Maintenance and upgrade of the 60 kW RF Amplifiers for the 70 MeV Cyclotron at LNL

INFN-LNL-279/2024

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April 18, 2024

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Abstract

During the year 2024 we maintained and pointed out the upgrades on "RF Amplifiers system for 70 Mev Cyclotron" made by Amplifier Systems and installed by Best Th. in 2017. The main purpose of this maintenance is to lead a smooth operation of the cyclotron conditioning and run after a long shutdown due to the installation of ancillaries for SPES Project at LNL. In this document there's the descriptions of the activities performed.

1 Introduction

The Cyclotron is a circular accelerator operating at the LNL laboratories. It's able to accelerate H- ions, produced with energy of 40 keV from an external source, the final energies varying from 35 to 70 MeV. The H- ions are confined inside the accelerator by a magnetic field of 1.5 Tesla and accelerated by two RF cavities, these are delta type cavities, they reach a peak voltage of 70 kV, feeded by two 60 kW RF amplifiers at a frequency of 56.2 MHz.

2 RF Amplifiers description

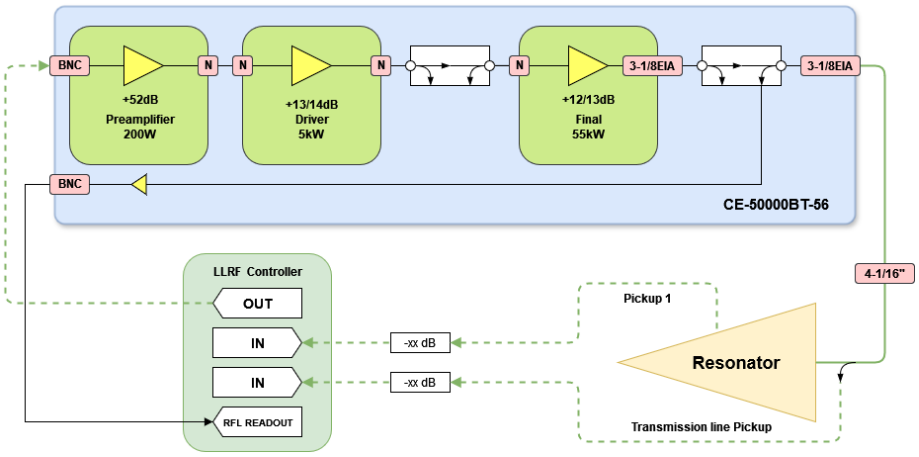

Figure 1: Simplified block diagram of RF path.

The CE-50000BT-56 are nominal 60 kW RF amplifiers made from Amplifier Systems inc. based in USA. They are 3 stage amplifiers forced air/water cooled. The predriver stage is a solid state amplifier based on N-Channel Enhancement-Mode Lateral MOSFETs capable of minimum 50/52 dB gain that is fed directly from the LLRF exciter. The driver and final stages are grounded-grid design, cathode driven tube type amplifiers, designed around YC-275(Driver) and YC-311(Final) ceramic triodes, the two triodes are customized, thus outside the Richardson catalogue. They are capables respectively of minimum 13/14 dB gain and 12/13 dB gain, for a total of 80 dB gain. In figure 1 the block diagram for the RF path is shown. The signals coming from the two resonators pickups are processed through a LLRF block that generates the RF drive signal for the amplifier; the signal is amplified and then feeded into the cavity couplers by 4-1/16" RF coaxial lines.

3 Maintenance

Due to the prolonged stop of a couple years, an accurate inspection of the amplifiers was necessary, in order to point out all the corrective actions needed for a smooth and reliable operations, and to investigate on strange behaviours noted during the previous operations of the cyclotron.

3.1 Cleaning

The first things solved was the dust accumulated outside and inside the two units. This dust due to masonry work performed without protection of the apparatus inside the room. The first action was to clean the room and subfloor, after that we focused our attention on all the internal components and connectors with vacuum cleaner, brushes and clean wipes. The power amps final and driver boxes were opened and the tubes removed; then we proceeded to remove the dust and, in the power amplifiers, to clean the corrosion due to condensation of the copper jackets that surround the vacuum tube. The solid state predrivers were removed and cleaned of both dust and residues of flux used for soldering the components. The boards that control the interlocks of both the drivers and the power amplifiers have been dismantled and also in this case cleaned of flux residues.

