International Journal of Microwave and Wireless Technologies, 2012, 4(5), 553–558.
doi:10.1017/S1759078712000505

INDUSTRIAL AND ENGINEERING PAPER

Upgrade of the 88-Inch Cyclotron Power Amplifier

MICHEL KIREEFF COVO

The radiofrequency (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 The tube is obsolete and makes its continued use impractical.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 4W150,000E. The new amplifier was successfully commissioned and has been reliable and easy to operate.

Keywords: Circuit design and applications, Power amplifiers and linearizers

Received 1 February 2012; Revised 19 March 2012; first published online 8 August 2012

I. 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.

The 88-Inch Cyclotron supports a local research program in nuclear science and is the home of the Berkeley Accelerator Space Effects (BASE) Facility [2].

The nuclear science program has ongoing research in nuclear structure, astrophysics, heavy element studies, fundamental interactions, symmetries, and research and development technologies.

The BASE Facility provides well-characterized beams of protons, heavy ions, and other medium energy particles, which simulate the space environment to understand the effect of radiation on microelectronics, optics, materials, and cells.

The Cyclotron has three ion sources that have led to progressively higher intensities and charge states of heavier ions. The first generation of electron Cyclotron resonance (ECR) ion source was coupled to the Cyclotron in the early 1980s [3]. The second generation, the advanced ECR (AECR-U) source, was built and upgraded in 1990s [4]. The third generation, the superconducting ECR source named versatile ECR ion source for nuclear science (VENUS), was operational in early 2000s [5].

The Cyclotron operates in the frequency range of 5.5–16.5 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 radiofrequency (RF) system.

The Cyclotron frequency is given by $f_c = BQ/(2\pi A)$, where B is the magnetic field, Q is the particle charge, and A is the particle mass. From historical data the maximum main magnet current of 2296 A was obtained during the run of deuterons at 65 MeV at the RF of 12.47 MHz; therefore the average magnetic field of ~1.64 T was obtained in the Cyclotron, corresponding to the magnetic rigidity ($B\rho$) of ~1.64 Tm.

The Cyclotron energy in MeV is given by $E = KQ^2/A$, where K is the Cyclotron energy constant, Q is the particle charge, and A is the particle mass. As the Cyclotron energy constant is defined by $K = 48.24(B\rho)^2$, the machine reached energy constant K of ~129.9 by using the magnetic rigidity of 1.64 Tm. The machine is nominally designed to achieve energy constant K of 140 and accordingly is the Cyclotron energy.

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 [6]. The mass resolution is high, because the path of the ions inside the magnetic field of the Cyclotron is long (200–300 turns) [7].

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.

During the Cyclotron operation, the ions are tuned out of the source together and the Cyclotron acts as a charge-to-mass analyzer to separate them and provides different ion species and charge states for energy variable experiments.

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

Lawrence Berkeley National Laboratory, 1 Cyclotron Road Mail Stop 88R0192, Berkeley, CA 94720, USA. phone: +1 510 486 7701
Corresponding author:
M. Kireeff Covo
Email: mkireeffcovo@lbl.gov

accomplished in approximately 1 min. This means, for instance, that the linear energy transfer to silicon delivered to the BASE experiments can be quickly changed from 1 to 100 MeV/mg/cm^2.

The wide-band driven RF system used the RCA 4648 tube and was commissioned in 1972. The system offered Dee voltage stabilization to the order of 0.01% or better [8].

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 500 kW.

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

II. RF SYSTEM

Figure 1 shows the 88-Inch Cyclotron RF system. The RF signal is generated by a frequency synthesizer. The redundant chain, RF driver, and RF clamp circuits can turn off the RF signal.

The redundant chain circuit 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 goes off if the vault, pit, or trench are open, the remote I/O datalink is not working, or the caves have the beam plug out.

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

The RF clamp circuit turns off the RF signal if excessive drive is applied to the 10 W driver amplifier or the screen current from a wide-band current shunt exceeds a preset value. These features are important during the resonator turn-on and 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 ~20 kW at the low end of the operating band, assuming the 70 kV rated voltage. Consequently, the FPA is easily overdriven when tuned up because it can deliver up to 500 kW.

