

# UPGRADE AND COMMISSIONING OF THE 88-INCH CYCLOTRON FINAL POWER AMPLIFIER\*

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## Abstract

The RF system of the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory is a resonant system based on the quarter-wave cantilever type resonating structure. Power is fed to the Dee from the anode of the 500 kW RCA 4648 tetrode tube operating in grounded cathode configuration, which is coupled to the side of the Dee stem. The tube is obsolete and makes its continued use impractical. A new final power amplifier was designed and built using the commercially available tube Eimac 4CW150,000E. The new amplifier was successfully commissioned and has been reliable and easy to operate. An overview of the system upgrade and details of the commissioning will be presented.

## INTRODUCTION

The 88-Inch Cyclotron at Lawrence Berkeley National Laboratory is a sector-focused cyclotron with both light- and heavy-ion capabilities.[1] The Cyclotron accelerates protons through uranium to maximum energies which vary with the mass and charge state. It supports a local research program in nuclear science and is the home of the Berkeley Accelerator Space Effects (BASE) Facility.[2]

The cyclotron has three ion sources that have led to progressively higher intensities and charge states of heavier ions.

The cyclotron operates in the frequency range of 5.5 to 16.5 MHz, but it can operate using harmonic acceleration, so the energy range of the machine is limited only by the capabilities of the magnet, not the RF system.

Earlier it was realized that the variable frequency of the cyclotron translated to a mass resolution of 1/3000, meaning that the cyclotron could separate most ions of near identical mass-to-charge ratio emanating from the ion source. [3] The mass resolution is high, because the path of the ions inside the magnetic field of the cyclotron is long (200 to 300 turns).

The combination of cyclotron and ECR sources provide the unique ability to run “cocktails” of ions. A cocktail is a mixture of ions of near-identical charge-to-mass ratio.

The wide-band driven RF system for the 88-Inch cyclotron provides fast beam tuning, allowing users to switch back and forth between several ion species of the same cocktail with small adjustments of the accelerator frequency, so a new beam does not require retuning the whole accelerator and is accomplished in approximately one minute.

The wide-band driven RF system used the RCA 4648 tube and was commissioned in 1972. The system offered

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Dee voltage stabilization to the order of 0.01% or better.[4]

The tube was chosen because of the multi-gun structural principle, where each gun was separately recessed into its own slot in the body block. It was suitable for wide-band applications with good mechanical and thermal stability and resistance to spark damage. Furthermore, the tube had high gain and was able to deliver up to 500KW.

The following sections will describe the current RF system, the final power amplifier (FPA) upgrade that occurred last year, and results obtained from the commissioning.

## RF SYSTEM

Fig. 1 shows the 88-inch cyclotron RF system with the RCA 4648 tube. The stable RF signal is generated by a frequency synthesizer. The redundant chain, RF drive and RF clamp circuits can turn off the RF signal.

The redundant chain turns off the RF signal if the redundant radiation chain conditions that ensure personnel safety are not satisfied or the watchdog timer goes off. The redundant radiation chain is made up if the vault, pit, and trench are closed, the caves have the beam plug in or the safety chain made up, and the remote I/O datalink to the PLC is working.

The RF driver turns off the RF signal if the conditions for running cave 1 are not satisfied, such as the deflector voltage is in range, the gas flow is on to cool down Berkeley Gas Filled Separator, and the neutron flux and target current are below certain thresholds.

The RF clamp turns off the RF signal if excessive drive is applied to the 10W driver amplifier or the screen current from a wide-band current shunt exceeds a preset value. These features are important during the turn-on and resonator spark-in periods.

The RF clamp is an important circuit because the RF tank resonator demands ~130 KW at the high end of the operating band and only ~20KW at the low end of the operating band, assuming the 70 KV rated Dee voltage. Consequently, the FPA is easily overdriven when tuned up at low frequencies because it is capable of delivering up to 500 KW.

The signal after the RF Clamp circuit is attenuated by a FET RF transistor configured in series (RF modulator, Fig. 1). The base of the transistor is driven by the error signal generated from the difference between a sample signal from the tube anode and a reference voltage.

The signal is then amplified by a 10W wideband amplifier, providing a signal for the RF Clamp circuit, and then manually attenuated before being applied to the power splitter that feeds the FPA drivers.