3.2 Checking and components replacement

During the maintenance the air and water cooling system (see par. 3.4), electrical connections, PCB boards, electronic and power components and signal wiring have been checked. The checks revealed that some electromechanical and electronic components showed signs of damage and needed replacement.

3.2.1 Unit 1

The cable passages were closed, with adhesive film/adhesive gasket to prevent dust entering (as specified by the manufacturer). On control boards (Driver and Final) both PCB and connectors were labeled, and active ground points on fixing screws were identified. Replaced R26 which present discolouration. Undocumented double diode (named "D8" for future reference) found in the biasing section of the power amp (Removed, because being burnt it behaves like a low value resistor and shifts the working point of the power amp). Mapped the components and added the labels with the missing identifiers. Identified the part number of "Q1" and "Q2", as "14N05L"; from BOM it was identified as Production Date code instead of P/N. Find 2 resistors, value 220Ω, not present in the schematics (named "R1" and "R2" for future reference), on both Drive and Final control panels. Found a Box, not present in the schematics, probable Best Th. origin used to adapt the signals coming from the power amplifier and directed to the PLC, performed the reverse engineering and designed the schematic the tubes voltage was not read from PLC, on this unit one of the

feedthrough was interrupted and no signal was sent to the units, replaced the feedthrough. PL1 bulb on powerpanel burnt out and needs to be replaced (CM85 28V chicago miniature). Phase presence indicator bulbs on Powerpanel partly burnt out and all need to be replaced.

3.2.2 Unit 2

Except for R26, and the feedthrough on the undocumented unit all the entries seen on unit 1 are valid, furthermore: Replaced R25 which was discoloured. A 3.9 $k\Omega$ resistor not present in the diagram has been identified in parallel with R23. Connector, named "JBE3" during operations, was not draw in the schematics and is present only on amplifier 2. Found that the connectors TB25 has been replaced with two "TE Connectivity 2 pole" connectors, the numbering was not present, labels added and the cables identified. Replaced K9 Relay on Driver PCB board ; it had the coil with a low resistance of 180 Ω instead of approximately 600 Ω and had an anomalous color on the coil insulation. Broken F3 fuse holder needs to be replaced.

3.3 Documentation review

Many discrepancies were found on the electrical diagram, especially regarding the internal connections, now all annotated on the redraw schematics. Also an hardware component (see par. 3.2.1) present inside the cabinets was completely undocumented in the schematics and needed of a reverse engineering approach to obtain the schematics for repair purpose. All the connectors present in the units were identified and annotated in the documentations. A complete schematics redrawing action is ongoing, and is mandatory for the future maintenance/troubleshooting, during the cyclotron operation.

3.4 Cooling system survey

From the survey it appears that the hydraulic cooling system on the RF amplifier cabinets need to be modified, some construction critical issues are highlighted such as brass fittings, rubber hoses, plastic parts, poor manufacturing level, which requires intervention to ensure long-term reliable operation in continuous service avoiding significant damage to the equipment, in case of breakages or leakages. On Unit 1 we have found a leakage at one of the water supply collector, inside the cabinet, it was temporary replaced with a brass collector. On Unit 2 The final's flow meter regulation valve has a tendency to stick closed when the flow decreases, obstructing the flow of cooling water, this must be replaced; SW4 airflow switch on the final tend to locks, cleaned and lubricated.

4 RF Path inspection and test

During the previous operations was noticed that the unit 1 does not output power until an input level of -15 dBm. Also the recorded data form the cavity conditioning enhance an unstable power output from both units especially at low power outputs. The inspection start from the RF path, it was found that both RF interconnection (30 cm) that connects the LLRFs at the lines that goes directly to the predrivers was defective, opening the connectrors reveal that the assembly of the connectors was wrong and the screen has a very poor contact on the connector. Both interconnections were replaced.

4.1 Predrivers section

The predrivers are two solid state 3 stages amplifiers capable of 150 W power output. The first stage is a MHW6182, an integrated RF amplifier made from Motorola, the second stage is a single mosfet amplifier based on MRF134, the third stage is also a single mosfet amplifier based on MRF6V2300. The units are specs for 50/52 dB gain. They are mounted on a heatsink and air cooled by a fan. The units are energized from two switching PSUs at 28 V DC.

