RF Control System for CEBAF*

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ABSTRACT

The design goal of 2.5×10^{-5} rms energy spread for the CEBAF electron beam demands strict control of the phase and amplitude of the 1.5 GHz accelerating field. To achieve such control in the presence of microphonic excitations, a separate system for each of the 338 superconducting cavities is required. The RF control system employs a heterodyne scheme which allows the use of high precision analog circuits operating at 70 MHz. Presently, the 45 MeV CEBAF injector with 18 superconducting cavities is being commissioned, and this effort provides the first full integrated test in the accelerator tunnel, including cryogenics, RF, beam transport, and beam diagnostics. The RF control system design and objectives are discussed and compared to measured performance during this first commissioning phase. Hardware reliability and operational challenges experienced for RF control are presented.

INTRODUCTION

RF control systems for superconducting cavities such as used at CEBAF[1,2] have to be designed for the specific requirements which high Q cavities impose on such a system. The possibility of CW operation allows the use of negative feedback control. Microphonic noise in the form of mechanical vibrations, which modulate the resonance frequency of the cavities, cause phase fluctuations up to 20° and associated amplitude fluctuations of up to 5%. These fluctuations have to be suppressed by the control system by a factor of 100 for phase and 1000 for amplitude.

For cost reasons it would be preferable to power several cavities (*e.g.*, the eight cavities in each cryomodule) from one klystron. Since phase and gradient error signals have to be derived from the sum of the eight cavity probe signals, this system relies on very high precision and stability of the probe calibration. The CEBAF design therefore uses a separate control system for each cavity.

RF CONTROL REQUIREMENTS

The CEBAF accelerator combines high energy, high current, high duty factor, and high beam quality as shown in Table 1. The 200 μA beam current can be distributed in controllable ratios between the three end stations.

Table 1
Accelerator design specification

Energy	0.5 – 4 GeV
Current	200 μA
Duty factor	CW
Emittance (1 GeV)	$\leq 2 \times 10^{-9}$m
Energy spread (1 GeV)	$\sigma_E \approx 2.5 \times 10^{-5}$

The energy spread is mainly determined by the bunch length and amplitude stability and phase stability of the accelerating field. The RF tolerances required to yield an RMS energy spread of 2.5×10^{-5} are listed in Table 2.

Table 2
RF control requirements with vernier

RMS error	uncorrelated	correlated
σ_A	2×10^{-4}	1.1×10^{-5}
σ_f	0.25°	0.13°
σ_s	2.6°	∞

σ_A : relative RMS amplitude error
σ_f : fast RMS phase error
σ_s : slow RMS (along linac) phase error

In the uncorrelated case the phase and amplitude fluctuations are statistically independent from cavity to cavity. In the correlated case the phase and amplitude fluctuations are in synchronism in all cavities. The calculations assume that the linacs are always operated on crest, *i.e.*, the overall phase adjusted to maximum energy gain. This is accomplished by a phase vernier system using the measured beam energy as probe signal. Slow errors are defined as slower than the update rate of the vernier; fast errors are corrected by the RF control system using the cavity field as probe signal. The requirements for the fast phase error in the uncorrelated case can be relaxed to 0.75° if the slow phase error is reduced to 0.64°.

RF SYSTEM

The major components of the CEBAF RF control system are shown in Figure 1, and include the high power amplifier (HPA), the power transmission system, the cryostat with the superconducting cavity, and the low level RF control module. Computers control the RF control modules through CAMAC. A phase stable frequency distribution system provides the control modules with the required frequencies.

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High Power Amplifier

The high power amplifier (HPA) houses 8 klystrons, a common 11.6 kV cathode power supply, and separate power supplies for the filaments and the modulating anodes[3]. Each klystron (a modified version of the VKL-7811 from VARIAN) provides up to 5 kW of CW RF power with a gain of 37 dB and is driven by a 2.5 W preamplifier with 53 dB gain.

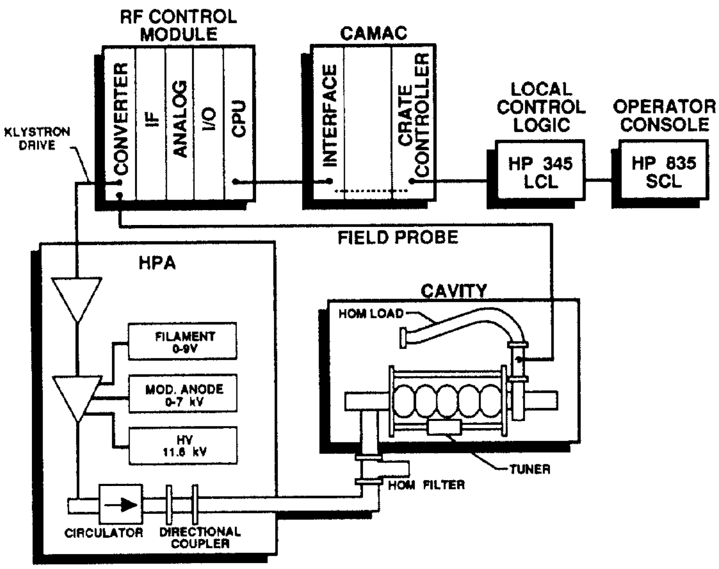

Figure 1. RF control system configuration (one channel)

