MODULAR MULTIPLE-FREQUENCY RF AMPLIFIER

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Abstract

RF amplifiers for accelerators are expensive. To reduce their cost, Diversified Technologies, Inc. (DTI) is developing a modular amplifier design under a DOE SBIR grant. This amplifier can produce outputs at different frequencies by changing the output tube and drive amplifier, while retaining common components, including the communication, controls, and power supplies.

DTI is designing and building the initial version of this amplifier for a proposed energy-recovery linac at Argonne National Laboratory. The amplifier will deliver 20 kW CW at 704 MHz with an amplitude variation less than 0.01%. This paper discusses the specifications and design of the amplifier.

OVERVIEW

Commercially-available RF power amplifiers are generally designed for broadcast service or wideband laboratory application. Broadcast amplifiers do not have the amplitude and phase accuracy required for present accelerators; laboratory amplifiers are costly and inefficient. In neither case are the controls designed for accelerator application. Because of this RF amplifiers for accelerators are typically custom-designed, and so the construction and support of these amplifiers is costly.

Under a DOE SBIR grant, DTI is developing a cost-effective modular RF power amplifier to meet the requirements for accelerators and other high-power applications. This amplifier will consist of solid-state power conditioning, control circuitry, and RF drive, along with a high-power RF tube.

Substantial cost savings are provided by the standardized control and monitoring systems. All of the amplifiers will have the same control interface, network interface and software drivers. The control system will interface using Ethernet and will be designed for the EPICS environment. The use of standard components and software will allow simple adaptation to other network and software environments as required.

A similar standardization and cost savings is possible in the low-level RF (LLRF) control system. Specialized phase, amplitude, and resonance controls are a key, expensive difference between off-the-shelf communications transmitters and accelerator RF stations. The core of the LLRF system will be the same for all systems, allowing reuse of the field-programmable gate arrays (FPGAs) and digital signal processing (DSP) control algorithms. While the up and down conversion stages may be frequency-dependent, most of the overall design can remain unchanged.

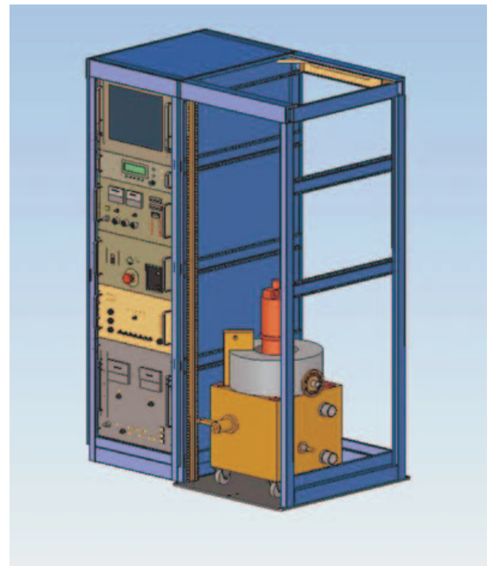

Figure 1: Modular multiple-frequency RF amplifier. The left rack holds the instrumentation common to a wide class of RF tubes. The right rack contains a 704-MHz IOT and cavity.

Power efficiency is important for large accelerators. Modern switching power supplies can operate vacuum-tube amplifiers in Class C, with high bandwidth amplitude modulation capability. This gives a significant increase in efficiency. Plate modulation has been employed in older accelerator transmitter systems, but at the cost of greater power consumption. The availability of low loss modulation may be especially important for high gradient, high current superconducting systems where the beam loading power can demand wide dynamic range from the RF amplifier.

Frequency Capability

The initial amplifier will be designed for CW operation at 704 MHz. The amplifier, however, will be capable at operation at frequencies ranging from 10 MHz to 1.3 GHz and more by changing the RF tube, the drive amplifier, and the mixers and feedback on the digital control board.

A tetrode will be used for operation at frequencies below 400 MHz. From 10-30 MHz the resonator for the will be made of discrete inductors and capacitors. From 30-60 MHz the amplifier will use a strap resonator, and between 60 to 400 MHz the resonator will be a coaxial cavity.