The signal after the RF clamp circuit is attenuated by a field-effect RF transistor configured in series (RF modulator). The gate of the transistor is driven by the error signal generated from the difference between a sample signal from the anode tube and a reference voltage.

The signal is then amplified by a 10 W wideband amplifier, providing a sample signal for the RF clamp circuit, and then manually attenuated before being applied to the power splitter.

Two Electronic Navigation Industry linear amplifiers, model A-1000, amplify the signals 60 db. Each amplifier can deliver 1000 W in the frequency range of 2–50 MHz. The RF signals are then combined and up to 2000 W is supplied to the FPA grid circuit.

Low input capacitance gives an input circuit bandwidth of at least 20 MHz when driven by a 4:1 step-down matching transformer terminated at the grid with a 12.5 Ω resistor.

The modulator voltage is filtered from ripples and RF by a π-filter and supplies up to 20 kV at 10 A to the RCA 4648 anode.

Power is fed to the side of the Dee stem from a DC blocking capacitor connected to the anode of the RCA 4648 tetrode tube operating in grounded cathode configuration.

The RF system is a driven resonant system based on the quarter-wave cantilever-type resonating structure, where the Dee is cantilevered from the rear of the RF tank with movable panels around it. The system is resonant at the lowest frequency of 5.5 MHz, when the movable panels are next to the walls, and the highest frequency of 16.5 MHz, when the panels are lying flat along the Dee stem.

Coarse frequency adjustments are manually accomplished by moving panels that varies the Dee-stem inductance and varying the anode trimmer capacitor located in the Cyclotron resonant tank. Fine frequency adjustments are automatically accomplished by comparing the phase of the tube with the

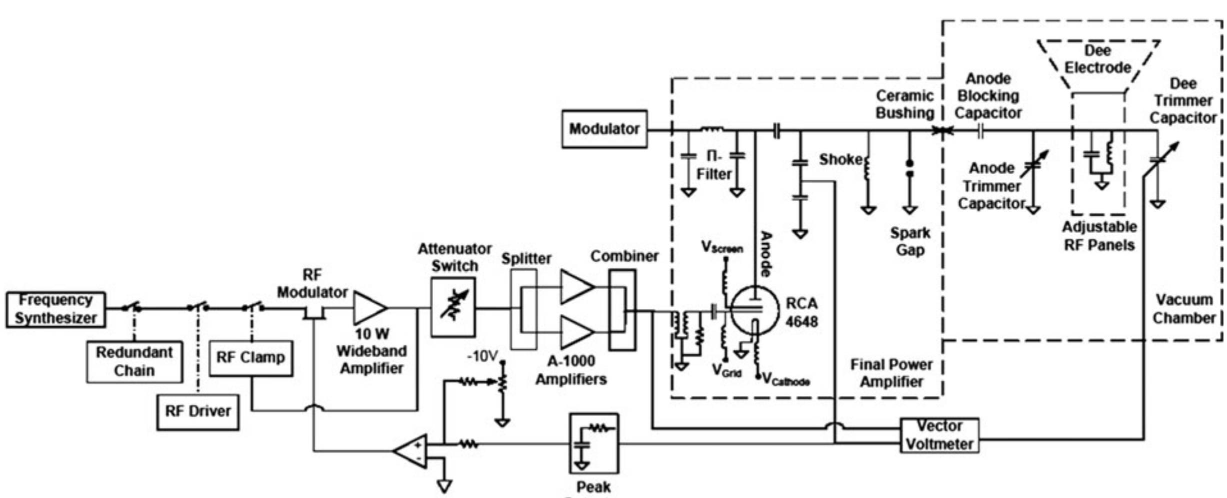

Fig. 1. 88-Inch Cyclotron RF simplified system. The frequency synthesizer provides the RF signal that is modulated to keep the output power constant. A vector voltmeter compares the phase of the output power coming from the RCA 4648 tube with the phase of the grid signal and drives the Dee trimmer capacitor to maintain the RF tank in resonance.

phase of the driver signal and by generating an error signal, which controls the Dee trimmer capacitor and keeps the RF tank at the resonance, similar to other Cyclotrons [9].

