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Modifying CERN SPS Cavities and Amplifiers for Use in RHIC

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Abstract

A system of ten rf cavities operating at 197 MHz will provide longitudinal focusing during beam storage in the Relativistic Heavy Ion Collider (RHIC). The cavities and tetrode amplifiers are from CERN where they had been used in the Super Proton Synchrotron to accelerate leptons for injection into LEP. The amplifier-cavity system had an impedance pole about 3 MHz below cavity resonance which was a possible source of oscillation with rf feedback. This was not a problem at CERN because the cavities were operated without feedback. The impedance pole was moved lower in frequency by extending the length of the drive line. When this was done it was no longer possible to tune the amplifier to give a good match to the drive loop resulting in about 50% anode efficiency. In the class of operation we are using, an efficiency of 65%-70% is expected. A good match was achieved by increasing the loop coupling from 16Ω to 19Ω.

Introduction

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab will accelerate and store beams ranging from protons to gold nuclei [1]. One system of four rf cavities operating at 28 MHz [2] accelerates the beam from injection energy to storage energy, and a system of ten cavities operating at 197 MHz provides longitudinal focusing during storage. The storage system cavities and tetrode amplifiers are from the Super Proton Synchrotron at CERN where they accelerated leptons for injection into LEP [3].

The amplifier-cavity system has an impedance pole about 3 MHz below cavity resonance which is a possible source of oscillation with rf feedback. At CERN the cavities were operated without feedback and care was taken to avoid external feedback, so the impedance pole was not a problem [4].

Experiments were conducted at RHIC to move this pole away from cavity resonance. We found that the pole could be moved lower in frequency by increasing the length of the final drive line. Evidently the drive line had been made quite short because of space limitations in the SPS tunnel. When the longer drive line was installed it was no longer possible to tune the amplifier to give the required impedance transformation, limiting the amplifier to about 50% anode efficiency. The efficiency was increased to about 70% by increasing the loop coupling from 16Ω to 19Ω. This paper describes these experiments and the performance results.

Impedance Pole

Figure 1 shows the 16Ω drive line with the base of the amplifier clamped to the flanges on the top of the coaxial elbow and the drive loop installed in the cavity. The line has forward- and reverse-power directional couplers and the cavity has small pickup loops. Two S_{21} network analyzer traces, fig. 2, were made by driving the amplifier with the analyzer.

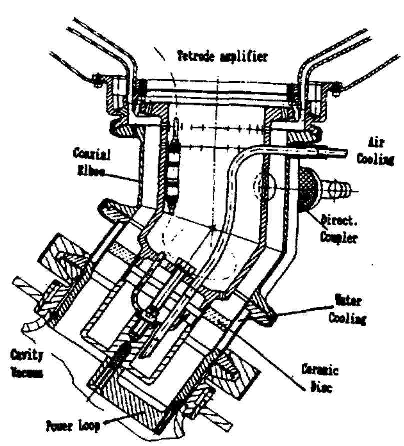

Figure 1. The transmission line connecting the amplifier to the cavity. This figure is copied from reference 3.

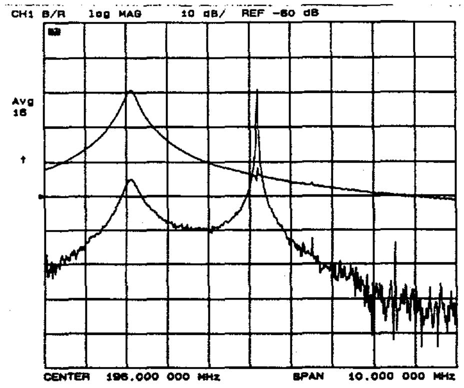

Figure 2. Network analyzer traces showing the impedance pole and cavity resonance. Top trace is the signal from the forward-power coupler in the drive line, and the bottom trace is from a loop inside the cavity. The cavity was tuned to 196 MHz when these measurements were made.

The top trace is the signal from the forward-power coupler in the drive line and the bottom trace is the signal from one pickup loop. In the cavity, the power received at the pole frequency is only 25 dB lower than at cavity resonance. With rf feedback this resonance can be the same or larger than the cavity resonance.