Transmission System

The power transmission system consists of a WR-650 waveguide with a circulator and 40 dB directional couplers on the klystron side, and a higher order mode filter on the cavity side. The distance between klystron and cavity is about 50 ft.

Cavities

The five-cell accelerating cavities have been developed at Cornell University and are built by Interatom. Ten of the 18 superconducting cavities for the 45 MeV injector are installed and accelerate the beam to an energy of 28 MeV compared to the 25 MeV design value. This is achieved when operating the cavities at 90% of the maximum accelerating field. The main characteristics of the CEBAF superconducting cavities are shown in Table 3. For RF control, it is required that the resonance frequency be well within one bandwidth of the operating frequency. An external Q of 6.6×10^6 corresponds to a bandwidth of only 125 Hz. Mechanical vibrations with amplitudes less than 1 μm cause frequency excursions of one bandwidth of the cavity. Sources for mechanical vibrations are roughing and turbo pumps, fans, the cooling water system, and the He-transfer line. Typical frequency excursions due to vibrations are 10 Hz to 40 Hz. The noise spectrum shows discrete lines at mechanical resonance frequencies of the cavity and at frequencies of excitation. Most of the microphonic noise is concentrated in the frequency range from 0 – 300 Hz.

Table 3
Characteristics of the superconducting cavities

f_0	1497.000000 MHz
E_{acc}	> 5 MV/m
Q_0	$> 2.4 \times 10^9$ at 5 MV/m
Q_{ext}	$6.6 \times 10^6 \pm$ 20%
Δf (change in length)	0.5 Hz/nm
Δf (press. sens.)	80 Hz/mbar
Δf (pond. force)	-3 Hz/(MV/m)^2

The cavities are also sensitive to He-pressure variation. Pressure stability will be ± 100 μBar at 31 mBar (2K). Radiation pressure (ponderomotive force) will decrease the resonance frequency by 75 Hz at a field gradient of 5 MV/m. This corresponds to a change in the detuning angle of 30° and has to be considered when tuning the cavity to the operating frequency.

RF Control Module

The RF control module regulates gradient and phase to the required stability. The gradient and phase setpoints are controlled through computers. Other functions of the RF control module are:

- HPA control such as filament, modulating anode voltage and monitoring of forward and reflected power, and cathode and body current.
- cryomodule interlocks such as waveguide arc and IR detector, field related interlocks (*e.g.*, quench) and cavity and waveguide vacuum.

CAMAC Crate

The interface between hardware and control computers is a CAMAC crate. The RF control modules are connected to the CAMAC bus via interface cards, one per control module. The crate also contains stepper motor drivers for the frequency tuners, an LVDT card which measures the tuner positions, digital and analog I/O cards for HPA and system sensor control, and cards for the beam loss monitor (BLM) and the fast shut down (FSD) system. The crate controller provides the interface to the control computers.

Computers

In the Machine Control Center (MCC) five HP 835 computers run TACL[4,5] logic which provides the user interface in the form of control displays with interactive control through trackball, knobs, and keyboard. A network connects these computers with the ten HP 345 computers in each linac. Each local computer runs the TACL logic for 16 RF control modules. The RF control software is a combination of embedded code[6,7] on the CPU board and TACL logic. The local computers control all I/O to the hardware through CAMAC.

Master Oscillator and Frequency Distribution

The master oscillator (M.O.) generates several frequencies which are phase locked and therefore coherent to a low noise 10 MHz reference (FTS 1050A). The output frequencies are

- 1497 MHz for the fiber optic reference
- 499 MHz for distribution to service buildings
- 70 MHz for distribution to service buildings

In the service buildings for the injector and the linacs, the LO signal of 1427 MHz is generated by multiplying the 499 MHz by 3 and subtracting the IF frequency of 70 MHz.

In the linacs, the LO power is distributed to the 20 RF stations, each with 8 control modules each. The 1427 MHz signal is first amplified to 200 W and then distributed through a temperature stabilized $1\frac{5}{8}$" coaxial cable with a variable directional coupler at each RF station[8]. The 70 MHz IF signal is distributed through $\frac{1}{2}$" coaxial cable in thermal contact with the $1\frac{5}{8}$" line.

