CPI EDB's 1.3 GHz, 90 kW PULSED IOT AMPLIFIER*

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Abstract

The VIL409 Heatwave™ IOT-based RF HPA (RF High Power Amplifier) was designed to meet the requirements of the EMMA electron accelerator at the Daresbury Laboratory. The VIL409 was successfully commissioned in September 2009. The VIL409 provides up to 90 kW RF output power over a 5.5 MHz bandwidth centered at 1.29875 GHz. It operates at fixed 1.6 millisecond pulse duration at up to 20 Hz. The user has control of the IOT beam voltage and the IOT grid bias voltage. In normal operation, smooth control of the output is accomplished via RF input from the LLRF system. The IOT grid may be pulsed or operated at a constant voltage; pulsing achieves greatly enhanced energy efficiency. The VIL409 has an embedded processor that controls all internal functions of the amplifier system and interfaces directly to the EPICS control system. The embedded controller provides real-time pulse data to EPICS and operates slow-moving interlocks. Safety and IOT-protective interlocks are hard-wire circuits which operate in the microsecond timeframe. The VIL409 can be operated locally or controlled remotely on the EPICS controls network. This paper describes the VIL409 high-power RF amplifier system.

EMMA REQUIREMENTS

From the RF HPA perspective, a few of the more interesting EMMA accelerator operational conditions and amplifier performance requirements are as follows.

Table 1: EMMA Requirements

Parameter	Operating Condition
Pulse duration	1.6 mS (fixed)
Duty cycle	3.2% (maximum)
LLRF (input to the amplifier) RF Power Frequency (High) Frequency (Low)	 1 mW (maximum) 1,301.5 MHz 1,296.0 MHz

Parameter	Requirement
Peak RF output Power Gain	 90 kW minimum 79.54 dB minimum

USER INTERFACE

The Daresbury user wanted the ability to control the IOT beam voltage and grid voltage to some extent so that RF amplitude/phase pushing characteristics of the IOT could be optimized for use in the EMMA accelerator. Therefore, the user has the ability to remotely set IOT Beam voltage within the range from -38 to -45 kV (with respect to Earth/ground) and the IOT grid bias voltage within the range from -85 to -130 V (with respect to the IOT's cathode potential). In addition to a straight forward DC grid bias voltage set, the user may also elect to pulse the grid.

Figure 1: VIL409 high power RF amplifier installed at the Daresbury Laboratory

With a DC grid bias applied to the IOT, the quiescent current (beam current between RF pulses) can be significant in the IOT. For example, with the beam at -45 kV and the grid bias at -85 volts, the quiescent current is typically 240 mA or in some cases greater than that. Therefore, the non-RF producing beam power that is dissipated within the IOT's collector is at least 11 kW CW. That translates to even more power at the prime power feed to the RF HPA system. By simply adjusting the DC grid bias to -120 volts the quiescent current is reduced to less than 15 mA. The non-RF producing beam power is reduced to less than 700 watts but the IOT gain in this case also suffers because of the larger (magnitude) grid bias voltage.

To reduce utility power consumption, to reduce the IOT's collector loading, and to be able to use a smaller beam power supply, CPI EDB developed a proprietary grid modulator circuit that pulses the grid during the RF pulse to the desired voltage level that results in high IOT gain. During the inter-pulse period, the IOT grid bias returns to a value (between -120 and -130 volts) that assures a low quiescent beam current.

The grid pulse in the VIL409 is shown in Figure 2 below. To make the operator interface less complex, the

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operator provides two unsigned values for the desired grid voltage levels. GCUTSET (Grid Cut-off Voltage Set-point) is the value provided by the operator for the voltage that will be on the grid during the inter-pulse period. GBIASSET (Grid Bias Voltage Set-point) is the value with respect to GCUTSET that is the magnitude of the pulse. In Figure 2, if GCUTSET is 120 volts and GBIASSET is 25 volts, then the voltage applied to the grid by the grid modulator circuit will be -120 volts with respect to the cathode during the inter-pulse period and - 95 volts with respect to the cathode during the RF pulse period.

Increasing the value of GBIASSET generally increases the gain of the IOT amplifier stage and applies a less-negative voltage (with respect to the cathode) on the grid during the RF pulse period. Increasing the value of GCUTSET generally reduces the quiescent beam current but that also reduces IOT gain without also making a similar adjustment to the GBIASSET value. In most cases the operator would provide values for GCUTSET and GBIASSET that result in both low inter-pulse quiescent beam current and high IOT gain while assuring that the IOT pushing performance is acceptable.

