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HIGH POWER RF SYSTEMS FOR THE BNL ERL PROJECT*

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Abstract

The Energy Recovery Linac (ERL) project, now under construction at Brookhaven National Laboratory, requires two high power RF systems. The first RF system is for the 703.75 MHz superconducting electron gun. The RF power from this system is used to drive nearly half an Ampere of beam current to 2 MeV. There is no provision to recover any of this energy so the minimum amplifier power is 1 MW. It consists of 1 MW CW klystron, transmitter and power supplies, 1 MW circulator, 1 MW dummy load and a two-way power splitter. The second RF system is for the 703.75 MHz superconducting cavity. The system accelerates the beam to 54.7 MeV and recovers this energy. It will provide up to 50 kW of CW RF power to the cavity. It consists of 50 kW transmitter, circulator, and dummy load. This paper describes the two high power RF systems and presents the test data for both.

OVERVIEW

The Energy Recovery Linac (ERL) project at BNL is a test bed for all future upgrades at the Collider Accelerator Department (C-AD). They include e-RHIC and electron cooling. The main part of the project is developing superconducting technology (5 cell cavity and e-gun) as well as RF power sources to drive them. In the ERL, electrons are accelerated in a CW cavity to ~ 2 MeV, focused, and injected into the 5 cell SRF cavity. In the SRF cavity, electrons gain 15 MeV of energy after which beam re-enters the cavity in decelerating phase, giving energy back to the cavity. The e-gun RF cavity relies entirely on external RF power to accelerate up to a 0.5 Ampere beam load and therefore will need to be driven by a very high power (1 MW) amplifier. But because the 5 cell cavity recovers energy from the returning beam, the power of the transmitter will only need to be on the order of 50 kW. Most of the power is used for over-coupling the cavity to lower the Q and only insignificant amount of power (10 watts) will actually be used for RF losses. At this time all power sources have been purchased and tested to the full RF power. This paper will describe them as well as present full power test data.

1 MW system

There are four main components to the 1 MW system: Klystron, transmitter, water load and circulator:

Klystron (Fig.1), manufactured by CPI, is rated to produce over 1 MW of CW power at 703.75 MHz. This tube is similar to one produced by CPI for LANL, but the

BNL tube does not have a modulating anode. The output of the tube is WR1500. The collector is grounded, and -92kV at -17.1A will produce 1 MW in our tube. While the maximum drive specified for 1MW is 100W (40dB gain), this tube only requires 15.2W to get full power.



Fig. 1 Klystron

Transmitter consists of the power supply (Fig.3), filament power supply, two solenoid power supplies, two vacuum pump controllers, several water monitoring circuits (for calorimetric power measurements as well as interlocks), two air blowers (one for klystron window and the other for gun windows), 100 watt RF amplifier and the PLC to keep track of everything, including interlocks and monitoring of directional couplers (RF power) in the system. (Fig.2)

- Electrical Characteristics
 - AC Input: 4160 VAC (chosen to match the previous design)
 - DC Output: - 100 kV at - 21 A
 - Filaments: 30 Vrms at 30 Arms, isolated to operate at - 100 kV.
 - Solenoid PS: 30 A at 30 V and 30 A at 300 V
 - Vac-Ion Controllers: For 8 I/S pumps.
 - Water circuits: Three at 400 GPM max (collector, RF load, beam dump), Four at 35 GPM max (body, output cavity, circulator, spare).
 - Cooling Air: Two 100 CFM, filtered air
 - RF Amplifier: 200 W max output, 52 dB gain

The largest part of this transmitter manufactured by Continental Electronics Corporation is the power supply. Its basic design is to stack 96 isolated IGBT gated power supplies in series. Because the IGBTs permit a fast shut down mode, a crow bar is not required to limit the energy in an arc to 40 Joules.



Fig. 2 Transmitter



Fig. 3 Power supply

Water load (Fig.4), manufactured by CML Corp, is rated for 1.3 MW of continuous power. It has a WR1500 waveguide input, a ceramic window, and a stand with six point levelling. It requires water cooling of 200 GPM at full power.

The load could not be tested at full power at the factory, but VSWR was measured using water heated to 33°C to simulate the heating effect at full power.



Fig. 4 Water load



Fig. 5 Circulator

- Electrical Characteristics
 - Continuous Power: 1.3 MW
 - Centre Frequency: 703.75 MHz
 - VSWR: 1.05:1 at ± 2 MHz, 1.2:1 at ± 20 MHz

Circulator (Fig.5) is manufactured by AFT Microwave. It is water cooled (4.5 GPM of de-ionized water) and is rated 1 MW into any port.