As the Cyclotron load is maintained in parallel resonance, the inductive and capacitive reactances cancel out, leaving only the resistive component, so the impedance of the load as a function of frequency is purely resistive.

Dee voltage regulation is accomplished by detecting the peak Dee RF voltage and adding it with a negative reference voltage level. The result is applied to an RF modulator that controls the RF driver power, keeping the Dee voltage constant.

III. FPA UPGRADE

The RCA 4648 tube used in the former FPA is obsolete and the cost to refurbish it has become prohibitively high (U$120 000), besides the lead time of more than a year, making its continued use impractical.

FPA measurements show that the required RF power necessary to cover resistive wall losses for 70 kV nominal Dee voltage changes from 19.2 kW at the 5.5 MHz frequency to 127.5 kW at 16.5 MHz frequency, corresponding to a shunt impedance of the resonance structure (Fig. 2) in the range of 146.5–14.1 kΩ.

As the anode voltage is less than 100 kV and the output power is less than 150 kW, the new final amplifier design utilizes an Eimac 4W150,000E water-cooled tube (Fig. 3) that is available off-the-shelf at the cost of ~ $20 000.

The new tube is water cooled and characterized by low internal lead inductance and input and feedback capacitances. It also operates in a grounded cathode configuration and the neutralization to minimize the coupling between the grid circuit and the anode circuit is provided by a feedback network, which has an adjustable capacitor C16 and a balun transformer T1 made of heliax with ferrites, which prevents high frequency self-oscillation problems.

The tube neutralization was adjusted to minimize the parasitic frequencies that were generated at the driver frequency of 16.5 MHz. Unfortunately the RF system is broadband (5.5–16.5 MHz), so the neutralization does not work the same way for all the frequencies, but in general the harmonic content is usually 26 db below the fundamental.

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 wrapped around the inner cylindrical aluminum tube.

A load resistor R of 100 Ω 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 4W150,000E tube characteristics show that the 100 Ω input impedance R requires a grid voltage swing of 390 V in order to provide the maximum power, which corresponds to a driver power of ~750 W and can be accomplished with a single A-1000 amplifier.

The new FPA cabinet (Fig. 4) 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 tunable input grid circuit is designed to make the input impedance of Lg-C14 high compared 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 1 pF.

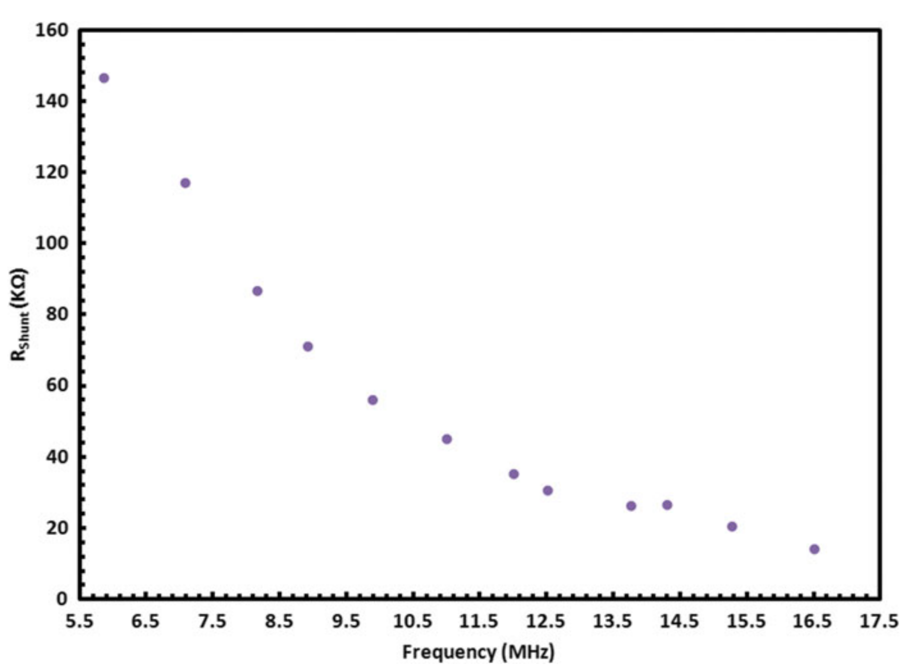

Fig. 2. Shunt impedance as a function of frequency. FPA measurements show a shunt impedance of the resonance structure in the range of 146.5–14.1 kΩ.

