approximately 4.2A of beam current in the klystron due to the loss of control over mod-anode voltage at values over approximately 19kV. System troubleshooting indicated that a problem had developed in the DTI anode regulator, which may have been the root cause of the vacuum trip experienced with the klystron during the previous run.

An attempt was made to operate the klystron directly from the RF1 anode tank was made using custom-made long Pantak cables that were used several years ago to commission the DTI anode tank using the RF1 klystron. However, this was not successful due to a breakdown problem somewhere in one of the three cables which caused the RF1 crowbar to fire repeatedly at approximately 50kV. At this point further operation of the klystron was suspended.

To rule out any problem with the klystron being responsible for the crowbar firings, the klystron gun was tested for high-voltage breakdown and excessive leakage current with the spotknocking power supply. The results of this test were normal, with no breakdowns noted across either gun ceramic.

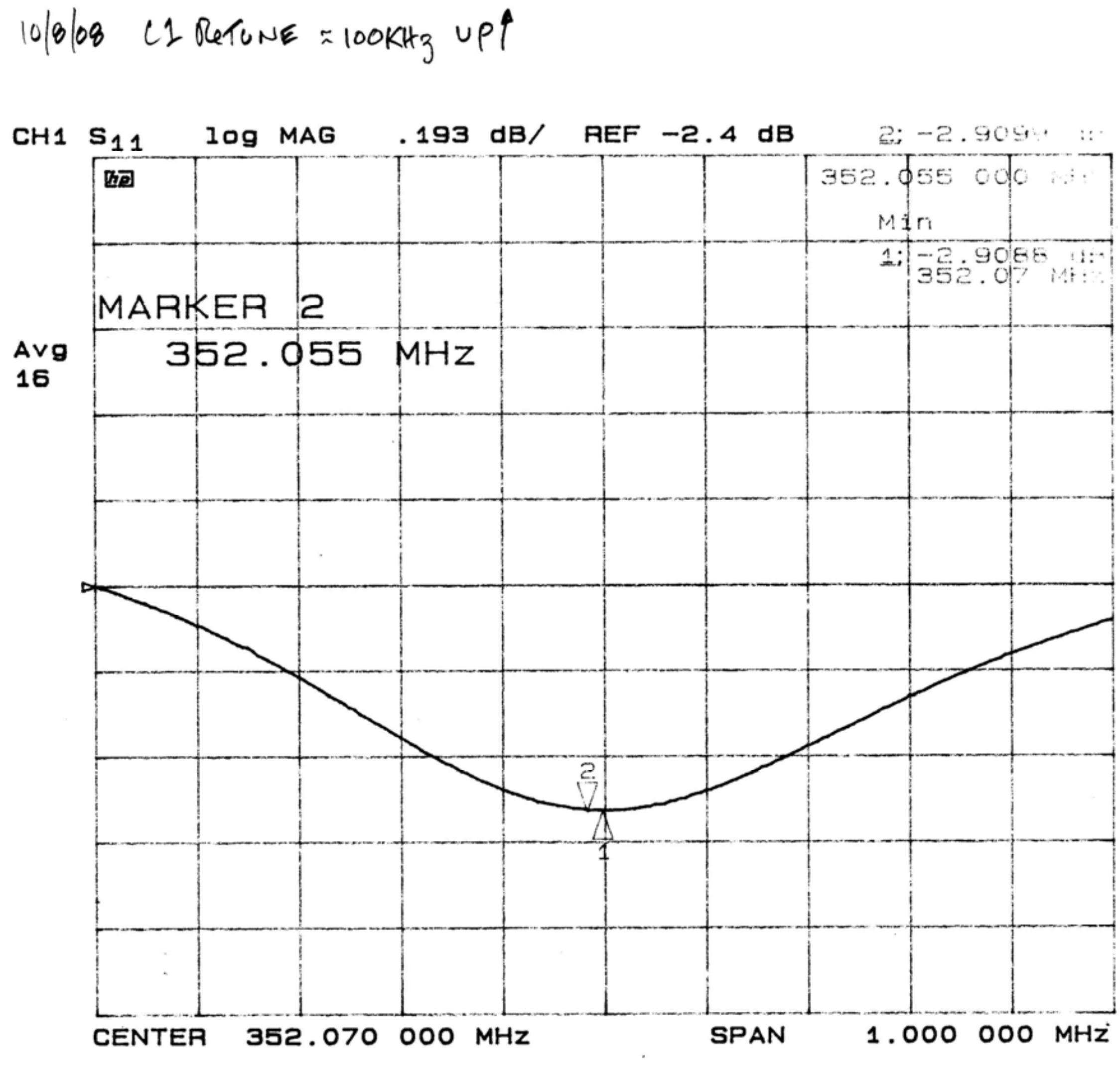

Figure 6 – C1 frequency after tuning approximately 100kHz up.

VI. Operation after Second C1 Retuning

On 2/17/09, the klystron was again operated into the 1MW test load at 351.93MHz to verify the effects of the second retuning of C1 (see Figure 6). As expected, the rf gain of the klystron was further increased by the retuning, which allowed the klystron to be operated at close to rf saturation with less than 100 watts of drive power.

At a beam power of 85kV/15A and an rf drive level of 89 watts, the klystron produced approximately 875kW rf output power at the klystron output flange, and resulted in 800kW dissipation (calorimetric calculation) into the test load. Based on the power dissipation in the 1MW rf load, the demonstrated efficiency of the klystron was 62.7%. The actual efficiency could be as much as 4% higher due to the appreciable accumulated transmission loss between the klystron output flange and the rf load. The klystron operated at this level for approximately ten minutes with no problems. Due to studies-period time constraints, operation at 1MW was not attempted. However, the klystron had demonstrated 1MW output previously with no problems, and it was clear from this test data that 1MW output at 351.93MHz would be easily achievable.

VII. Conclusion

Test data indicates that retuning C1 is the only change necessary to allow this klystron to operate efficiency at 351.93MHz, and that the klystron will now operate in the APS rf systems with no performance degradation. Two tuning changes were made on C1, the first of which recovered rf gain to the point that the klystron could be driven close enough to saturation to achieve 65% efficiency. A second tuning of C1 was made to increase rf gain slightly and reduce the rf drive requirements necessary for 1MW operation to less than 100 watts at the klystron rf input connector. This C1 retuning will now allow the klystron to be used as an operational spare for the APS booster and storage-ring rf systems with little modification necessary to the installed system support hardware.

The low operating time on this klystron suggests that it could provide many years of reliable service in support of APS operations. The close similarity between the Philips and EEV klystron design makes this klystron an ideal candidate to replace the EEV klystrons presently in service at RF1 and RF3. The 1MW collector dissipation limit on the Philips klystron design will require adjustment of interlock trip points and rf system operating procedures to limit collector dissipation during system start up and when interlock systems inhibit rf drive to the klystron. However these adjustments will be minor and within the range of the existing APS booster and storage ring rf interlock systems.

VIII. Acknowledgements

I would like to acknowledge APS RF Group staff members Gian Trento and Tim Berenc, RF Group Technicians Mike Drackley, Dave Jefferson and Mark Moser, and Hans Frischholz, a retired CERN rf engineer, for their valuable assistance during this work.