- Electrical Characteristics
 - Centre Frequency: 703.75 MHz
 - Bandwidth: ± 17 MHz
 - At Centre Frequency:
 - Insertion Loss: < 0.05 dB, typ. 0.03 dB
 - Isolation: > 30 dB
 - VSWR: < 1.06
 - In Bandwidth:
 - Insertion Loss: < 0.1 dB
 - Isolation: > 20 dB

HIGH POWER TESTS

Prior to connecting the High voltage power supply to the klystron all test were run into the 25 M Ω resistive load. This checked the performance of all controls, interlocks and cabling. Significant efforts were put into making sure the fast shut-down protection of the power supply were fully functioning. This feature assures that in case of failure the klystron tube will be protected.

Full set of tests into the klystron and dummy load followed. Shorting plate at the output of the circulator acted as a full reflected condition for all tests.

At the power output of over 700 kW the 2nd and 3rd harmonics grew very unexpectedly. It took us some time to determine that it was an error in measurements: Since the sharp rise in VSWR as the output power was increased to 1MW was not matched by a sharp increase in temperature of the output cavity, we knew there was an error in the measurement of VSWR. This led us to the source of the VSWR measurement problem, which was the directional coupler gain at harmonic frequencies.

1 MW system was successfully tested to the full power level. To keep the system ready to operate and maintain the level of knowledge, we are running it every two month for a shift. So far the system proved to be very reliable and relatively easy to operate.

50 kW System

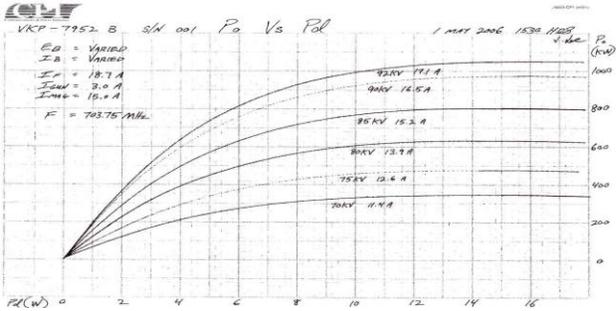


Fig. 6 This set of data was used to determine the amount of expected at a given beam Voltage

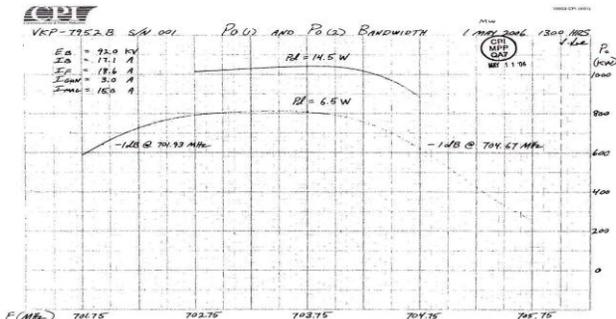


Fig. 7 Bandwidth at two different drive levels. This tube could also be designed with a greater bandwidth and a lower gain.

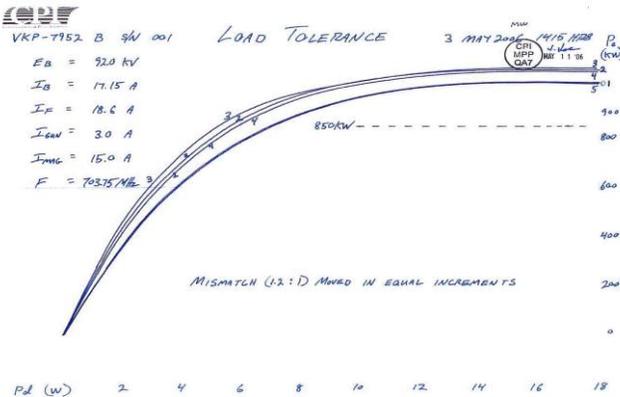


Fig. 8 Load tolerance was measured at the factory with calibrated mis-matches. It shows the effect on the output due to load VSWR

SRF cavity for the ERL is designed to operate up to 20 MV/M. With external mechanical noise driving the mechanical mode of the cavity on the order of 5 Hz, the power to compensate this and to maintain a maximum energy error of 1.4×10^{-6} is around 20 kW. The frequency of 703.75 MHz is very fortunate for the choice of the amplifier: digital television transmitters are readily available in the power of up to 50 kW. We chose the one manufactured by Thomson Broadcast and Multimedia (Fi.9), which utilising Thales (TH793) 80 kW Inductive Output Tube (IOT). It is a type of vacuum tube with high efficiency (40 to 60% depending on the power output) but lower than klystron gain (23 dB). It's operated in class AB and requires 500 watts from solid state driver. IOT has electro magnetically focused electron beam. RF from solid state driver enters input cavity and then coupled to the grid, which density modulates the electron beam. The IOT beam power varies with the amplitude of the modulating signal. The 50 kW system was installed, tested and in operation for the last 4 years. It proved to be robust and extremely reliable: after all it's being operated only a day or two a month.



Fig. 9 SRF 50 kW transmitter

REFERENCES

[1] S. J. Lenci, et al, "Design, Construction, System Integration, and Test Results of the 1 MW CW RF System for the E-Gun Cavity in the Energy Recovery Linac at Brookhaven National Laboratory, PAC'09, 2009