RF POWER UPGRADE FOR CEBAF AT JEFFERSON LABORATORY*

R. Nelson, A. Kimber, JLAB, Newport News VA, USA

Abstract

Jefferson Laboratory (JLab) is currently upgrading the 6GeV Continuous Electron Beam Accelerator Facility (CEBAF) to 12GeV. As part of the upgrade, RF systems will be added, bringing the total from 340 to 420. Existing RF systems can provide up to 6.5 kW of CW RF at 1497 MHZ. The 80 new systems will provide increased RF power of up to 13 kW CW each. Built around a newly designed and higher efficiency 13 kW klystron developed for JLab by L-3 Communications, each new RF chain is a completely revamped system using hardware different than our present installations. This paper will discuss the main components of the new systems including the 13 kW klystron, waveguide isolator, and HV power supply using switch-mode technology. Methodology for selection of the various components and results of initial testing will also be addressed.

BACKGROUND

Thomas Jefferson National Accelerator Facility (JLab), in Newport News VA, USA includes CEBAF, the Continuous Electron Beam Accelerator Facility. CEBAF was designed and built as a 5 pass, 4 GeV, 200 μA CW machine with simultaneous beam delivery to three experimental halls. While designed for 4 GeV, CEBAF has operated at up to 6 GeV. An upgrade program is currently under way designed to increase the maximum energy to 12 GeV. Among other upgrade areas, this includes significant additions to the RF system. At the same time, an additional experimental hall (Hall D) is being built to accept this new higher energy and provide additional science opportunities.

CEBAF includes an injector and two superconducting linacs. The injector includes a warm capture section and 2.25 superconducting cryomodules. Each of the two linacs contains twenty superconducting (SC) cryomodules for a total of 42.25 cryomodules including the injector. Each cryomodule has eight SC cavity assemblies with each cavity having its own RF source based on a 1497 MHz CW klystron.

12 GEV UPGRADE

The upgrade will add 10 new zones plus and add an additional half pass, increasing total gradient from 6 GeV to 12 GeV. As with our present zones, each consists of the SC cryomodule plus a full RF system, both low level and high power for each cavity in the zone. To achieve the higher gradients, each upgrade cavity will be powered by a 13 KW [1] RF source, that besides the high power element, also includes new digital low level RF controls and other subsystems to tie it all together. Previous high power systems relied on the low level RF (LLRF) and CAMAC for interlocks and controls. The LLRF will not monitor power functions and CAMAC is being eliminated for new zones, so an additional FPGA controller chassis was developed and will handle all HPA (high power amplifier) controls.

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SOLID STATE OR TUBE

Developing 13 kW CW at 1497 MHz could be accomplished by various means: klystron, IOT, or multiple solid state amplifiers with splitters, and combiners. As regards solid state, over the past decade several SBIR proposals were funded to develop a possible solid state replacement for our existing (5 kW) klystrons. Size and cost were concerns with solid state, and our previous experience with 1 kW, 499 MHz amplifiers found that transistors went obsolete rather quickly as improved devices replaced them. Sadly however, newer devices are rarely drop-in replacements, so a redesign of system boards is required to accommodate them. While tubes aren't exactly off-the-shelf items in most cases, unlike transistors, one can generally have them manufactured in small quantities when needed.

Though many facilities are moving, or are considering moving to, solid state for various reasons (efficiency, lifetime, cost, soft failure mode to minimize downtime) our own experience with the 5 kW klystron design supplied by Varian (CPI) and Litton (L-3 Communications) shows pleasantly long life, averaging >150k hours[2] between failures (as of 2008). Some of those are hard failures, and some replacements due to gradual degradation. CEBAF is capable of achieving design goals with several systems offline at any given time so there is a built-in margin to accommodate hard failures. Not only that, but trips cause less impact to our operations than might be true for other machines. Beam is typically restored in seconds following a trip.

The performance requirements for the new RF source remain essentially unchanged from the original 5kW spec, with the exception of power and efficiency. The existing 5 kW klystron offers only 32% efficiency so we raised the bar to 50%. Even that efficiency relates to operation at rated power and since we typically run below that, net efficiency will be less.

An option considered, but determined to be more costly and offer higher risks, was that of using a single higher power device capable of powering a full RF zone (8 cavities). This configuration would also require high power splitters to provide 8 outputs, and because the RF to each cavity must be regulated to high precision for both amplitude and phase, the additional controls and fast high power modulator required were soon found to cost more than using individual RF sources. The added complexity and component count was also a concern.

