352 MHz TETRODE RF STATIONS FOR SUPERCONDUCTING SPOKE CAVITIES

M. Jobs†, K. Gajewski, V. Goryashko, H. Li, R. Ruber, and R. Wedberg
Uppsala University, Uppsala, Sweden

Abstract

The FREIA facility has commissioned two 400 kW 352 MHz pulsed RF power amplifiers. Both stations are running dual Thales TH595 tubes and are capable of generating up to 3.5 ms pulses with a repetition rate of 14 Hz with one of the stations power supplies support a repetition rate of 28 Hz. The stations have an overall efficiency of about 50% and a total gain of 74 or 85 dB. Both stations uses solid state drivers to power the tetrode vacuum tubes and to provide a high overall gain. A complete RF-distribution line has also been incorporated in the setup.

INTRODUCTION

In order to drive the linear accelerator (LINAC) powering the European Spallation Source (ESS) in Lund, Sweden, a number of high-power radio frequency (RF) amplifiers are required. Depending on the power requirements of the different accelerator stages of the LINAC the amplifiers are based on either klystron, inductive output tube (IOT), or tetrode technology. The ESS LINAC design requires the RF-amplifiers to be specified to operate up to a maximum of 3.5 ms pulses

Although klystrons is the typical source chosen for high power RF generation the initial stages of the ESS LINAC only require power levels in the range 300-400 kW with a working frequency of 352 MHz to power the first section of superconducting spoke cavities [1]. This allows the RF amplifiers to be built based on tetrode technology rather than klystrons.

The FREIA laboratory at Uppsala University, Sweden has been in charge of commissioning and running the first tetrode based RF station prototypes which are used onsite at FREIA to as the RF power sources required to perform conditioning, test and evaluation measurements of the superconducting spoke cavities which will be installed and used at ESS. FREIA has been working in close collaboration with the manufacturing companies of the tetrode stations during both design and commissioning.

POWER-STATION 1

The first prototype RF station in operation in FREIA was manufactured by Itelco-Electrosys, Orvieto, Italy and operated using dual Thales TH595 tetrodes, a switched mode Anode Power Supply (APS) and 10 kW pulsed power SSA drivers(see Fig. 1). Each tetrode has a maximum output power of 210 kW and allows the station to produce 3.5 ms pulses at 400 kW peak output power at 14 Hz repetition rate. The tetrodes are operated in class AB close to class B. The entire station uses an externally supplied blanking signal for enabling/disabling the power-supplies and driver stages in order to further improve the overall efficiency.

The station was factory acceptance tested [2] (FAT) before being shipped to FREIA, Uppsala University and then was subjected to a thorough Site Acceptance Test [3] (SAT) in order verify that that the station performance adhered to tender specifications.

Internal Layout

The station is divided into two tetrode sections with separate pre-amplifiers and tetrode grid power supplies. Both tetrodes share a common APS isolated by IGBT series switches. A central control unit (CCU) is monitoring supply voltages, currents, RF power meters, temperatures and flowrates in order to provide complete monitoring and interlock protection in case of internal errors or out-of-bound operating conditions.

Tetrode Power Supplies

The main component of the RF output power is supplied through the tubes APS. The Itelco-Electrosys station uses a single stacked Technix switched mode power supply to generate a peak anode voltage of 18 kV.

The screen-grids are operated at 900 V and uses Technixsupplies with an additional 70 uF capacitors on the output to prevent output ripple.

The control grid is supplied by a custom power supply and provides negative bias in the range of -400 to -150 V. The filament supply is an 8 V, 180 A DC power supply model SM 15-200 Delta Elektronika.

Total station average power consumption is 45 kW at maximum output power and it has 10 kW idle power consumption. The overall station efficiencyat maximum output power is roughly 45%.

Figure 1: 400 kW Itelco-Electrosys RF Power Station.

RF Performance

The power station generates well defined RF pulses in the range of 40 kW to 400 kW. All harmonics are below -40 dBc and short term amplitude and phase stability are +/- 0.3 dB and +/- 1.5 degrees, respectively. The total station gain is about 85 dB and is shown in Fig. 2.The solid state drivers have the option of running either with or without active gain–control (AGC). When the AGC is active the drivers keep a fixed 70 dB total gain, however if the average RF power is modulated quickly the AGC does possess some overshoot and as such in FREIAs facilities it is normally run with the AGC deactivated.