The first experiment was to separate the amplifier from the drive line flange and to short the inner and outer conductors at the amplifier base with copper tape. A network analyzer and broad-band amplifier were used to drive the amplifier and the signal was picked up on a diagnostic probe at the base of the amplifier. The result, fig. 3, shows that the amplifier transforms an electrical short at its output to impedance poles which are symmetrical about 197 MHz. Since the drive loop is a short circuit off resonance this shows that the pole does not result from the impedance transformation in the amplifier.

Next an adapter was placed on the drive line flange and an S_{11} measurement was made of the impedance presented to the amplifier. The network analyzer measurement showed the electrical length of the transmission line to be about 3/8 λ giving an off-resonance impedance which is capacitive. By adding a phase offset equivalent to 19.4 cm of transmission line at 197 MHz the transformed impedance presents an impedance zero off resonance.

Reference 4 describes the impedance transformation within the amplifier as being approximately a λ/4, 3Ω transmission line in series with a λ/4, 18.5Ω line. PSPICE was used to calculate the impedance of a short circuit transformed through a 3/8 λ section of 16Ω line in series with the two λ/4 lines of the amplifier. This calculation gives poles at 197 and 232 MHz and both move lower in frequencies when the 16Ω line is lengthened. When the line is λ/2 long the upper and lower poles are symmetric around 197 MHz.

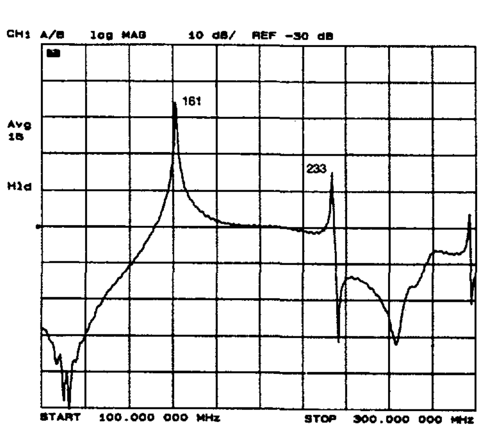

Figure 3. Anode impedance as a function of frequency with an electrical short across the output of the amplifier.

The drive-loop transmission line was lengthened by adding a 17.1cm insert in the coaxial elbow section. This insert initially was made 19.4 cm but measurements made before the pieces were welded indicated it was too long. With the longer line installed the impedance poles were 12 MHz below and 18 MHz above resonance. The initial length of 19.4 cm would have placed them symmetrically about the resonance.

Amplifier efficiency

After the drive line was extended it was no longer possible to get the required power from the tetrode without exceeding the tube specification for power dissipation on the screen. A storage cavity has a shunt impedance of 8.5 MΩ and requires about 60 kW of rf power to produce 1 MV in the gap. To deliver 60 kW without drawing excessive screen current requires the loop impedance be transformed to an anode impedance of about 625Ω. This transformation is accomplished by two sections of transmission line in the amplifier base which approximate λ/4 transformers of 3Ω and 18.5Ω connected in series.

The tetrode amplifier that drives the cavity is operated in class AB with the grid biased at -200 V, the screen at 900V and the anode at 10kV. At full power the conduction angle is 190° and the tetrode should give ~70% efficiency. We measured 54% efficiency (see table) on a test stand consisting of a 50Ω water-cooled load transformed to 16Ω by a λ/4 transformer of Z_t=28.3Ω. To increase the efficiency it was necessary to measure the loop-anode impedance transformation from the operating parameters of the tube.

For small anode rf voltages the electron current in a tube varies with grid voltage approximately as,

$$I(t) \propto (V_{g0} + V_{g1} \cos \omega t)^{1.5} \quad (1)$$

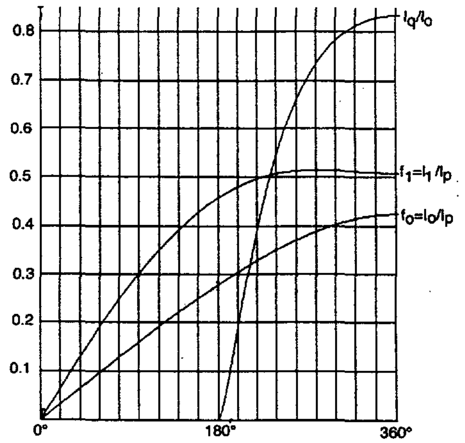

Figure 4. Tube current form factors calculated by W. Pirkl. Bottom axis is conduction angle of tube. All measurements were made with an angle of 190°-200°.

