

# 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\*

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## Abstract

Brookhaven's ERL (Energy Recovery LINAC) requires a 1 MW CW RF system for the superconducting electron gun cavity. The system consists primarily of a klystron tube, transmitter, and High-Voltage Power Supply (HVPS). The 703.75 MHz klystron made by CPI, Inc. provides RF power of 1 MW CW with efficiency of 65%. It has a single output window, diode-type electron gun, and collector capable of dissipating the entire beam power. It was fully factory tested including 24-hour heat run at 1.1 MW CW. The solid state HVPS designed by Continental Electronics provides up to 100 kV at low ripple and 2.1 MW CW with over 95% efficiency. With minimal stored energy and a fast shut-down mode no crowbar circuit is needed. Continental's transmitter includes PLC based user interface and monitoring, RF pre-amplifier, magnet and Vac-Ion pump supplies, cooling water instrumentation, and integral safety interlock system. BNL installed the klystron, HVPS, and transmitter along with other items, such as circulator, water load, and waveguide components. The collaboration of BNL, CPI, and Continental in the design, installation, and testing was essential to the successful operation of the 1 MW system.

## OVERVIEW

Brookhaven's ERL (Energy Recovery LINAC) requires a 1 MW CW RF system for the superconducting electron gun cavity. Designing, installing, and testing this system required a high degree of collaboration between BNL and all the contributors to this system, especially the klystron manufacturer, CPI, and the transmitter manufacturer, Continental Electronics. This cooperative effort was essential at every stage of development, starting with specification and continuing all the way to the final system testing where the equipment was run with the full 1 MW CW.

This paper will describe the klystron, the transmitter and HVPS, the facility and finally the successful testing of the complete system.

## KLYSTRON

The 703.75 MHz klystron made by CPI, Inc. provides RF power of 1 MW CW with efficiency of 65%. It has a single output window, diode-type electron gun, and collector capable of dissipating the entire beam power. It was fully factory tested including 24-hour heat run at 1.1 MW CW. The klystron is based on the VKP-7952A which was developed for the Accelerator Production of Tritium project (APT) at Los Alamos National Laboratory. That klystron was designed to provide 1 MW CW at 700 MHz. with an efficiency of >65%. The electron gun of the APT klystron had a modulating anode which allowed for optimizing efficiency at lower output powers. The klystron for Brookhaven National Lab was to be optimized at 703.75 MHz. Since operation at lower powers was not a critical concern, a diode gun was developed to simplify the tube and power supply.

The klystron design and building was straightforward. At test, the klystron processed reasonably quickly. Preliminary data met spec and the customer source inspection was scheduled. During the heat run at 1.1 MW CW, the coaxial output window failed. Analysis did not find any conclusive evidence as to why, so some minor redesign work was performed to improve the cooling of the center conductor. The tube was rebuilt with the improved output window. Again at test, the tube processed quickly. This time the tube passed the 24-hour heat run at 1.1 MW and the Factory Acceptance Testing was completed.

Table 1: VKP-7952B Performance Summary

	Specification	Test Data
Frequency	703.75 MHz	703.75 MHz
Cathode Voltage	95 kV max	92 kV
Beam Current	21 Amps max	17.1 Amps
Perveance	.55 nom	.6
Output Power	1,000 kW min	1,030 kW
-1 dB Bandwidth	$\pm 0.7$ MHz min	$>\pm 0.7$ MHz
Efficiency	65 % min	66.2 %
RF Drive Power	100 Watts	15.2 Watts
Gain	40 dB min	48.4 dB

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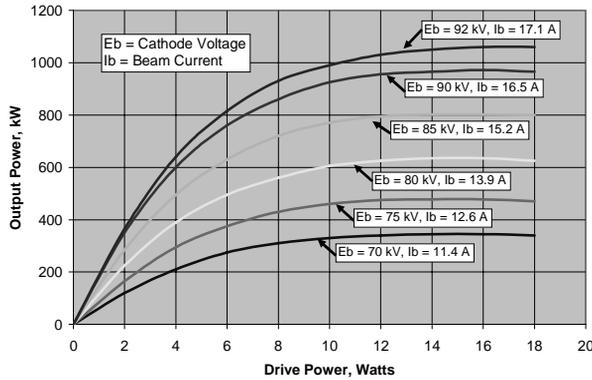


Figure 1: VKP-7952B Family of transfer Curves.

