PERFORMANCE OF RF AMPLIFIERS FOR ISAC-II MEDIUM BETA LINAC OPERATION

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Abstract

A heavy ion superconducting linac at TRIUMF to increase the final energy of radioactive beams from the existing room temperature ISAC accelerator is now operational. The linac consists of twenty quarter wave cavities operating at 106 MHz to produce an accelerating voltage gain of 20 MV. This paper describes the operational experience of the 106 MHz rf tube amplifiers which were installed and commissioned for the medium beta linac in October 2005. Total rf power installed is 16 kW where one quarter power is used for regular linac operation. During the initial commissioning of the amplifiers, only one power tube was found to be noisy and was replaced. The first major tube failure occurred in April 2007 after 9000 operating filament hours. Soon thereafter five more tubes showed signs of loss of gain. It was evident that most of the tubes reached their tube life by this time and all were replaced with new tubes. The extension of tube life, and prediction of tube failure are the main concerns of these tube amplifiers. Efforts are being made to incorporate reduced filament power operation in order to get longer tube life. Systematic check of the amplifier performance during scheduled maintenance and shutdown period is undertaken. Reduction of tube emission and hence gain degradation from their nominal value causes excessive drive power from the rf control system to keep the cavity voltage constant under closed loop. Hence monitoring the drive power is useful to predict early tube failure. Input drive power and gain of all the 20 amplifiers are available at the EPICS data archive which can be monitored and plotted. This will allow early warning of tube failure so that tubes can be replaced before they actually fail. The failure modes of the tubes and diagnostics to predict tube failure will be described.

INTRODUCTION

A heavy ion superconducting linac is being commissioned at TRIUMF to increase the final energy of radioactive beams from ISAC and provide at least 6.5 MeV/u of beam energy. The superconducting linac has been grouped into three stages, namely low beta, medium beta and high beta. In October 2005, the medium beta section comprising of 20 quarter wave bulk niobium cavities have been installed and commissioned [1]. Each cavity, operating at 106.08 MHz is energized by independent rf amplifier with power out put of 800 watts [2]. Operational experience of these rf amplifiers for last 2 years are described here. Extension of tube life and predicting early tube failure are the main concerns of these amplifiers for smooth running of the linac.

RF POWER AMPLIFIERS

The amplifiers employ EIMAC 3CX1200Z7/YU-181 high mu triode with Thoriated Tungsten filament. The amplifiers operate in cw mode and on an average 150 watts of power is required for each cavity for nominal operation of the linac. However, only 7 watts is required to produce a gradient of 6 MV/m when the cavity is critically coupled. The total installed rf power of the amplifiers is 16 kW. Conditioning of the superconducting cavities are done with 600 watts of rf power with a 50% duty cycle and pulse duration of 1 second. The amplifiers were tested against specified amplitude and phase linearity and also on phase noise. During commissioning of the linac in 2005, only one tube was found to exceed the phase noise margin specified [3] and was replaced. The first major tube failure occurred in April 2007 after 9000 hours of filament life. Soon after this, five more tubes showed lower cathode emission and were replaced. This was evident from the fact that more and more drive was required to sustain the same output power of the amplifiers [4]. Since all the tubes had been running on an average for 8500 hours, it was decided to replace all old tubes with new tubes in June 2007. The 20 amplifiers for medium beta linac are installed in a power supply room which is above the linac vault. These amplifiers are grouped in four amplifiers and feed 5 cryomodules which constitute the medium beta linac. Figure 1 shows the layout of the amplifiers along with rf control and other supporting systems. Two racks on extreme right side of each row house 4 amplifiers required for each cryomodule.