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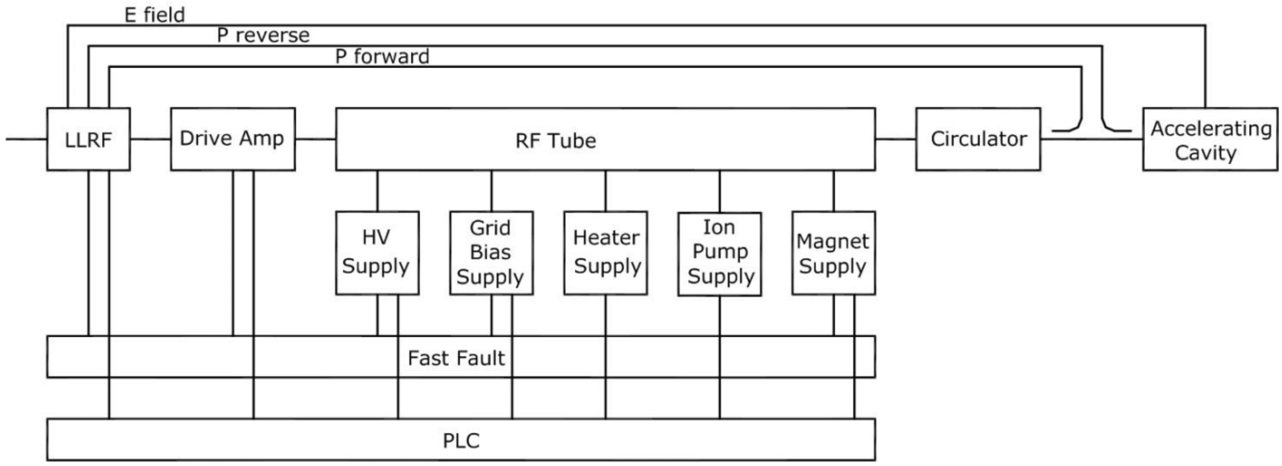

Figure 2: Simplified system-level diagram of the modular multiple-frequency RF amplifier.

For frequencies between 400 MHz to 1.5 GHz the amplifier will use an IOT; above 1.5 GHz a klystron will be used.

To further extend the amplifier's performance to pulsed operation, an energy-storage capacitor and a high-voltage switch can be added.

Initial Specifications

Argonne National Laboratory is considering an energy-recovery-linac upgrade[1] to increase the brightness of the Advanced Photon Source by two-to-three orders of magnitude This potential upgrade will require RF amplifiers with tight control of the amplitude and phase. Argonne has specified these to be 0.01% and 0.05° RMS, a substantial increase in the state-of-the-art. For comparison, the most recent superconducting accelerator built, the Spallation Neutron Source, requires amplitude and phase variations of 1% and 1°. The major specifications for the amplifier are listed in Table 1.

For the RF frequency Argonne chose 704 MHz. This is a tradeoff between the increased accelerating gradient at a high frequency, and the reduced beam scrape-off of a large cavity at a low frequency. In addition, 704 MHz is twice the present 352-MHz frequency, and so allows the upgrade to use the existing ring. Furthermore, this frequency is within the TV broadcast range (470-806 MHz), and the UHF tubes in the range are well developed.

Table 1: Specifications for the initial implementation of the RF amplifier. Note that this amplifier can operate at different frequencies by changing the RF hardware.

Frequency	704 MHz
Power	20 kW CW
Phase variation	0.05° RMS
Amplitude variation	0.01% RMS
Communication	EPICS

Argonne further specified an amplifier power of 20 kW. This is larger than the 5-kW power needed when the accelerating cavity is matched. The greater power allows for mismatch of the accelerating cavity while still producing the required accelerating fields. Note that the resonant frequency of the accelerating cavity needs to be precisely controlled, since the bandwidth is only a few hertz out of 704 MHz.

An additional specification for this amplifier is that it needs to communicate with the EPICS system control.

SYSTEM ELEMENTS

The system elements are shown in Figure 2. The principal element is the RF tube. The system also includes the RF drive and feedback, DC power supplies, fast fault control, and PLC. We discuss these below.