In addition to the Test Data summarized in Table 1, the klystron also demonstrated stable performance in all phases of a 1.2:1 mismatch and the collector successfully dissipated the entire beam (no RF drive applied) for 1 hour.

**Load Testing**

BNL needed a 1 MW load for the reflected power port of their circulator. It would be used as the load for the acceptance testing of the klystron at the lab. The supplier chosen had not demonstrated the capability of the design. In order to mitigate risks at the lab, BNL asked CPI to test the load during the klystron factory testing. The testing revealed the load had a fairly high VSWR (>1.2:1). It subsequently failed at 250 kW of power. The basic design of the load simply wasn't suitable for the needed power level. BNL pursued a load from a supplier that had a proven design and were able to order the replacement load in parallel with the shipment and installation of the klystron and power supply. The performance testing at CPI avoided a delay of the project that would have occurred if the load inadequacy was determined at the lab.

**HIGH VOLTAGE POWER SUPPLY**

Continental Electronics provided the High Voltage Power Supply (HVPS) and integrated transmitter system, which includes PLC-based user interface and monitoring, RF pre-amplifier, magnet and Vac-Ion pump supplies, cooling water circuits for the klystron and instrumentation, and integral safety interlock system. Most transmitter functions had been incorporated in a similar system designed previously by Continental for Los Alamos National Laboratory's APT program. The differences were primarily in the HVPS, which required minor performance enhancements.

During the systems engineering phase, it became clear that a major hurdle in factory testing of the HVPS would

be identifying a load to permit full-power testing. Because of the expense and risk in building a 2 MW DC load, it was decided instead that the HVPS would be tested at maximum voltage (100 kV) for a nominal current level (1 A), and separately at full current (21 A) under a nominal voltage of about 1.5kV. Testing at full power would have to wait for system integration at BNL. All functional tests of the transmitter and HVPS were then successfully completed at the Continental factory, including the fast shut-down mode (FSDM) testing. Because the Continental IGBT HVPS has minimal stored energy, a conventional crowbar circuit is not needed.

However, due to the layout required at BNL, a rather long coaxial cable was required from the output of the HVPS to the klystron. Thus Continental's systems engineering work included making certain that the energy transferred to the klystron at the far end of the cable was limited to less than 5 J. Simulations were conducted at a moderate voltage as well as at the maximum of 100kV. The results of the simulation conducted at 30 kV and the measured response compared favorably, and are shown in Figure 2. A simulation conducted at 100kV indicated the desired cable length would not cause the maximum fault energy to be exceeded.

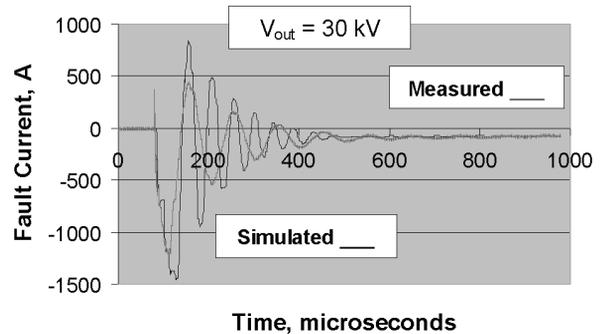


Figure 2: HVPS Fault Current vs. Simulation at 30 kV.

**SYSTEM INTEGRATION**

Once the klystron, HVPS, and transmitter were integrated at Brookhaven, two issues arose, one expected and one unexpected. First, the regulation feedback loop gain required software tuning and minor component changes. Second, corona was observed at the HVPS switch module frame. No corona had occurred in full voltage testing at BNL prior to integrating the klystron. Fortunately, simply revising the corona ring mounting corrected this unexpected development. Although the BNL facility is air conditioned, it is believed that the slight difference in atmosphere (perhaps accumulated salt air) was sufficient to have lowered the tolerance to corona formation.