RF DRIVER AMPLIFIER

All 20 final power amplifiers are driven by solid state amplifiers. These amplifiers also contribute to down time of the linac operation. During the 2 year operation of the amplifiers, none failed, however cooling fan of a spare amplifier failed. The cooling fans of these drivers are mounted directly on the amplifier units and are not interlocked with the amplifier system. Interlocking these fans using thermocouples will be incorporated in next shutdown. The sold state amplifiers require an average of 20 watts of output power to obtain 400 watts from the final amplifier. As part of maintenance, these amplifiers are tested against a 50 ohms dummy load. Figure 2 shows the dc current drawn by the driver from the 24 V dc power supply to produce 400 Watts of output power at the final amplifier and gain of the drivers for all

Figure 1: Layout of RF Amplifiers for Medium Beta Linac in the Power Supply Room

20 amplifiers. As the gain of the final amplifier drops with tube aging, more drive power is required which in turn draws more dc current from the dc power supply. Hence dc current measurement gives good indication of tube condition. Dc current excess of 10 A under normal operating conditions indicates tube problem.

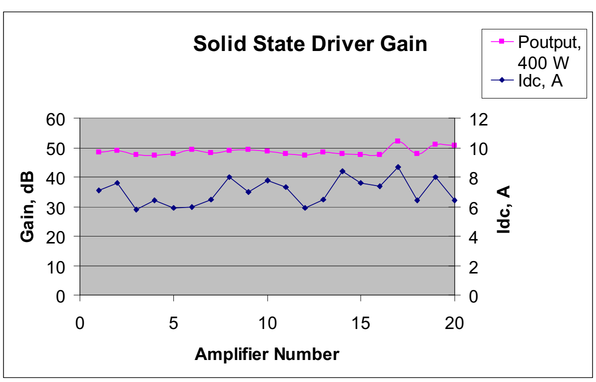

Figure 2: Amplifier gain and dc current for solid state driver amplifiers for 400 Watts output from the power amplifier

TUBE LIFE

Extension of Tube Life

Tube life can be extended by reducing filament power to a point that output power and gain remain nearly unchanged. Tube manufacturers recommend to run the filament for a period of 100 to 200 hours at its rated filament voltage which allows vacuum of the tube to be established in its actual operating temperature. After this initial filament run, it is recommended to operate the filament at a reduced voltage provided the proper operating parameters of the amplifier can be obtained at this reduced voltage. The method to achieve the reduced filament voltage is as follows. Run the filament at the rated filament voltage and obtain the normal operating parameters of the amplifier. Using a variac in the ac input of the filament, slowly reduce the filament voltage till power output starts to fall without changing drive power or tuning of the amplifier. This point is the beginning of the emission limited operation. Operating the tube at this point can be destructive to the tube. Running the filament 0.1 to 0.2 volts above the lowest voltage will maximize the tube life. Figure 3 shows gain of the 106 MHz amplifier as a function of the filament power for output power ranging from 100 to 300 watts. The power output starts dropping around 85% of the rated filament power. A power tube operated in this manner will generally yield life at least 50 % greater than a tube run continuously at the rated voltage. Running the filament at 85% of the full rated power is expected to yield twice the nominal tube life [5]. Hence, it is expected that the tube life will be increased from 50% to 100% by lowering the filament

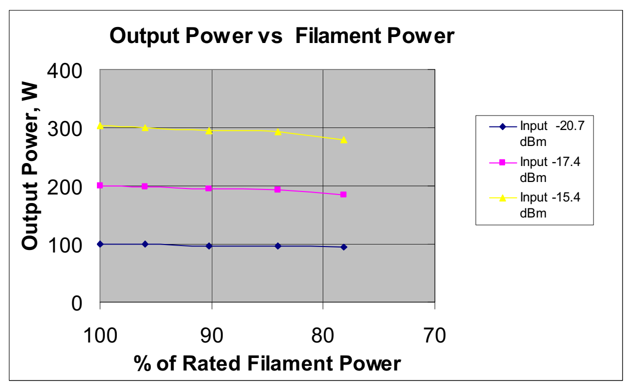

Figure 3: Output power of amplifier with varying filament power

voltage. The tubes failed after running for 8500 hours with nominal filament voltage, hence with the reduced filament voltage the tubes are expected to last at least 12000 hours. However, the guaranteed lifetime from tube manufacturer is about 5000 hours. With 2 months of shutdown /year and some time off for regular maintenance, the tubes should last for 2 calendar years. It should be noted that the filament power management works with Thoriated Tungsten filament and not for oxide cathodes. Figure 4 shows power output vs. power input at two different filament powers. The test has been conducted in a test stand using identical amplifiers as installed in the linac. The test will be conducted uninterrupted for extended period so as to establish tube life with filament power set at 85% of the rated value.

