DEVELOPMENT OF 35 KW POWER AMPLIFIER AT 350 MHZ FOR RFQ BASED NEUTRON GENERATOR

Manjiri Pande, Atul Soni, Niranjan Patel, K.R.shinde, M.K.V.Rao, V.K.Handu
Vacuum Physics and Instrumentation Division,
Bhabha Atomic Research Centre, Mumbai-400085, India

INTRODUCTION

A 400 KeV, 1 mA (deuterium ion) radio frequency quadrupole (RFQ) based 14 MeV Neutron generator [1] is being developed in BARC to study physics of coupled neutron sources, sub-critical assembly and radio frequency (RF) coupling to accelerator. RFQ will accelerate the deuterium ion beam from 50 KeV to 400 KeV which will impinge upon a tritium target inside a sub-critical assembly to generate 14 MeV neutrons. Two RF systems of power around 35 KW each, are under development to feed the RF power at two ports of the RFQ. This paper describes the system design aspects, operating conditions and current status of the RF power system.

RF SYSTEM DESCRIPTION

Each 35 kW amplifier is a three-stage amplifier chain, comprising of a 100 W solid-state driver, a triode based intermediate power amplifier (IPA) of 1.5 kW and a tetrode based high power amplifier (HPA). Auxiliary power supplies, forced air/water cooling circuits and circulators are part of the associated electronics.

Driver

The solid-state driver [2] requires a maximum input of 20 dBm and provides up to 100W of power. It is coupled to Intermediate Power Amplifier (IPA) via a Y-junction circulator. The IPA uses EIMAC 8938 coaxial base triode. It is configured in cathode driven i.e. in grounded grid mode. Its input matching circuit uses 'L' type circuit using lumped components, output matching circuit uses a single ended half wave-length strip line (Fig. 1), capacitively loaded by the tuning capacitor at one end and by the tube output capacitance at the other end. This plate line is a short transmission line with characteristic impedance of 53 Ω. The triode is operated at an anode dc voltage between 1.5 kV to 3 kV by means of a variable 4 kV power supply.

Table 1: Test results of IPA at various frequencies.

Frequency (MHz)	Output power (W)	Efficiency (%)	Gain (dB)
343	500	25	8.3
350	200	12	4.0
368.8	740	34.3	10.2
368.8	420	60	7.25

A 47-Ω/50 W series resistance is inserted between the power supply and anode to dissipate energy in case of internal tube arc. Operating bias is established using 15 V zener. The test results of IPA are summarized in table 1. Efforts are being made to increase the rated output with better efficiency. Simultaneously a coaxial cavity based configuration for 8938 is being tried. Its design and simulation work is in progress.

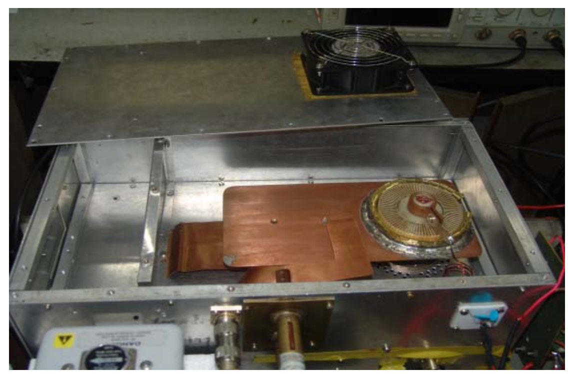


Figure 1: Intermediate Power Amplifier (IPA).

THE HIGH POWER AMPLIFIER (HPA)

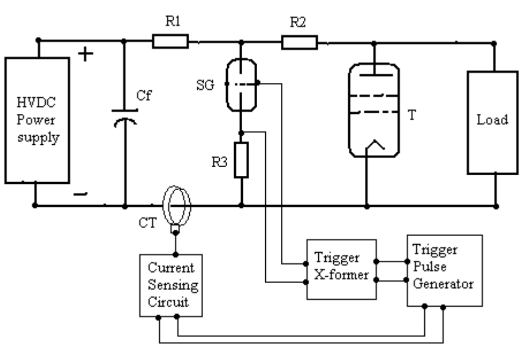
DC Power Supplies

The HPA is powered by a variable 12 kV/10 A EHT supply (Fig. 2) and associated control grid and screen grid power supplies. EHT uses a 3 Phase, 6 Pulse thyristor based ac regulator on the primary low voltage (LV) side. The controlled output voltage is stepped up and rectified in a transformer unit. Suitable L-C filter is incorporated to keep output ripple within the desired limit of 1%. The power supply has been installed and tested at full load for a voltage regulation of 1%. Various protection circuits like over-voltage, over current, under voltage, phase failure, thermal overload, oil temperature sensor and its protection, spark/arc protection have been incorporated in this power supply. Various fault conditions were simulated in this power supply and all above-mentioned protection features were checked. Many LED indication features are provided in the front panel for quick detection and rectification of any fault condition. These include phase failure/phase reversal; fuse fail trip, thermal overload, oil temperature indicator, under voltage trip, over-volt trip, SCR over-volt, etc. A well regulated dc supply for screen grid (800 V / 500 mA) and control grid (-300 V/500 mA) has been bench tested and installed.

Figure 2: Anode power supply and its transformer unit.