RF Tube

The RF tube at 704 MHz could either be an inductive output tube (IOT) or a klystron. We chose to use an IOT because its phase is less sensitive to power-supply ripple than a klystron – and delivering an output with low phase variation is crucial. Furthermore, IOTs are less expensive and more efficient than klystrons. The tradeoff is that IOTs require a higher-power drive amplifier The 200-W drive required, however, is not difficult.

We chose the rated peak-vision power to be 75 kW, substantially larger than the 20 kW required, and so the tube will have a long life. The amplifier can operate with an IOT from any of the major manufacturers; the initial design will use the CPI K275W tube.

Drive Amplifier

The output of the drive amplifier is determined by the gain of the IOT, which about 150 at 704 MHz. For an output power of 20 kW, then, the drive amplifier needs to supply at least 130 W. A larger drive power, however, gives greater IOT efficiency, so we have specified the drive amplifier to deliver 200 W. This power needs to be

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linear (with a gain compression of less than 1 dB) to ensure stability.

The input power to the drive amplifier is 1 mW, which comes from the low-level RF control board.

For the drive amplifier we chose a Pineapple Technology PA1K, which is capable of delivering 900 W. This power capability gives a very long life.

Digital Low-Level RF Control

The feedback needed to achieve the very-small RF phase and amplitude variation comes from a low-level RF control board. A digital control board is desirable for the accuracy required and ease of modification. We plan to use the board[2] developed by L. Doolittle of Lawrence Berkeley Laboratory. This board, an evaluation board for the ILC, has evolved from the control for the Spallation Neutron Source. We will program the feedback in this board as needed for the loads applied. Note that this board has the capability to control a fast cavity tuner, which will probably be required for the superconducting accelerator cavity.

Table 2: Power supply specifications

Supply	V (V)	I (A)	Ripple
High voltage	25 kV	1.6	2.5 V
Heater	10	30	-
Grid bias	200	+0.2/-0.1	7 mV
Ion pump	4 kV	0.001	-
Magnet	8	27	-

Transmission Components

The RF output power will be coupled on 3 1/8” coaxial cable. Directional couplers will measure the forward and reverse power. To protect the tube from a mismatch at the cavity, a circulator and dummy load will be installed; these will be capable of handling the full 20-kW output power.

Power supplies

The IOT needs supplies for high voltage, heater, grid bias, ion pump, and magnet. The specifications for these are listed in Table 2 below. DTI will build all of these except for the magnet supply, which will be purchased.

The ripple needs to be minimized in the high-voltage and grid-bias supplies (and for the supply for the RF-drive amplifier as well) since ripple will modulate the RF output. Ripple in the power supplies ripple is a major limitation to achieving the required tolerances for RF amplitude and phase. Even though the RF control board provides feedback to compensate for the ripple, the best performance will occur when the feedback has a clean signal to start with. This requires a good filter on the supplies.

The filter should also store little energy, so that in event of a fault the high-voltage supply can simply be shut down instead of needing an opening switch or a crowbar. To produce a low-ripple output with low stored energy, the filters for the high voltage supply and the grid bias will use a pi-section design; this gives much greater ripple attenuation than a simple capacitor filter. We calculate that in a tube arc less than 1 J and 0.2 A^2s will be coupled into the tube.

Fault Control and Communication

In event of a fast fault the high voltage should be shut down in about 1 μs. The fault detection is handled by a fast-fault control board. Slow faults, such as the ion pump current, are handled by a programmable logic controller (PLC). Any safety-related faults, such as the cabinet interlock, are hard-wired.

The PLC will monitor the system status, and provide both the local and remote control for the accelerator. The PLC will be compatible with EPICS, used at Argonne and other large accelerators.

STATUS AND PLANS

The overall design of the modular RF amplifier is complete, and the IOT has been ordered. Design of the electronics systems is proceeding, and we expect construction to be completed at the end of 2007. The complete modular RF amplifier will be tested at DTI prior to installation at ANL in the summer of 2008.

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[1] Configuration, Optics, and Performance of a 7-GeV Energy Recovery Linac Upgrade for the Advanced Photon Source, Michael Borland, Glenn Decker, and Alireza Nassiri, Proceedings of this Conference.
[2] L. Doolittle, http://recycle.lbl.gov/llrf4/.