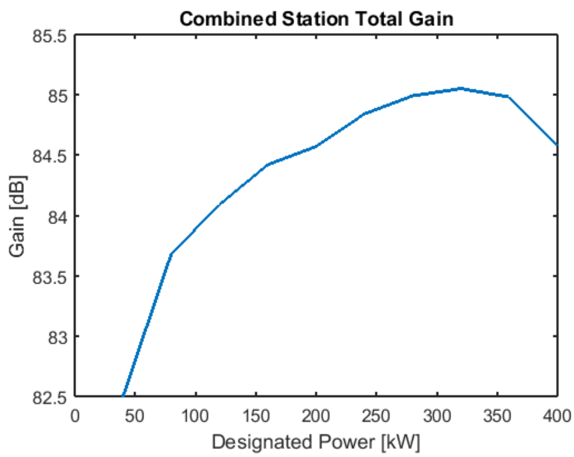

Figure 2: 400 kW Itelco-Electrosys power station gain curve.

POWER-STATION 2

The second prototype RF station tested at FREIA was purchased from DB Science, Padua, Italy (Fig. 3). It is also based on dual TH595 Thales tetrodes providing a maximum output power of 400 kW. However, unlike Station 1 the average output power is doubled in order to generate both 14 and 28 Hz 3.6 ms pulses. The higher average output power allows for testing of new tetrode versions capable of supporting higher average power dissipation.

Figure 3: 400 kW DB Science RF Power Station.

Internal Layout

The power station is divided into two separate sub-amplifiers each one running a TH595 tetrode tube with each sub-system equipped with an individual set of control modules and supplies. In normal operation they are run in a Master-Slave configuration and both outputs are combined in a common 400 kW combiner located on the top of the station. The station is equipped with separate CW and Pulsed RF pre-amplifiers allowing the station to be operated at 400 kW pulses or 10 kW CW.

Tetrode Power Supplies

The power station uses high-voltage high-power transformers switched at 300 Hz in order to generate the tetrode anode voltage. Unlike Station 1 each tetrode has a separate anode supply with a separate capacitor bank.

The screen-grid power supplies are custom built by the manufacturer and also have a separate small-scale crowbar circuit used to discharge the screen-grid power supply in case of interlocks. The control grid supply is also custom built and uses -400 V and -200 V for blanking and operative control grid biasing.For the filament supplies Delta Electronica SM-15-200supplies are used operating at the same 8 V 180 A as Station 1.

The overall station efficiency when operated at maximum output power is roughly 50 %.

RF Performance

The main difference of Station 2 at nominal operation conditions is the difference in amplitude and phase noise of the system. Since Station 2 uses a low frequency switching transformer based APS the frequency of the amplitude and phase noise is in the sub kHz range which is 10 to 20 times lower than Station 1.

The overall gain of Station 2 is about 10 dB lower than Station 1. The cause of the gain difference is due to the drivers of Station 2 having traded some of the gain for better linearity. The non-linearity of the station as whole, however, is mainly governed by the tetrode gain curve and is shown in Fig. 4.

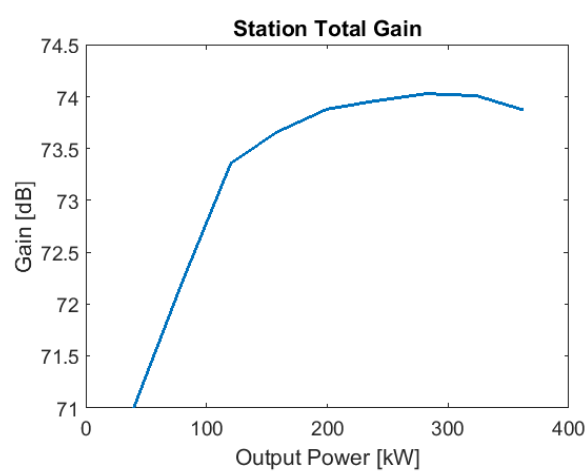

Figure 4: 400 kW DB Science power station gain curve.

ISBN 978-3-95450-182-3

RF DISTRIBUTION

The RF distribution connecting the power stations with the superconducting spoke cavities consists of coaxial and waveguide transmission lines, patch panels used to simplify reconfiguration of the distribution, circulators, dummy loads, arc-detectors, directional couplers and avariable short used on one of the patch panel dummy loads.. The main components were purchased from Exir Broadcasting AB, AFT microwave and Mega Industries LLC.

