A 200 KW POWER AMPLIFIER AND SOLID STATE DRIVER FOR THE FERMILAB MAIN INJECTOR

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Abstract

A limitation of the existing Main Ring rf system is the power that it can deliver. The Fermilab Main Injector will require 112 KW for accelerating the full intensity at 240 GeV per second, which is pushing the upper limits for the present rf power amplifiers used in the Main Ring. New 200 KW power amplifiers will be placed on the cavities in the tunnel with 4 KW solid state drivers and 30 KV series tube modulators in the equipment gallery. Design, reliability, and solid state driver operating in a Main Ring rf station will be presented.

I. INTRODUCTION

Reliability testing of the newly designed equipment built under an R&D program by the rf department was made by installing it in the present Fermilab Main Ring accelerator. This gave real time operating experience under beam loading conditions before the equipment went into full production for the Main Injector. The 200 KW power amplifier and a 4 KW solid state driver were installed in May of 1994 on RF-RF station 7. For over 11 months they have operated flawlessly.

II. 200 KW POWER AMPLIFIER

The new amplifier design is based on the following:

1. Reliability. Since this component is located in the tunnel and mounted on top the MR cavities, a failure requires downtime. Only the power module housing the Y-567B tetrode and the cathode resonator would now be in the tunnel. Previous designs have a 14 tube cascode and a 6 tube distributed amplifier attached to the power module in the tunnel.
2. Geometry of the mounting flange and anode circuit had to be compatible with the present MR-RF cavity.
3. We will use the Y-567B power tetrode along with Fermilab's existing tube socket parts (fingers and collets). We have used the Y-567B in our existing amplifiers for many years and the power stage has proven to have excellent reliability.
4. Provide improved water cooling on and around the tube socket and bypass capacitors to remove heat.
5. Provide peak rf current of approximately 21 amps.

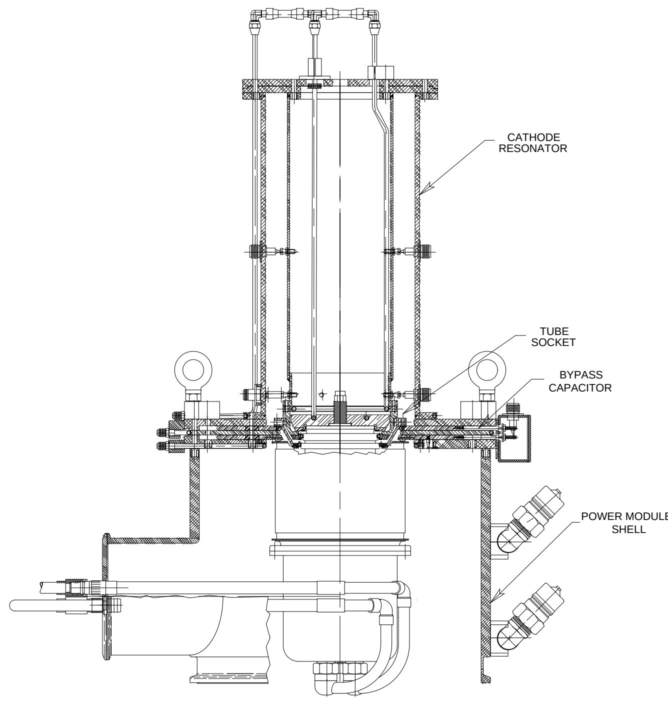

Figure 1. Cross section of the 200 KW power amplifier.

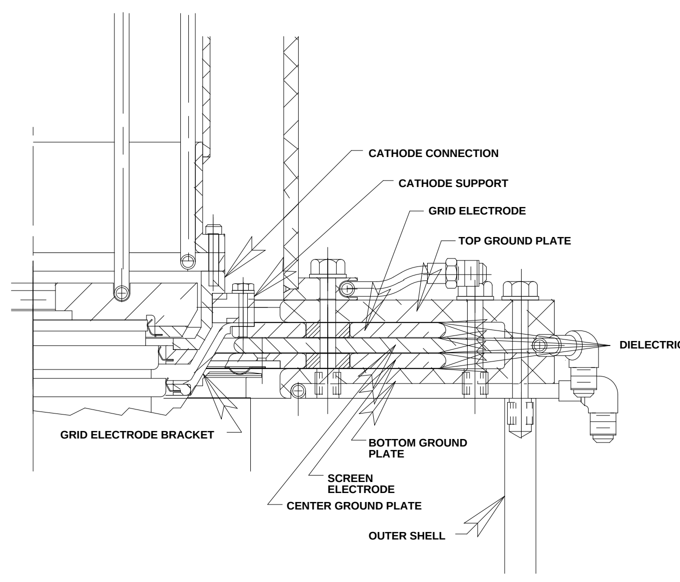

Figure 2. Detailed cross section of tube socket.

* Operated by Universities Research Association, Inc. under contract with U.S. Department of Energy.