DESIGN CONSIDERATIONS

Phase and amplitude fluctuations in the cavities are caused by vibrations which modulate the resonance frequency of the cavity. Therefore control of the resonance frequency is desirable. It also minimizes the RF power requirements. A system which uses a variable reactance (VCX) strongly coupled to the cavity can be used as a frequency controller[9]. Unfortunately, the high reactive power combined with finite losses in this system limits the tuning range, especially at the high operating frequency of 1497 MHz. A mechanical tuner (magnetostrictive or piezoelectric) cannot suppress fast fluctuations since mechanical resonances of the cavity (there are several resonances between 50 and 300 Hz for the CEBAF design) cause instabilities in the system.

Off resonance systems modulate the cavity drive frequency to correct the amplitude and phase fluctuations. One possible choice is the use of vector feedback[10] which requires a highly stable RF reference. Other designs operate the cavities in a self excited loop[11] or at a fixed frequency drive use phase and amplitude controllers in the drive line. The latter solution has been chosen for CEBAF.

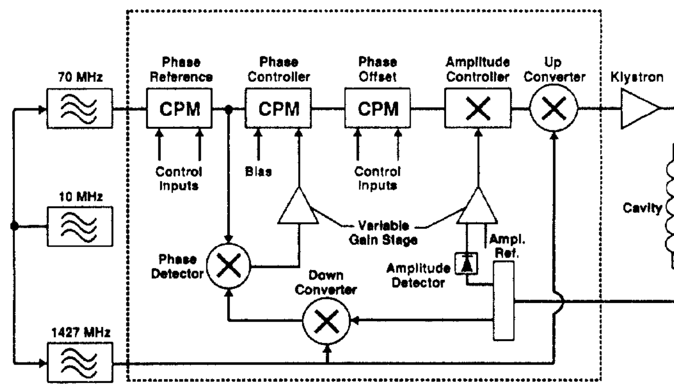

Figure 2. RF control Diagram

A simplified schematic of the CEBAF RF control system is shown in Figure 2. A heterodyne scheme is used to convert the cavity frequency of 1497 MHz to an IF frequency of 70 MHz. The amplified error signals drive controllers for amplitude and phase operating at 70 MHz. An up converter translates the resulting IF signal back to the operating frequency of 1497 MHz.

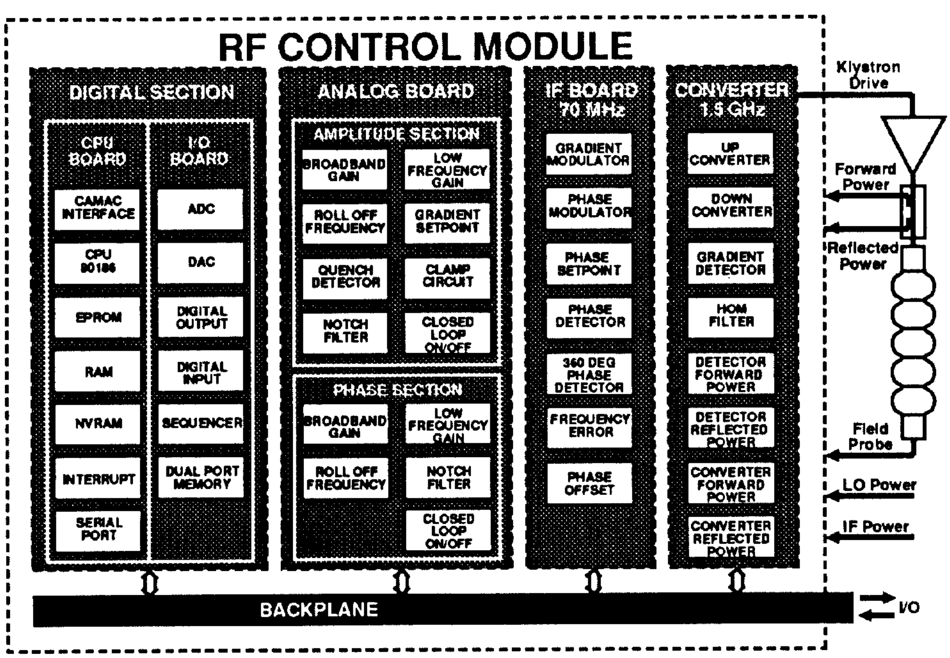

Figure 3. Modular design of the RF control module

RF MODULE HARDWARE

The CEBAF RF control module is divided into five sections separated by functionality as shown in Figure 3:

- RF converter board which transforms the 1497 MHz cavity probe signal to an intermediate frequency (IF) of 70 MHz
- IF board with phase detector and controllers for phase and amplitude
- analog board containing adjustable gain stages for amplitude and phase control
- I/O board with all required analog and digital I/O functions
- CPU board which provides the local intelligence and communicates with the I/O board and the control computers.

A common backplane serves as the interface between the five boards and external signals.