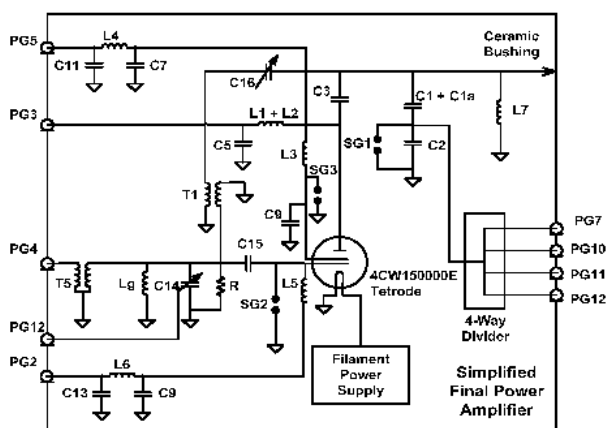


Figure 2: Simplified FPA schematic.

The screen bypass capacitor C9 is a custom-made large disc capacitor assembled as a copper disc sandwiched between two 0.005" kapton layers. The blocking capacitor C3 is also a custom-made cylinder capacitor. Three layers of 0.005" kapton film are rapped around the inner cylindrical aluminium tube.

A load resistor R of 100  $\Omega$  is connected to the grid. Matching the low input impedance of the FPA stage is accomplished with a 1:2 step-up broadband transformer T1. The low input impedance and low input capacitance allow wideband operation of the input circuit of the FPA unit. The Eimac 4CW150,000E tube characteristics show that the 100  $\Omega$  input impedance R requires a grid voltage swing of 390V in order to provide the maximum power, which corresponds to a driver power of ~750 W that can be accomplished with a single A-1000 amplifier.

The new FPA cabinet is constructed to allow testing the new configuration in a reversible way. The output circuit remains electrically identical to the circuit used with the RCA 4648. The new tube uses the existing anode, screen, and grid DC power supplies, but a new filament power supply, including the filament transformer, is conveniently built inside the cabinet.

A tuneable grid input circuit is designed to make the LC input impedance of T5-Lg-C14 high compared with to the resistor R, consequently giving low SWR at all drive levels. The LC network is tuned with the variable capacitor C14 that is controlled by a stepper motor. The input capacitance ranges from 25 to 4000 pF with resolution of 1pF.

The variable capacitor C14 of input network was set to the minimum 25pF capacitance and a resonance frequency of 17.5Mhz was measured using an E8357A Agilent Network Analyzer, consequently the combined inductance at the input from Lg and T5 is 3.31 $\mu$ H.

The minimum resonance frequency of 4.38MHz is obtained using the calculated inductance and the highest capacitance of 400pF. The LC input network frequency range is appropriate because it is larger than the 88-Inch Cyclotron frequency of 5.5MHz to 16.5MHz.

## COMMISSIONING

The new FPA was successfully commissioned in May 2010 and provided a power gain of ~22 db. In the former FPA, the tube was able to deliver 500 KW, so the RF power was limited by the ~200 KW modulator power supply. In the present FPA, the tube is able to deliver only 150 KW, so a new clamp circuit was used to protect the new tube when the RF tank is driven out of resonance during the RF tuning or a RF tank breakdown.

The circuit clamps the driver 20 db below its value if the anode current is over 9 A and requires a manual reset after each event. It has the advantage of keeping a low RF drive that maintains the RF tank in resonance after a RF tank breakdown, allowing a fast recovery.

Nonetheless, during the past year a strong second harmonic was observed when the FPA was tuned to 14 MHz. The harmonic frequency did not couple with the RF tank, but was strong enough to confuse the vector voltmeter and drive the RF tank out of resonance, triggering the clamp circuit that protects the tube. The problem was mitigated by adding a low pass filter BLP-15+ from Mini-Circuit Inc. that has a stopband of 20db at 23MHz and by monitoring the RF signal inside the RF tank.

## CONCLUSION

A new FPA was designed and built using the commercially available tube Eimac 4CW150,000E. The interchangeable configuration using the same dimensions of the cabinet, method of connection to the resonator, signals, and general installation arrangement allowed to commission the new amplifier in only one week of May 2010.

A new tuneable input circuit increases its efficiency by requiring half of the driver power. The new tube is limited to 150KW, which is enough for the cyclotron operation; however, as the modulator can provide ~200KW, it requires a new clamp circuit to protect the tube when the RF tank is driven out of resonance.

Until now only a weak harmonic oscillation problem at 28 MHz that did not couple with the RF tank was observed and remediated. Over more than a year of continuous operation the new FPA demonstrated to be reliable and easy to operate.

## REFERENCES

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