The plan adopted is to build new zones in the same fashion as the existing the zones, meaning a single RF power device per cavity. Potential vendors were asked to provide proposals for both an IOT and a klystron. Especially at less than full power, the IOT has better efficiency, but has the disadvantage of low gain and require a more expensive driver amplifier. A klystron might require < 2watts while an IOT roughly 130 watts (assumes 20dB minimum gain).

We've seen good life from our klystrons, but lifetime on non-UHF IOTs is less well known. A small number of IOTs had been built at 1.3 GHz but none at 1.497 GHz. Compared to klystrons, no significant numbers of hours have been logged yet. Once pricing came in we found the cost of the IOT was higher than a comparable klystron. Adding the cost of the driver made it still more costly. Assuming a successful IOT could be produced, the limited operational experience with 1300 MHz devices gave no guarantee of longevity so the IOT was abandoned in favor of a klystron.

Table 1: Summary of RF Power Requirements

Parameter	Old	New	Units
Center Frequency	1497	1497	MHz
Bandwidth, -1dB	5	5	MHz
Bandwidth, -3 dB	6	6	MHz
0.5 dB incremental gain at	4	10	kW
Efficiency (at rated power)	32	>50	%
Gain	38	>42	dB
Harmonics	<-20	<-20	dBc
Spurious	-70	-70	dBc
Beam voltage	11.6	<16	kV DC
Heater voltage	7.3	7.3	V DC
Modulating anode	Yes	Yes	
Isolated collector	Yes	Yes	
Cavities (klystron only)	4	5	
Focus	PM	EM	
Cooling	liquid	liquid	

Two offers were received and evaluated, and a contract was awarded to L-3 Communications in Williamsport PA for a new 5 resonator, solenoid focused device. The coaxial 1-5/8" output window is water-cooled and used before in a 20 kW L-band IOT. The gun is also essentially the same as our existing klystron and as rated voltage and current are only slightly higher than running that unit at 8kW, we should expect long life. Cathode density is approximately $08.A/cm^2$.

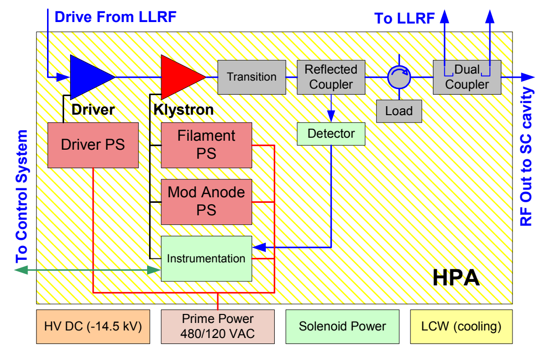

Figure 1: Block diagram of high power RF system.

L-3 developed the design and built the first article device which was delivered to JLab. The first article passed all tests, meeting or exceeding specs. The first two production units are expected at JLab in early 2011. 24 will be needed for the 2011 6 month down when installation begins.

Table 2: L-3 L-4313 Klystron Performance

First Article Parameter	Req	Actual	Units
Output power	13	13	kW
Efficiency (includes solenoid and heater power)	≥50	50.9	%
Beam Voltage	<15	14.5	kV
Beam Current	Voltage dependent	1.7	A
Micro perveance	Not def	~1	-
Filament voltage	< 10	7.0	V
Filament Current	<10	3.9	A
Drive for 13 kW	< 33	16	dBm
Solenoid power	Not def	873	Watts

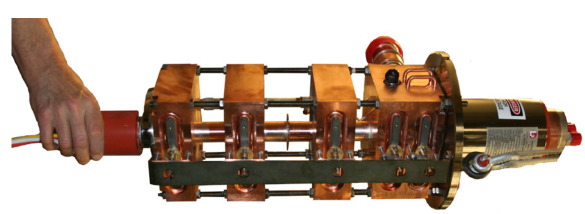
Figure 2: L-4313 13 kW klystron (L-3) w/o solenoid

Once the klystron had been designed and tested, operating voltage & current were defined and we could specify the power supply requirements. Here again we had options for powering the new klystrons, from a single supply for each linac powering 40 klystrons, to 1 supply per klystron. One per linac was discarded as offering too much risk should the single supply fail. We presently power 8 from a single supply and suggested proposals could be for a single package with 1 or more power supplies, each powering from 1 to 8 devices.