where V_{g0} is the grid bias voltage and V_{g1} is the grid drive amplitude. This expression can be used to calculate the Fourier components of the current [5]. The dc and rf fundamental components are,

$$I_0 = \frac{1}{T}\int_0^T I(t)dt = I_P f_0 \qquad (2)$$
$$I_1 = \frac{2}{T}\int_0^T I(t)\cos(\omega t)dt = I_P f_1$$

where I_P is the peak current during the rf cycle. These form factors, f_0 and f_1, are plotted in fig. 4 together with a curve of quiescent current divided by anode current, I_q/I_0. We measured the ratio I_q/I_0 and read the conduction angle from the graph. The ratio f_1/f_0 could then be determined from the graph and the rf current, I_1, calculated as the anode current times this ratio. The tube power and anode current were measured and the impedance calculated from $P=I_1^2R/2$.

A series of measurements was made on the test stand in which output power was measured as both the frequency and the amplifier tuning position were varied. The tube socket can be raised and lowered for tuning and it was not known whether this changed only the frequency or both the frequency and transformed impedance. Figure 5 shows the family of curves generated. For all of these measurements the anode current was 3.1A and the quiescent current was 0.6A giving a ratio of f_1/f_0 equal to 1.52. All of the tuning curves peak at 6.1 kW showing the tuning changes only the frequency of the impedance transformation. A power of 6.1 kW with an rf current of 4.7 A gives an impedance of 550Ω. The same analysis on other data sets gave values in the range of 515Ω-550Ω. From these measurements we concluded that the amplifier transforms 16Ω to about 525Ω.

The test stand presents an impedance to the amplifier equal to $(Z_t)^2/50$. The impedance of a coaxial line increases as the diameter of the center conductor decreases so we were able to increase the impedance presented to the amplifier in 1Ω steps by machining down the inner conductor of the λ/4 transformer. The measured efficiency peaked at 20Ω, however the screen current started to get very high. We chose a loop impedance of 19Ω.

Conclusion

The loop was rotated to give 19Ω coupling and the drive-line extension was installed. The cavity was then conditioned to a peak gap voltage of 1.0 MV at which time the measurements in the third column of the table were made. These two modifications have increased the amplifier efficiency from about 50% to about 70% and have moved the impedance pole 12 MHz away from the cavity resonance.

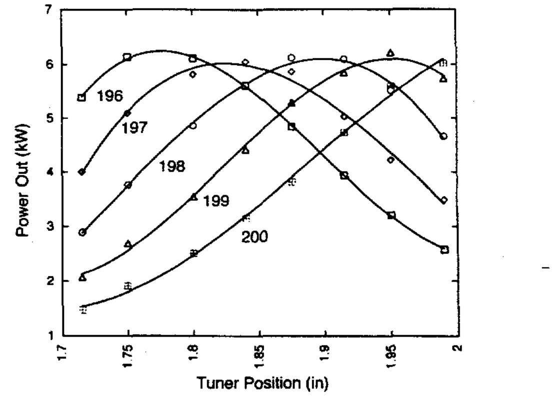

Figure 5. Measured power as a function of tuner position for five frequencies. Tuner changes the frequency of maximum anode impedance but not the magnitude.

Comparison of amplifier parameters reported by CERN [4], those measured at BNL on 16Ω load, and those measured on cavity after modifications. The final efficiency of 73% is from a single measurement and is probably a little too high.

	CERN	16Ω load	Final
Anode voltage	10 kV	10 kV	9.8 kV
Anode quiescent current	0.5 A	0.5 A	0.5 A
Anode current	9.4A	9.95 A	7.77 A
Screen grid voltage	900 V	900 V	900 V
Screen grid current	320 mA	405 mA	150 mA
Control grid voltage	-200 V	-200 V	-200 V
RF output power	62 kW	53 kW	57 kW
RF drive power	1.8 kW	1.75 kW	1.44 kW
Gain	15.4 dB	14.8 dB	16.0 dB
Anode efficiency	64%	54%	73%

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