MEASUREMENT AND MONITOR OF GAIN

It is very important to be able to predict within some certainty the end of tube life so that spare tubes can be stocked in-house and can be installed without causing beam delivery delays. A program has been taken up to measure gain and amplifier performance during shutdown and long maintenance period. This will indicate any deterioration of tube performance and hopefully will give early warning of tube failure due to limited filament life.

MEASUREMENT OF GAIN

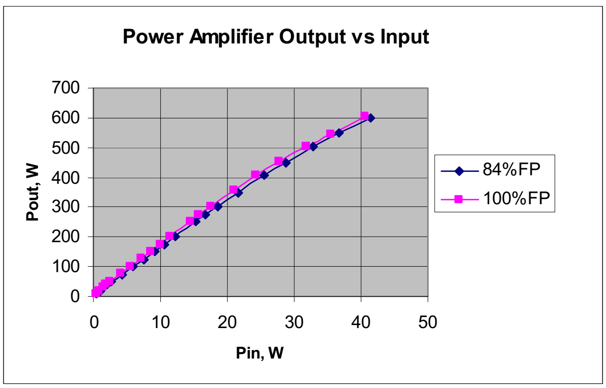

Figure 4: Output power of final power amplifier with different filament powers

The gain performance of all 20 amplifiers have been measured over two years period. The gain of all amplifiers as they were installed in 2005 and gain of all tubes replaced in 2007 are shown in figure 5. All amplifiers have an overall gain of at least 62 dB except amplifier number 3 which has a slightly lower gain. This could be due to the corresponding lower gain of driver amplifier and improper tuning of the power amplifier. The performance of all the drivers and the power amplifiers as measured in June 2007 are listed in table 1. SCB1 to SCB5 are the five cryomodules each has four cavities fed by 4 rf power amplifiers. Tubes in amplifiers 1,5,8,10 and 20 uses tube type Y229 where as the remaining tube types are EIMAC YU181-E1. Both tubes are close in their electrical ratings and are recommended as replacement tube.