Figure 1 is a detailed cross section of the complete amplifier. The grid and screen electrodes, grid bracket, cathode collet, filament block, center ground plane, and cooling rings are made of OFHC copper. The top and bottom ground plates are fabricated using aluminum tooling plate. Most of the other major parts are made from aluminum alloy 6061 T6.

Figure 2 shows the tube socket assembly with bypass capacitors. The screen and grid bypass capacitors are made of copper clad Kapton that is photo etched for the desired copper outline. The use of copper clad Kapton is preferred over plain Kapton. Copper clad provides a more uniform surface area for the electrodes, thus eliminating localized heating due to imperfections in electrodes or ground plates. It also provides consistent capacitance from unit to unit. The grid bypass capacitance is 12.9 nF and the screen bypass capacitance is 12.4 nF.

A filament lead bypass capacitor is located at the top of the cathode resonator. It is constructed using a copper electrode connected to the filament lead. Plain .005" Kapton sheet is sandwiched on either side of the electrode. Capacitance is 14.9 nF. The filament is powered by a commercial DC high efficiency switching supply (15.5 volts at 225 amps) located in the series to modulator.

The cathode resonator is tuned to 53.1 MHz. and has a Q of 10. The low Q and hence wide bandwidth is accomplished by tapping the cathode resonant structure with two 50 ohm terminations tapped for a 4:1 impedance transformation at the cathode (100 ohms). The terminations are physically located upstairs in the equipment gallery and connected to the amplifier's cathode circuit by two 1/2 inch Heliax cables. Over the full dynamic swing of cathode impedance the rf power loss in the cathode circuit is minimal and the impedance range is limited for the solid state amplifier load.

The cathode is driven directly at the base of the tube socket with four phase matched 50 ohm 1/2 inch Heliax cables in parallel (for 12.5 ohms) from the output combiner of the solid state amplifier. The combiner's output impedance is 12.5 ohms, but due to the dynamic impedance swing of the cathode, we only approach a matched 12.5 ohm cathode impedance at full output. Therefore, these cables are not always run as a flat line so lengths are kept near 1/2 λ multiples of 53.1 MHz. This provides tight coupling between driver and cathode.

The grid bias supply is a fast 100 KHz (bandwidth) programmable type with compliance of -500 volts to 0 volts for 0 to 10 volt program. The screen supply is a 3 phase bridge type rated at 1050 volts at 2 amps. Both of these supplies are identical to the ones used in the Tevatron rf system (Fermilab design).

A cathode monitor is installed at the same point as the rf drive. This serves as a voltage monitor and phase reference for system tuning. A second monitor (anode monitor) is placed in the outer shell's side wall in the anode circuit and is used for voltage monitoring. The cathode and anode signals are monitored by a phase detector which controls cavity tuning.

III. 4 KW SOLID STATE DRIVER AMPLIFIER

When we first started our R&D program for the new power amplifier, we made the decision it would be driven by a solid state amplifier located in the equipment gallery. With 20 years' experience maintaining our existing power amplifiers which have tube drivers built on top of the power module we learned that a lot of our failures, while acceptable, were related to the driver components. Our existing 2 KW drivers are made up of 14 parallel 4CW-800F tetrodes (cascode amplifiers) driven by a 6 tube 100 watt distributed amplifier mounted on top of the 2 KW driver. The complexity of small tubes in the tunnel along with their associated power supplies in the equipment gallery led to a higher mean time to failure than we liked.

Initially we could find no commercial solid state amplifier that met our specification (insisting on water cooled units). This led to an in-house design using the MRF-151G Mosfet for the output stage mounted to a copper water cooled heatsink which provided 250 watts of rf power per device. We assembled 16 of these devices (mounted two devices per copper heatsink) and combined them for 4 Kwatts to drive the cathode of the power amplifier. All our initial testing of the 200 KW amplifier was done using this solid state driver.

Later a commercial solid state amplifier was uncovered which, with the exception of narrower bandwidth, could nearly meet our requirements. This amplifier with a few modifications was adapted to meet our water cooling specification and bandwidth requirements.

Past experience with air cooled heatsinks in solid state drivers have led to poor long term reliability because of excessive junction temperatures. It has been our experience that water cooling has proven to increase mean time to failure by more than an order of magnitude. Requiring copper tubing for water paths rather than organic hose greatly reduces the chances of water leaks.

Two of the commercial 1 KW amplifier chassis were modified to give the desired results:

1. Wider bandwidth.
2. Faster gated pulse response without ringing.
3. Improved chassis shielding.
4. Added 37.5 degree flare fittings for water connections.
5. Eliminated all rubber hose inside the 1 KW chassis and replaced them with copper refrigeration tubing.

One of the modified chassis was sent back to the vendor to see if they would modify their design to incorporate our changes. Since they agreed to do this, we ordered 12 additional amplifier chassis for the completion of the three R&D amplifiers.

Table 1 is an abbreviated list of specifications for the 1 KW solid state amplifier chassis.