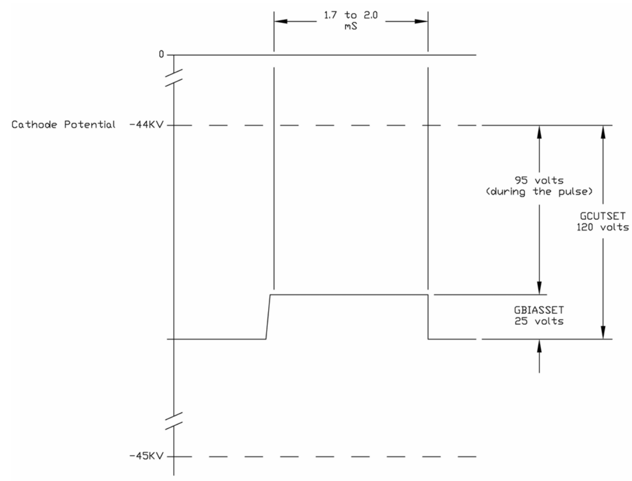

Figure 2: Grid Pulse diagram.

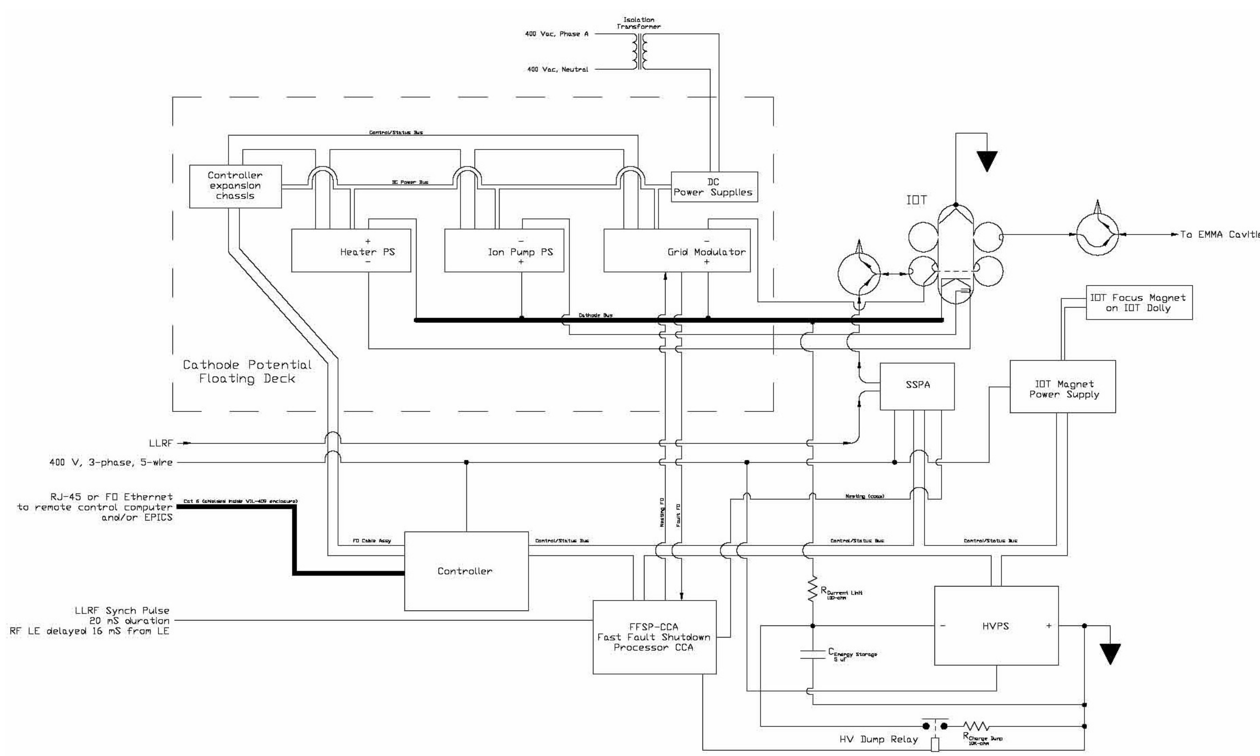

Figure 3: Schematic block diagram showing major component parts and subassemblies of the VIL409 RF High Power Amplifier.

FUNCTIONAL DESCRIPTION

The "heart" of the VIL409 RF HPA System is the IOT (Inductive Output Tube). The system at Daresbury uses the VKL9130B that is essentially the same as CPI EDB's 30 kW CW IOT. But the VKL9130B has a few minor modifications that optimize it for higher pulsed power applications. The IOT is the final RF amplifier device that is used in the RF HPA. Most of the ancillary power supplies, the RF SSPA (Solid State Power Amplifier), and other components are in the RF HPA to operate the IOT or provide protection for it. Figure 3, block diagram showing major component parts and subassemblies of the

VIL409 RF High Power Amplifier, may be used to follow the explanation for the functional description of the RF HPA below.