Crowbar Protection

All the power grid tubes operate at high voltages that can cause severe damage in the event of an internal arc across the tube, unless it is properly protected. This damage becomes catastrophic when power supplies use large capacitor resulting in large stored energy or follow on current. Hence to protect the tetrode from the stored energy of output filter of the power supply, a fast acting crowbar circuit is incorporated across HV power supply and tetrode. If the output current of the tetrode increases above the set value around 7 A, an appropriate pulse is generated to trigger the crowbar circuit. When crowbar is fired, it behaves like a short circuit, thereby allowing the capacitor to discharge its stored energy through crowbar instead of the RF tube. The spark gap breakdown voltage is 18kV and operating voltage will be between 10 to 14 kV depending upon insitu operating conditions.



Cf: Filter Capacitor T: Tetrode
SG: Spark Gap CT: Current Transformer
R1, R2 & R3: High Energy Resistance

Figure 3: Crowbar protection circuit.

A high-energy series resistor R1 (10 Ω/1 kW) (fig 3) is inserted between the power supply and the crowbar to limit the peak current into the crowbar as well as limit the peak current demand on the transformer and rectifier of the power supply. Another high energy series resistor R2 (10 Ω/1 kW) is used between crowbar and the RF tube to insure the majority of the current flows through the crowbar after trigger. Both the resistor will also damp the circuit ringing sufficiently to prevent current reversal in crowbar which will cause it to open before fault conditions are cleared. Energy dumping resistor R3 is provided in series with spark gap.

Filament Supply

This is a variac controlled, current regulated power supply with a regulation of ± 1%. A control circuit (Fig. 4) in the power supply adjusts the variac, as the supply output current varies beyond its set value. This ac supply ramps up the voltage from 0 to 8 V in 5 minutes with a minimum step voltage of 0.025 V. A provision is made in the circuit to apply permanent backup heating voltage of 1.5 V ± 5 % during amplifier off time. Heater current will be approximately 180 A corresponding to 8 V.

Figure 4: Filament supply.

Interlock and Protection Circuit

All the auxiliary power supplies and two low power RF modules of HPA needs to be switched ON and OFF in a predefined timing sequence to prevent damage to the high power RF devices. Hence a suitable interlock circuit (Fig. 4) has been developed. It initializes certain sequence and logically checks the actual presence of each parameter at its respective location. These parameters include low conductivity water (LCW) flow and temperature, airflow, filament voltage, control grid voltage, anode voltage, screen voltage and driver RF power.

Figure 5: Interlock and Protection circuit.

The protection circuit performs two functions. In the absence of any bias voltage, the next consecutive sequence is not activated. It also senses faults signals, such as fault in power sources like over voltage, over current, arcing in transmission line etc and generates a trip signal, which in-turn switches off individual parameter in a controlled sequence. The unit has manual reset switch, to reset the circuit after the trip condition. This unit provides indications for presence of all the voltages and trip condition on its front panel.

Tetrode Amplifier of HPA

The HPA (Fig.6) is designed [3] around TH571B tetrode in class-C mode. The tube is rated for 60 kW CW operation upto 400 MHz. It employs cavity configuration with λ/4 tuning circuit for anode and grid.

Table 2: Operating parameters of HPA.

Anode Voltage (kV)	10
Control Grid (Vg1) (V)	-300
Screen Grid-2 (Vg2) (V)	800
Power gain (dB)	14.6
Class of Operation	C
Efficiency (η)	74
Output RF Power (kW)	35

The operation of vacuum tube depends upon a number of interdependent parameters namely total cathode current, minimum instantaneous plate voltage, maximum grid voltage, plate and grid current conduction, which needs to be optimized to achieve high efficiency and high power gain. Hence behavior model [4] of TH571B is developed from its constant current curves using MATLAB. The code written in MATLAB uses asymptotic approximation method in order to get plate current, grid current and screen grid current as a function of grid and plate voltage.

Table 3: Optimized tube performance parameters given by the code.

Efficiency (η)	73.25 %
Power input (DC)	58.1 kW
Power output	42.56 kW
Total Peak Cathode current	40 A
Average anode current	5.81 A
Optimized anode conduction angle	94.96º

RF Transmission Line and Components

Coaxial line is used for transferring the RF power from source to accelerator in TEM mode. The HPA output is available on 6⅛” rigid coaxial line flange. Hence the RF transmission line was designed around 6⅛”, 50-Ω rigid line of EIA standard. It comprises of 90º miter elbow bends, straight sections of various lengths, directional couplers and RF load. These silver brazed components are made up of ETP copper with electronic grade brass flange. Each individual component has been designed and tested on VNA. The layout of this RF transmission line has been made for two cases: one for testing the RF power supply across 50-Ω resistive load and other for feeding the RF power to accelerator. The layout of the complete transmission system in the latter case has been simulated [5] in the Microwave Studio version 6.2.

Table 4: VNA Results (RCTL 304.8mm).

SWR	1: 1.067
Attenuation	0.356 dB/m
Reflection co-efficient	-29.58 dB
Forward transmission co-efficient	-0.0426 dB
Reverse transmission co-efficient	-0.0386 dB

The simulation gives SWR, Port impedance, surface current density, S-parameters, electromagnetic field analysis, etc. The test setup (Fig. 6) includes 571 B tube, cavity, transmission line, direction coupler and RF load. It has been assembled and installed with necessary water-cooling arrangements.

Figure 6: Tetrode based high power amplifier.

CONCLUSION

Most of the above-mentioned subsystems of 35 kW amplifier have been developed and evaluated for their expected specifications. Mechanical installation of cavity and tube has been completed.

ACKNOWLEDGEMENT

Authors wish to thank Dr. V. C. Sahni, Director, Physics Group and Dr. S. Kailas, Associate Director, Physics Group for their constant support and encouragement.

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[6] CST Microwave Studio software version 6.2.