Frequency:	30 MHz - 80 MHz
Gain:	50 dB
Gain Flatness:	+/- 1.0 dB
Phase Delay:	Less than 24 nSec
Phase:	All amps matched to +/-5 degree
Rf Power Out:	1000 watts
Cooling:	Demineralized LCW

Table 1. Abbreviated Solid State Amplifier Specification.

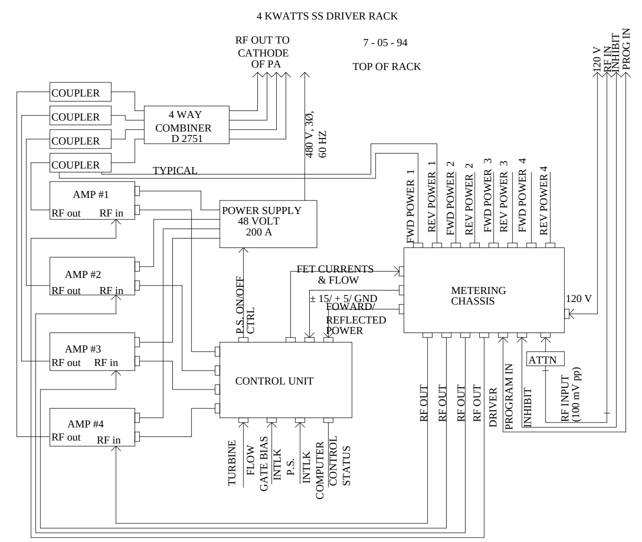

Figure 3. Diagram of the 4 KW solid state amplifier rack.

The control unit and metering chassis are Fermilab designed and fabricated. The final output combiner, dual directional couplers, and 48 volt 200 amp power supply were purchased commercially.

The metering chassis performs the following functions:

1. Measures and displays Mosfet current in each output stage.
2. Diode detectors for processing forward and reflected power of each amplifier for local and remote readout along with protection circuitry for each.
3. Variable gain rf amplifier for programming rf level to 1 KW amplifier modules in response to an input program of 0 to 10 volts (constant phase).
4. Program inhibit (TTL line).
5. Four - way rf splitter.

The control unit provides the protection, local control, and remote interface for the solid state amplifier. It utilizes a Europac HF 3U chassis with 9 plug-in modules. The modules include a water flow processor for the turbine flow meter, forward power, reflected power, amplifier monitor module for each 1 KW amplifier (4 total), power supply controller, and on/off master controller with remote status and control.

IV. INSTALLATION AT MR-RF STATION 7

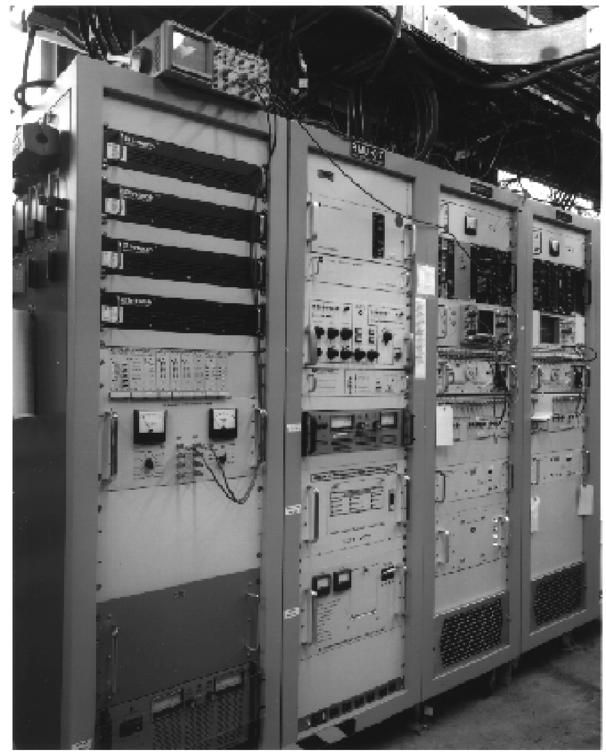

Figure 4. Installed Solid State Driver at MR-RF St. # 7.

In the foreground of Figure 4, is the 4 KW solid state driver rack positioned next to the station 7's control racks. From top to bottom are the four - 1 KW solid state rf amplifier modules, control unit, metering chassis, four - way output combiner, and power supply.

A condition for installing and running a long term test was the station had to be controlled in the normal fashion from the control room by the operations' group. The solid state driver's control unit was interfaced to the station's existing control system. With minor software programming modifications, new parameters for the solid state driver could be displayed on the usual parameter pages. This provided the operations' group full remote control, read-backs, and alarms to the control room as with a normal station.

In May of 1994 the station was made operational with the new 200 KW power amplifier and solid state driver. The 200 KW power amplifier typically runs with a peak anode voltage of 18 KV from the series tube modulator, a peak negative grid bias of -300 volts, and a peak forward power of 1700 watts from the solid state driver with beam intensities of 3.1 E12 on pbar production cycles (beam loading compensation active).

To date we have had no failures or downtime associated with the new 200 KW amplifier and solid state driver. Even though this is the only station operating this way, it is a good indication that the designs are sound.