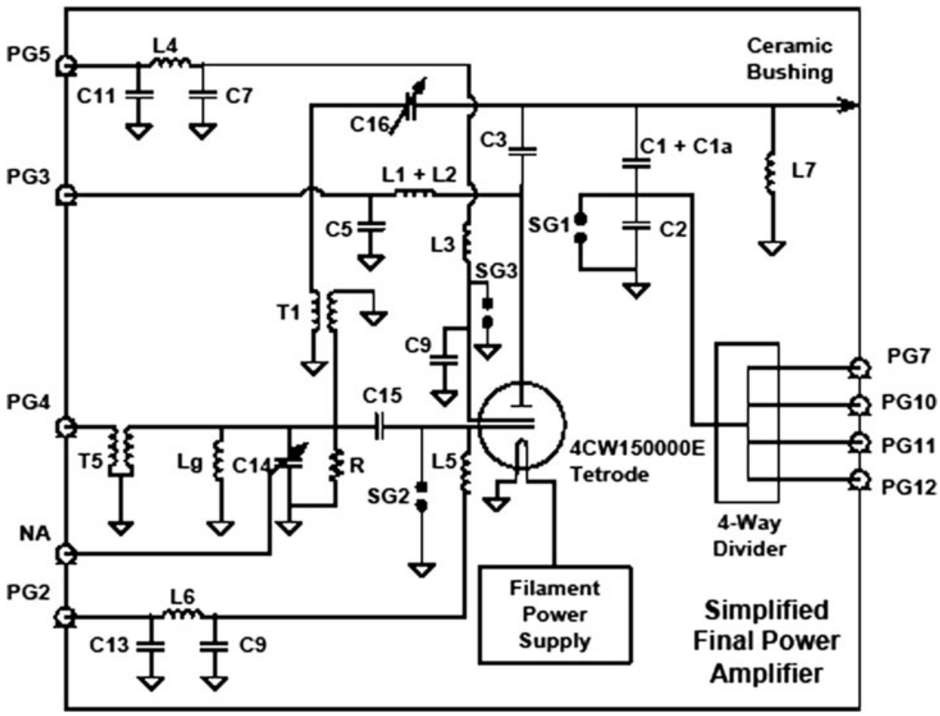

Fig. 3. Simplified FPA schematic. The new amplifier uses a 4CW150000E tube in the grounded cathode configuration. It has a tunable input circuit that decreases the driver requirement to 750 W.

The variable capacitor C14 of input network was set to the minimum 25 pF capacitance and a resonance frequency of 17.5 GHz was measured using an E8357A Agilent Network Analyzer, consequently the *Lg* input is 3.31 μH.

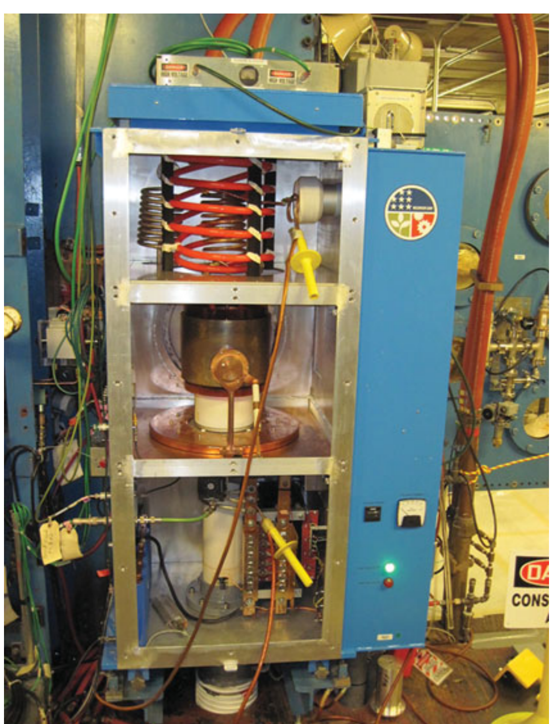

Fig. 4. New FPA cabinet. It has the same dimensions and is designed to operate with the existing signals and resonator structure, allowing testing it in a reversible way. The filament power supply is integrated in the new cabinet for convenience.