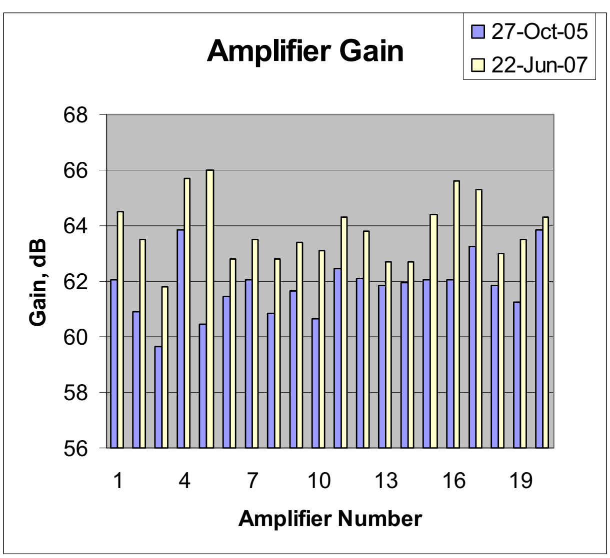

Figure 5: Amplifier gain measured in October 2005 and June 2007

Table 1: DC and RF parameters measured for all 20 amplifiers

Amplifier Installed in Linac /Amplifier no	400 Watts Output Power		RF Paramaters		Maximum Power Output, W
	Driver I(A)/V	Plate I (A)	Pin, dBm	Gain, dB	
SCB1/1	7.1/23.1	0.39	-8.5	64.5	700
SCB1/2	7.6/23.1	0.38	-7.5	63.5	720
SCB1/3	5.8/21.1	0.36	-5.8	61.8	760
SCB1/4	6.4/23.1	0.38	-9.7	65.7	800
SCB2/5	5.9/23.2	0.36	-10.0	66.0	670
SCB2/6	6.0/23.4	0.39	-6.8	62.8	880
SCB2/7	6.5/23.3	0.39	-7.5	63.5	910
SCB2/8	8.0/23.2	0.38	-6.8	62.8	720
SCB3/9	7.9/23.3	0.41	-7.4	63.4	760
SCB3/10	7.8/23.3	0.40	-7.1	63.1	670
SCB3/11	7.3/23.3	0.40	-8.3	64.3	1000
SCB3/12	5.9/23.1	0.42	-7.8	63.8	1000
SCB413	6.5/23.4	0.38	-6.7	62.7	980
SCB4/14	8.4/23.3	0.39	-6.7	62.7	910
SCB4/15	7.6/23.4	0.41	-8.4	64.4	840
SCB4/16	7.4/23.2	0.40	-9.6	65.6	840
SCB5/17	8.7/23.2	0.36	-9.3	65.3	960
SCB5/18	6.4/23.2	0.36	-7.0	63.0	860
SCB5/19	8.0/23.2	0.39	-7.5	63.5	950
SCB5/20	6.4/23.3	0.41	-8.3	64.3	860

MONITOR GAIN

Each rf amplifier system has dedicated rf control system for amplitude and phase feedback system. Gain of each amplifier is computed by the RF control software and is passed on to EPICS. Thus, the gain of all 20 amplifiers can be obtained from EPICS archive which saves data every 5 minutes. This data can be retrieved and plotted and hence any degradation of gain can be observed which will prompt action from the rf service group. A sample EPICS strip chart is shown in Figure 6 for 8 amplifiers where amplifiers were switched off. The traces are background noise picked up by the EPICS. The gain scale in the vertical axis is arbitrary and will be calibrated when amplifiers are running. The variable name for gain of each amplifier generated by RF software is : SCBx:CAVy:Gain, where x is 1 to 5 and y is 1 to 4.

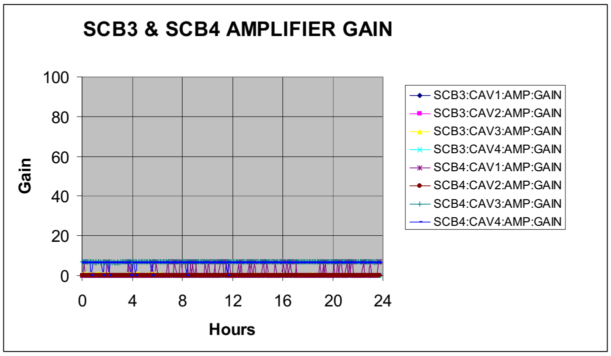

Figure 6: Gain of amplifiers in SCB3 and SCB4 obtained from EPICS archive

IMPROVEMENTS

During the commissioning and running of the accelerator over last 2 years, some of the deficiencies of the 106 MHz amplifier system were found. The input matching knob of the power amplifier is very sensitive and moves easily. The cure is to either provide a locking mechanism or make it less sensitive or do both. The output circuit employs resonant circuit which can add to amplitude noise induced by vibration. Vibration from cooling fans can induce line frequency modulation on the amplitude. Care is taken to mount the fans on vibration absorbing pads to reduce this noise. Since no prior history of these tubes were known, it was not possible to predict tube failure due to filament life. Keeping a stock of new tubes for immediate replacement is mandatory to keep down time of linac operation to minimum due to tube failure. One of the biggest advantages of modern power tubes with metal and ceramic vacuum envelope are not prone to gassing up while in storage. These tubes can be stored indefinitely without deterioration thus shell life is long. The filament power management program is now installed which will provide longer tube life. This will give rise to saving in running cost.

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