We received responses offering several topologies from conventional T-R units with SCR controls, to SMPS, to hybrid systems. Each was evaluated for benefits, company capabilities, and ultimately the best value for JLab. The award went to New Jersey-based NWL for a resonant mode switcher. The design had several advantages in that it was comprised of 4 separate supplies, each of which could power 2 klystrons. In the event of failure of a single power supply module the remaining 3 supplies could continue to power the remaining 6 klystrons in a zone in most cases. The power supply is a variant of a design NWL has had great success with in industrial electrostatic precipitator applications, having sold hundreds at the time we awarded the contract. Those systems operate at considerably higher voltage and lower current and are immersed in oil, while ours operates in air. Total output power is 225 kW. Output voltage is adjustable to -15 kV with a current of 3.75 amps per supply (15 amps total). Ripple was measured at less than 0.1% p-p at rated output. Each supply is independently adjustable though our normal operating mode will run all at the same voltage. Local control panels track output parameters, feedback gains, faults, and other diagnostics.

Figure 3: NWL 133201 power supply & HPA module.

Because of its higher switching frequency, low stored energy, and quick turn-off when compared to traditional T-R units, these units do not require a crowbar, passing the "wire test" repeatedly. The supply was designed to operate with regular arcing in precipitator duty, so the occasional klystron arc won't cause problems. The supply was tested into a dead short at turn on and repeated external crowbars with no problems.

As mentioned earlier, space was limited to what we already had, and with larger klystrons the previous HPA packaging was unworkable. Instead of housing 8 klystrons in a 5-bay assembly as we had done in the past, pairs of klystrons sit atop HPA (High Power Amplifier) modules, each of which contains filament and modulating anode power supplies for the klystrons on top. Interface and data acquisition boards complete the package in each HPA. Filament and mod anode boards and plug-in for easy replacement, and reside in a card cage inside the HPA while everything else is connectorized.

The old <80# 5kW klystron was easily handled. The new combination of klystron and solenoid weighs in at nearly 400# and the tight positioning makes handling more difficult. As with the 5 kW tube, the new tube has a 1-5/8" modified coaxial output which is immediately transitioned to WR650 guide. The klystron will be installed in an already positioned solenoid. This means the tube can't easily be "unplugged" from the coax transition and will be installed and removed with transition attached, negating the need to move the solenoid for klystron removal.

Figure 4 shows the proposed system with eight at 13 kW klystrons each. The NWL power supplies will be located to the right, two groups of four WR650 waveguides run down penetrations to the cavities in the tunnel.

Waveguide requirements are nearly identical to the existing systems with the exception of coupler attenuation values and power handling capability for the isolator and waveguide tuner. The isolator, by Ferrite Incorporated, has a fixed magnetic field so no additional power supplies or controls are required, and a water-cooled load. First article tests met or exceeded requirements, and all units have already been delivered. As groups of four are placed in close proximity, isolators were magnetically tuned for operation in close proximity to other devices.

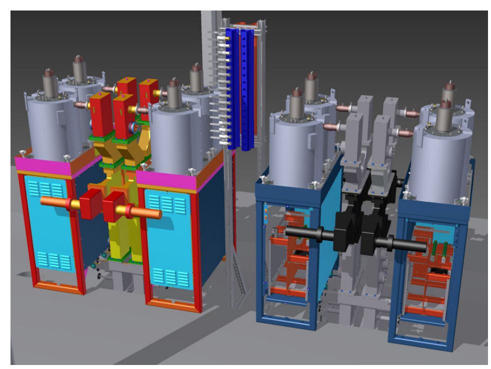

Figure 4: Drawing of HPA modules, klystrons, waveguide

Note that only the klystron, solenoid, and isolator are water-cooled using low conductivity de-ionized water. All power supplies including the CPS are cooled by either convection or forced air. A dual manifold is located between the two sets of 4 klystrons.

SUMMARY

The summer of 2011 will see a six month installation effort with a goal of installing and commissioning a minimum of two zones. Contracts have been awarded for klystrons, cathode power supplies, solenoid power supplies, driver amplifiers, HPA modules, isolators and other waveguide components. Low level RF controls and other subsystems are either already in house having been designed and built, or are on order.

REFERENCES

[1] J. Delayen and G. A. Kraft, "Comments on 12 GeV Klystrons", JLAB-TN-07-029

[2] R. Walker, R. Nelson, "Update of Operating Experience and Reliability for the 5kW CW Klystrons at Jefferson Lab", CWRF08