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

IV. COMMISSIONING

The new FPA was successfully commissioned. The input driver power was adjusted to give Dee voltage of 75 kV in the frequency range of 5.85–16.5 MHz. The driver power and the output power are shown in the Figs 5(a) and 5(b), respectively. The Dee voltage at 15.27 MHz was set to 70 kV and at 16.5 MHz to 60 kV because several breakdowns were observed inside the RF tank, probably resultant from the RF tank conditioning. The commissioning shows that the FPA has a power gain of ~22 db.

If the RF tank gets out of parallel resonance during the RF tuning or an RF tank breakdown, the load impedance decreases and requires more power from the FPA and modulator to keep the same Dee voltage amplitude. 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 designed to protect the new tube.

The circuit will clamp the driver 20 db below its value if the anode current is above 9 A, and will require 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.

As the FPA can handle up to 150 kW, the clamp circuit was implemented to protect the FPA.

https://doi.org/10.1017/S1759078712000505 Published online by Cambridge University Press

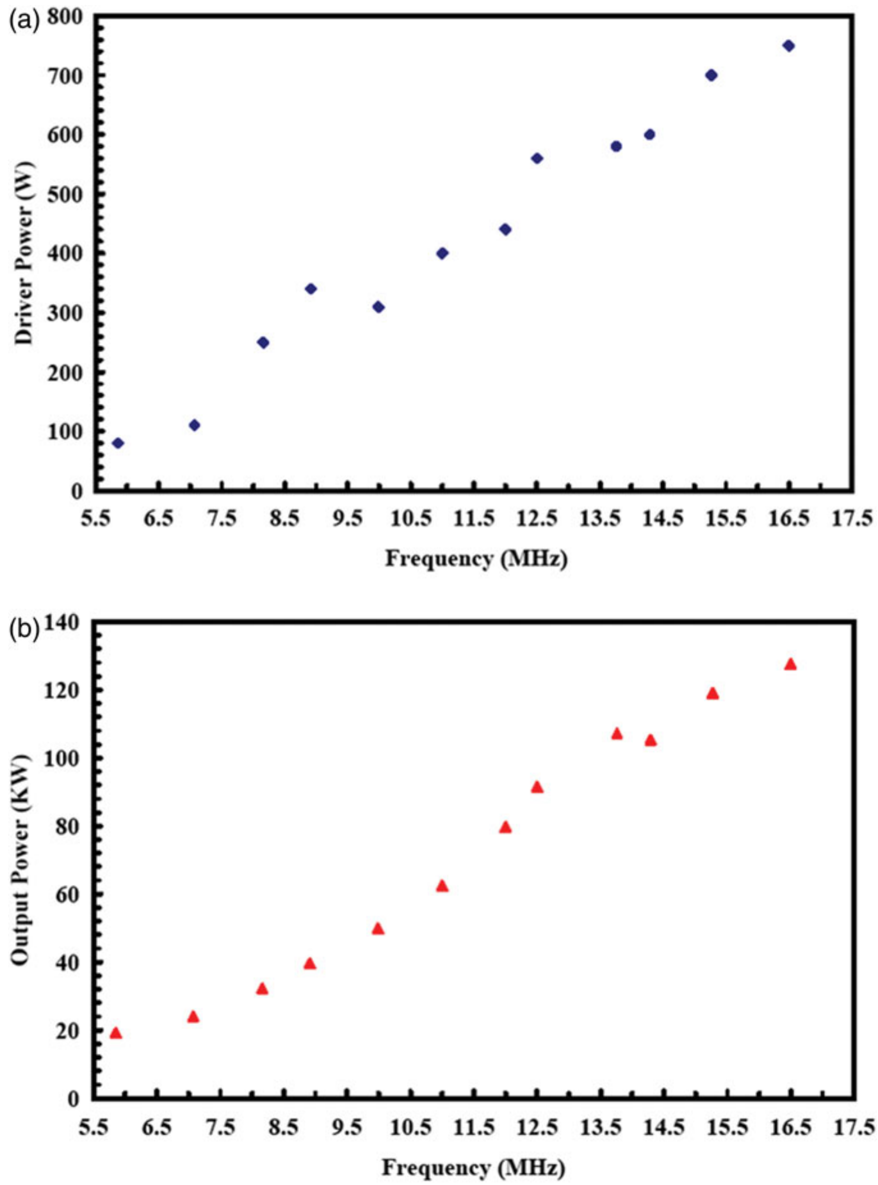

Fig. 5. Commissioning of the FPA. The driver was adjusted to keep Dee voltage at ~75 kV in the range of 5.85–16.5 MHz: (a) driver power and (b) output power.