The first operation was to plot the gain response of the predrivers, this was performed removing the predriver from the RF path of both unit and injecting an RF signal of well known power directly at the input of the predriver; at the output was present a calibrated dual directional coupler in series with a 50 Ω matched 150 W RF load. The Forward/Reflected signals coming from the directional coupler ports were acquired by a couple of calibrated powermeters.

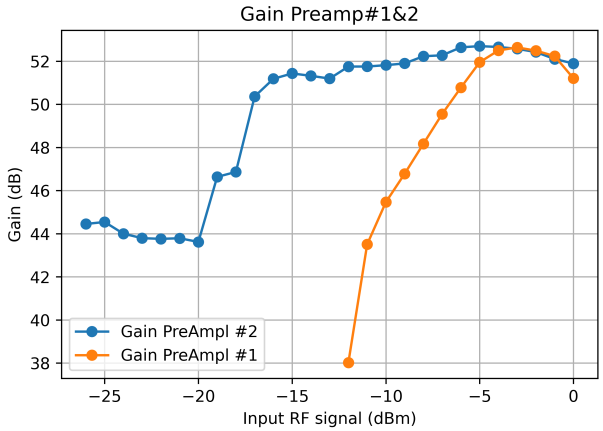

Figure 2: Gain comparsion between Predrivers

In the Figure 2 the gain plots resulted from the measurements are directly compared, and clearly highlights that the lack of power output for unit 1 comes from a malfunction of the predriver 1. The plot highlights also a poor linearity

in the gain response that it was suppose to be 52 dB on a wide input range for both predrivers. After this result the predrivers were removed from the units and tested again at the bench for further inspections, the new results was comparable, but also other behaviours appear clear for both predriver. After few hours of operation at constant power output of 50 W, to ensure the correct thermalization of the units, both predrivers at low power output (up to 15 W) exhibit a very unstable and noisy gain. In Figure 3 the plot of the gain instability. For reference on both units, with a very stable RF signal at 56.2 MHz of -19 dBm at the input, on unit 2 at the output we observed a jump from a minimum 31.14 dBm to maximum 33.62 dBm a delta in gain of 2.48 dB, and on unit 1 at the output we observed a jump from minimum 20.0 dBm to maximum 32.04 dBm a delta in gain of 12.04 dB. This clearly highlights that the problems of unstable power output from the two RF amplifier units during the low power conditioning operations comes from the predriver behaviour.

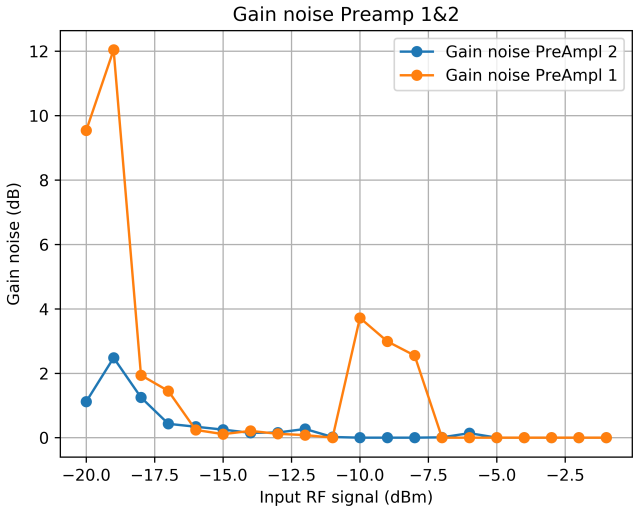

Figure 3: Predrivers Gain noise during bench test

Moreover for the units was found a high output distortion level in all input range, the pure sinusoidal signal at the input of the predriver, provided from a calibrated R/S SMB100 RF generator (sampled with a directional coupler and then acquired at CH1 of an 350 MHz Bandwidth oscilloscope), at the output of the predriver (sampled with an appropriate directional coupler and then acquired at CH2 of the oscilloscope), connected to an appropriate and 50 Ω adapted load, appear distorted.