The "controller" is embedded in the RF HPA system. The controller is split in two parts. One part (the main controller chassis) is resident at chassis ground/Earth potential and the remaining fiber optic connected part is resident in the floating deck assembly that is at the potential of the IOT's cathode. The controller

- manages operation of the IOT and other system components;
- communicates with internal system components;
- provides protection of the IOT and system in general for slowly changing conditions such as temperature;
- communicates with a locally attached laptop computer that is used for maintenance, test of the RF HPA, and system troubleshooting activities;
- communicates with a remote accelerator control system computer that is in an EPICS accelerator control environment; and
- logs operational numeric data and the condition of all status monitors and commands to non-volatile memory at approximately 2-second intervals. The data is available either remotely or by removal of and reading the SD memory card.

The FFSP-CCA (Fast Fault Shutdown Processor Circuit Card Assembly) is a CPI EDB-proprietary circuit card. The FFSP-CCA

- acts in 20 to 30 microseconds to shut down the RF SSPA (RF solid state power amplifier) IOT driver and high voltage power supply in the event of
  - focus magnet under or over current conditions,
  - an under voltage condition in any of the housekeeping low voltage power supplies,
  - an IOT beam over-current condition,
  - an IOT beam voltage out of range condition,
  - an IOT and/or VIL409 over-power condition, and
  - a high VSWR condition at the IOT output;
- disables the RF drive input to the IOT for approximately 1.5 seconds when an arc is detected in the output waveguide assembly; and
- captures the RF peak power levels and peak beam current values.

The HVPS (High Voltage Power Supply) assembly consists of a switching-topology 50 KV (maximum) power supply that is capable of driving the HVPS-load at greater than 12 kW (average power). The HVPS-load is made up of the IOT, the 5 microfarad smoothing capacitor, and a 100-ohm series current limit resistor whose functions are described below. The HVPS has an inhibit function that will stop the switchers in the power supply in less than 25 microseconds. There is no output from the HVPS during the time when it is inhibited.

The current limit resistor is a high voltage resistor rated for pulse operation at up to 70 KV. In the event of an arc internal to the IOT, essentially all of the energy storage capacitor voltage will be across the resistor. With the HVPS inhibited, the capacitor will discharge through the resistor and the internal arc-event within the IOT. No more than 10 Joules is dissipated within the IOT and the balance of the energy that was stored in the energy storage capacitor is dissipated within the current limit resistor. The standard IOT protection test that uses a 6- inch length of #32 AWG soft copper wire is accomplished with ease. Therefore, the VIL409 RF HPA system does not require the use of a generally unreliable crowbar circuit.

A 1.5 kW RF SSPA (RF solid state power amplifier) is used to drive the RF input cavity of the IOT. The RF SSPA accepts inputs up to 1 mW and it provides an output of up to 1.5 kW, i.e., a 61.76 dB minimum gain.

The floating deck enclosure of the RF HPA contains

- an embedded controller expansion chassis that is connected via fiber optic cable to the main chassis (at ground/Earth potential),
- a heater power supply that is controlled and monitored by the embedded controller,
- an ion pump power supply that is controlled and monitored by the embedded controller,
- housekeeping low voltage DC power supplies that are controlled and monitored by the embedded controller, and
- a grid modulator circuit card assembly (described in more detail below) that provides the bias voltage for the IOT's grid.

The floating deck is housed in a Faraday enclosure that assures that all of the components inside that enclosure are protected from high gradients that would otherwise exist. The enclosure is isolated from ground/Earth to greater than 60 kV. An isolation/step down transformer provides 115 Vac to the housekeeping power supplies within the floating deck enclosure.

The user may elect to pulse the grid to conserve electrical power that is delivered to the RF HPA. The grid voltage during each RF pulse event is very well regulated. In the inter-pulse period, the voltage of the grid is set to the cut-off level to stop the flow of significant quiescent beam current that would otherwise exist in the IOT. Since there is minimal quiescent beam current during the inter-pulse period the electrical utility usage will be less than it would otherwise be if the intra- pulse grid bias voltage was continuously maintained.

SUMMARY

At 1.3 GHz, CPI EDB's VIL409 RF HPA (RF High Power Amplifier) provides at least 90 kW of output at a minimum gain of 79.54 dB. Control of the RF HPA is user friendly. Grid pulsing assures the lowest electrical power utility cost. The VIL409 interfaces seamlessly into the EPICS control environment while also providing for operation of the RF HPA via a locally connected laptop computer.

For additional details, see the paper at this conference by Alan Wheelhouse, et. al. of the Daresbury Laboratory.