Nonetheless, during the past year a weak second harmonic component was observed when the FPA was tuned to 14 MHz. The harmonic frequency was 22 db below the fundamental frequency and it did not couple with the RF tank, but it 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 that has a stopband of 20 db at 23 MHz and by monitoring the signal inside the RF tank.

V. CONCLUSION

The RF system of the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory was commissioned in 1972. It is a resonant system based on the quarter-wave cantilever-type resonating structure, where power is fed to the Dee from the anode of the 500 kW RCA 4648. The frequency is adjusted using the movable panels and the anode trimmer capacitor located inside the RF tank. The system is resonant from the lowest frequency of 5.5 MHz to the highest frequency of 16.5 MHz.

The RCA 4648 tube is obsolete. The cost to refurbish it was prohibitively high with a lead time of more than a year, making its continued use impractical from the operational point of view.

Last year a new FPA was designed and built using the commercially available tube Eimac 4W150,000E. The interchangeable configuration used the same dimensions of the cabinet, method of connection to the resonator, and signals. The new FPA was the most affordable and fastest solution. It was installed and commissioned in only one week without disrupting the scheduled Cyclotron runs.

A new tunable input circuit increases its efficiency by requiring half of the driver power. The new tube is limited to 150 kW of power, which is enough for the Cyclotron operation; however, as the modulator can provide ~200 kW, it required 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 14 MHz that did not couple with the RF tank was observed and remediated. Over a year of continuous operation the new FPA demonstrated to be reliable and easy to operate.

ACKNOWLEDGEMENTS

This work was supported by the Director, Office of Federal Locations, US Department of Energy, American Recovery and Reinvestment Act (Recovery Act) under Contract No. DE-AC02-05CH11231A136.

REFERENCES

[1] Smith, B.H.: RF System of the 88-Inch Cyclotron. Report UCRL-10021, 1962.

[2] McMahan, M.A.: in Radiation Effects Testing at the 88-Inch Cyclotron. In Proceedings of the 5th European Conference on Radiation and Its Effects on Components and Systems, Abbaye de Fontevraud, France, 1999, 142. doi: 10.1109/RADECS.1999.858563.

[3] Xie, Z.Q.: Production of Highly Charged Ion Beams from Electron Cyclotron Resonance Ion Sources (Invited). Rev Sci Instrum **69**(1998) 625.

[4] Lyneis, C.M.; Xie, Z.Q.; Clarck, D.J.; Lam, R.S.; Lundgren, S.A.: Preliminary performance of the LBL AECR. In Proceedings of 10th International Workshop on ECR Ion Sources, Oak Ridge, TN, USA, 1990, 47.

[5] Lyneis, C.M.; Xie, Z.Q.; Taylor, C.E.: Design of the 3rd Generation ECR Ion Source. In Proceedings of the 13th International Workshop on ECR Ion Sources, Texas A&M University, USA, 1997, 115.

[6] Harvey, B.G.: Nuclear Spectroscopy and Reactions, Part A, Academic Press Inc., New York, 1974.

[7] Leitner, D. et al.: Heavy Ion Cocktail Beams at the 88 Inch Cyclotron, Report LBNL-51451, 2002.

[8] Flood, W.S.; Frazier, P.E.: The Wide-Band Driven RF System for the Berkeley 88-Inch Cyclotron, Report LBL-1294, 1972.

[9] Osterlund, J.W.; Smythe, R.: A Cyclotron power-amplifier RF system using a 4CW50,000/8350 tetrode. IEEE Trans Nucl Sci **12**(3) (1965) 174. doi: 10.1109/TNS.1965.4323615.