After this diagnosis, the BIAS of the sections were adjusted to improve the situation of the amplifier 1 and 2; the results wasn't effective, if a better low end gain response was reached (Figure 4), the gain instability and the distortion

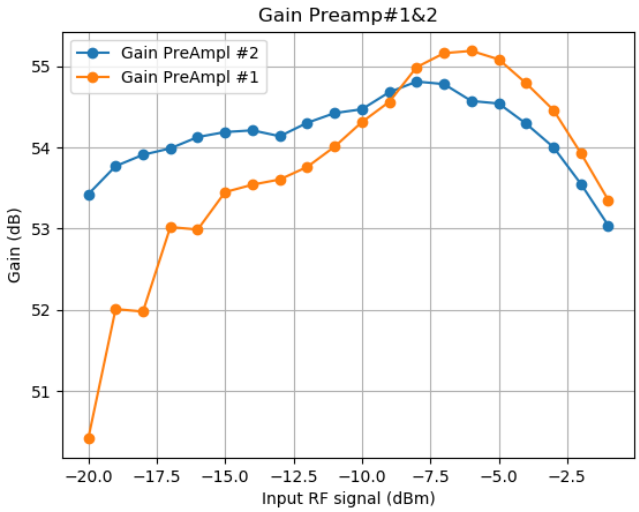

Figure 4: Predrivers Gains after BIAS regulations

(Figure 5 and Figure 6) was still present and problematic for the operations of the Driver and the Final stages.

Figure 5: Distortion on Predriver 1

The only acceptable and available short term solutions for stable operation was to substitute the original predivers with two power amp units with a similar gain. This temporary units are the linear wide band solid state class A power amplifier ENI 3100LA, installed in the LLRF rack, powered from the RF Amplifier units and connected directly at the Drivers inputs.

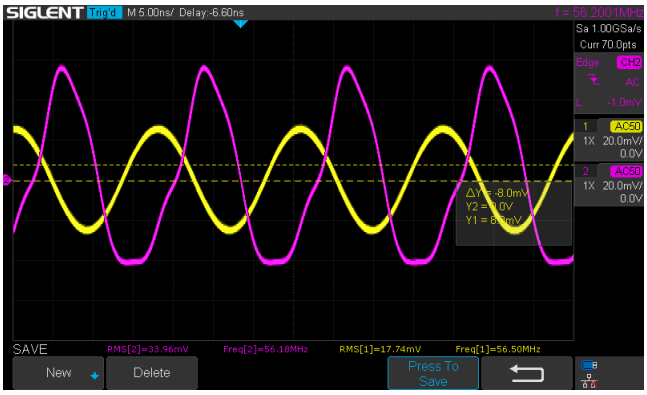

Figure 6: Distortion on Predriver 2

4.2 Drivers and Finals sections

The driver and final stages are grounded-grid design, cathode driven tube type amplifiers, designed around YC-275(Driver) and YC-311(Final) ceramic triodes. They are water/forced air cooled and capable respectively of minimum 13/14 dB gain and 12/13 dB gain.

As previously anticipated in par. 3.2.1 an undocumented double diode was found in the biasing section of the Final. This double diode it was removed, because of its position in the circuit, it was directly polarized and made a short circuit between the polarization network and ground, this high current burned it and after that it behaves like a low value resistor inserted in parallel with the polarizing network shifting the working point of the Final amplifier. This double diode, inserted in that way, instead of protecting the polarization network from discharges, was deleterious for its correct functioning.

On RF Driver Output the Type N connector was replaced, as the central pin had detached from the insulation during the calibration phases and allowed the movement of a metal tab which, if free to move, shorted to ground the floating filament network of the final.

After these operations the Driver and the Final were tuned on a 50 Ω 80 kW max. power dummy load, at the nominal operating frequency of 56.2 MHz, all parameters were as expected and no trouble occurred during the tuning procedure. The tuning parameters were logged in the service book as reference for future operations. Both units had reached the maximum power output of 55 kW at -3 dBm in input, this situation was maintained for one hour.

5 Mandatory upgrades

5.1 Water cooling

As improvements for continued use, it is recommended to upgrade the cooling system with stainless steel pipes and fittings of adequate cross-section both to avoid known corrosive phenomena with the use of demi-water and to increase the system's resistance to aging, the introduction of a regulator is also considered appropriate of pressure upstream of each cabinet, wells to allow the housing of thermocouples suitable for periodic verification operations of the cooling parameters of the tubes and filter to prevent that the tubes cooling vane become blocked from some dirt particles present inside cooling water.

5.2 Predrivers

Due to the problem encountered and obsolescence of the electronic parts for the Predrivers units, it's necessary an up to date, maintainable and reliable system. A document with all specifications needed for replacement of the units was drafted. The suggestion is to use an external solid state amplifier, similar to those normally used at LNL for ALPI operations.

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