Transmission Lines

The main bulk of the transmission lines connecting the power stations with the superconducting cavities are made up out of 6-1/8 inch coaxial lines. Coaxial lines were chosen mainly due to the fact that they allows for quick on-site modification of the transmission line distribution since they are cut and built by bulk components. They are also slimmer than the WR2300 waveguides otherwise used for 352 MHz. In the final stretch between the bunker chicane and the cavity coupler two different lines are used; one 6-1/8 inch coaxial and one WR2300 waveguide line. The main purpose of using two different transmission lines types in this section is to allow for an evaluation of the performance differences between the two types.

Patch Panels

The primary patch panel is a 7 port patch panel located directly at the RF power station outputs. The purpose of this patch panel is to distribute the main RF to either one of the two transmission lines into the bunker or to separate dummy loads for test-runs. Two smaller 3 port patch panels are also incorporated in the system in order to switch between different lines.

Circulators

Two 400 kW peak power, 352 MHz, manually tuned circulators are used to isolate the output of the RF stations from the rest of the transmission lines and loads. Due to internal heating at high power levels as well as the limitations in using manual tuning of the circulators the centre frequency of the circulators have to be set as a trade-off between performance at the high and low power limits. Figure 5 shows S_{11} of the circulator in the final tuning state. The circulator is tuned for optimum performance in the 200 to 400 kW range. As is expected the final S_{11} is also a function of the phase of the reflected signal. At high pow-er levels running 14 Hz, 3.5 ms pulses the circulators requires roughly 6-7 minutes to settle thermally. During the settling period there will be a drift in S_{11} of about 2 dB. Both circulators share a common dedicated deionized cooling system in order to maintain the circulator temper-atures at exactly 30 degrees as well as reduce the amount of thermal oscillations in the circulators, which would be present if the cooling system was part of the larger deion-ized cooling system used to cool both RF stations.

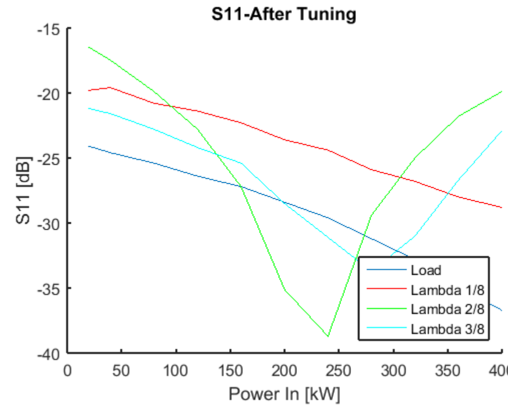

Figure 5: Circulator S11 measurements performed with the primary output shorted at different distances.

Dummy Loads

Water-cooled 400 kW 6-1/8 inch coaxial input dummy loads manufactured by AFT are used to dissipate reflected power to the circulators from the cavity as well as one load being used in conjunction with the primary patch-panel and variable short to allow the power stations to run directly to a load with variable reflection coefficient.

CONCLUSION

FREIA now have two active and verified 352 MHz RF power stations capable of delivering 14 and 28 Hz 400kW pulses with pulse durations from 10 us up to 3.5 ms. Both stations have been performance tested according to ESS tender specifications on both dummy loads as well as superconducting spoke cavities. The stations are also capable of supplying CW signals at reduced power which furthers broaden the possible usage applications of the stations. By basing the RF distribution around rigid coaxial lines in conjunction with multiport patch panels the setup can be modified with relative easy to allow for modified test-setups. Results detailing the Factory Acceptance Tests and Site Acceptance Tests can be found in [2] through [4].

ACKNOWLEDGEMENT

The authors would like to thank the staff at both Itelco-Electrosys and DB Science for the good collaboration in developing the tetrode stations as well as ESS for supporting the work.

REFERENCES

[1] R. Yogi, et. al, ”*Tetrode based Technology Demonstrator at 352 MHz, 400 kWp for ESS Spoke Linac*”, IVEC 2014, April 2014, Monterey, 06857516.

[2] M. Jobs, R. Wedberg, K. Gajewski, "*Itelco-Electrosys 400 kW RF Station Site Acceptance Test*" FREIA Report 2015

[3] M. Jobs, R. Wedberg, K. Gajewski, " *DB Science 400 kW RF Station Site Acceptance Test*" FREIA Report 2017

[4] M. Jobs, R. Wedberg, K. Gajewski, " *Report Electrosys 400 kW RF Station Factory Inspection Test*" FREIA Report 2015