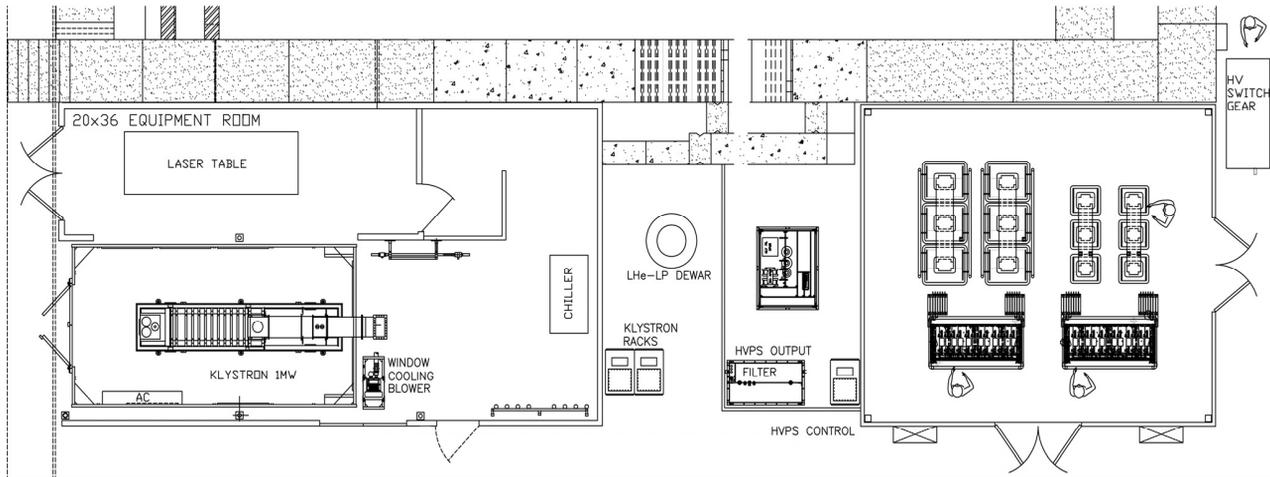


Figure 3: The floor layout of the 1 MW CW RF system. The area shown is approximately ninety feet wide.

## SYSTEM FACILITIES

The equipment was installed at BNL as shown in Figure 3. Starting from the right side of the figure, the four transformers and power modules of the HVPS were placed in an air-conditioned room to control dirt and humidity, while providing a physical barrier for electrical safety. Just outside this transformer room, switch gear controls and monitors the 4160 VAC that powers the transmitter.

Moving to the left, we have the two high voltage tanks which contain output filtering, filament transformers, and voltage and current monitoring. This is also the location of the three control racks.

The next room contains the water monitoring part of the transmitters. There are several water circuits. Collector cooling requires 380 gpm, and the water load, that absorbs power reflected from the cavity, requires 280 gpm. Smaller capacity circuits are needed for the circulator, the klystron gun, and the klystron output cavity. These smaller capacity water circuits are temperature controlled by a water chiller. The flow rates and temperature differentials on every circuit are sent back to the transmitter's PLC. This lets us know where the head is being deposited for any mode of operation. This room also contains a filtered air blower for cooling the RF vacuum window at the output of the klystron.

The klystron is next, in a totally enclosed steel room, which provides shielding. This steel room gives more access than one would have with a lead garage, and no lead handling is needed. This room is air conditioned to remove the heat from the non-water cooled components (primarily the solenoid magnets) of the klystron.

The output of the klystron travels in WR1500 waveguide up to a second floor, which is not shown in Figure 3. There, the RF power travels through a circulator manufactured by AFT, and goes on to the cavity. Power reflected from that cavity returns to a water load manufactured by CML Engineering.

## TESTING

Initial system testing was done with a 100kV, 25 MΩ resistive load on the HVPS. This portion of the testing checked out the switch gear, HVPS, vacuum controllers, water monitoring circuits, interlock systems, fast shut-down modes, and both control and power cabling.

Once we were confident in the system operation, we connected the klystron. The circulator had a blank plate installed on the output port to direct all energy to the water load.

Testing proceeded cautiously. Power to the klystron was increased in discrete steps. At each step, forward and reflected power were monitored, as well as tube parameters such as voltage, current, and temperatures. These tube parameters were compared to extensive data logged during the acceptance testing at CPI. When all parameters were as expected, we proceeded to the next level of power.

Throughout this testing process, BNL was heavily supported by both Continental Electronics and CPI. The highly specialized knowledge of these participants gave us much needed insight into the challenges we faced along the path to success.

Those challenges were overcome, and this system at BNL can now be operated routinely with 1MW CW out of the klystron.