RF Converter Board

The RF converter consists of three down-converting channels for the cavity field probe signal: the forward power, and reflected power, and one up-converting channel for the drive signal of the klystron. The amplitude detector is of the Schottky type, which has no improved performance at low frequencies and is therefore operated at 1497 MHz. This also avoids amplitude errors introduced in the down-converter. The local oscillator signal for the converter is derived from a frequency reference at 1427 MHz which is common for all modules. The most critical component on the converter board is the mixer for the down-converter of the probe signal. It is important to minimize phase changes due to temperature and power level variations in this channel. Measurements have shown that a phase stability $< 1^\circ$ for temperature changes of 50 degree °F and a stability $< 3^\circ$ for 20 dB changes in power level are achieved. By use of calibration tables in the CPU board, these errors are further reduced by one order of magnitude.

IF Board

The choice of 70 MHz as the IF frequency was mainly determined by the availability and low price of components at this frequency. All detectors and controllers on the IF board use analog multipliers (AD 834) for the design. This includes the precision phase detector, the 360° phase detectors for cavity phase, detuning angle and reflected power, and the amplitude modulator. The phase setting is accomplished by a vector modulator[12] which allows for a smooth unambiguous control of the phase of the reference signal. The vector modulator is also used as phase controller by biasing one of the inputs and using the orthogonal input for phase modulation.

Analog Board

The analog board provides the gain stages with the appropriate transfer functions. For stable operation of the loop, the broadband gain (up to 1 MHz) can be set to 60 dB in each of the channels. An additional low frequency boost of up to 30 dB allows for an error reduction by a factor of $> 10^4$ for frequencies up to 100 Hz. The operational amplifiers on this board were chosen for a high gain bandwidth product of 75 MHz and a low noise of 4 $\mathrm{nV}/\sqrt{\mathrm{Hz}}$ and are therefore not the dominating factor for the residual amplitude and phase fluctuations in the cavities. A notch filter at 4.5 MHz is needed to suppress excitation of the $\frac{4}{5}\pi$ passband mode in the cavity.

I/O board

The I/O board provides 32 digital inputs, 32 digital outputs, 20 analog outputs, and 40 multiplexed analog inputs. The data acquisition is supported by a multimode programmable sequencer to reduce microprocessor time. The sequencer can be used to scan a programmable address range or scan one channel in timed intervals. The data is accessible through dual port memory.

CPU board

The CPU board incorporates an 80186 microprocessor, an 8087 coprocessor, an 8259 interrupt controller, an 85210 asynchronous serial port controller, and a memory section. External and module internal calibration coefficients are stored in nonvolatile RAM. Embedded code is used for data acquisition, signal calibration, and interlock functions. Eight interrupt lines are available and allow for response times < 100 μs as required by some interlocks.

RF CONTROL SOFTWARE

The RF control software resides in several computer systems:

- Supervisory computers which run the Supervisory Control Logic (SCL) provide networks to other supervisory and local computers. These computers run the operator displays in the Machine Control Center
- Local Control computers run the Local Control Logic (LCL) in the accelerator service buildings
- CPU's in the RF control modules.

The highest level of software resides in the supervisory computers. Machine wide decisions which involve more than the 8 cavities in each cryomodule are made on this level. Examples are: recalling a setting for the whole machine and automated phasing of cavities for minimum energy spread.

The local control logic has access to all parameters in the RF control system. All "one per cryomodule" functions are controlled through CAMAC cards while all "one per cavity" functions are controlled through the RF control module. The embedded code provides the calibrations of the signals acquired through the control module. Some of the automated functions are handled by the embedded code while others (*e.g.*, tuner control) are implemented in the local computers.

PERFORMANCE RESULTS

The RF control module performance has been extensively tested with 6 RF control modules in the 5 MeV injector test[13]. The injector is now installed in its final location in the accelerator tunnel. With one of the two cryomodules in place (the second will follow during the conference) the beam was accelerated to the design value of 25 MeV using 10 superconducting cavities. The Central Helium Liquefier (CHL) provides stable 2 K operation except that the temporary use of a Kinney pump causes microphonic noise levels to be relatively high. Unregulated phase excursions up to $\pm 20°$ are observed. It is anticipated that the vibrations will be reduced when the cold compressor is operational. The control system has proven reliable when controlling 14 cavities which includes chopper, buncher, and capture section simultaneously. The RMS gradient and phase fluctuations as measured during 5 MeV operation are shown in Table 4.

Table 4
Measured RMS errors

Frequency Range [Hz]	Relative Amplitude Error	Phase Error [°]
$0 - 10^0$	5.5×10^{-6}	1.1×10^{-3}
$0 - 10^1$	1.1×10^{-5}	1.2×10^{-3}
$0 - 10^2$	3.5×10^{-5}	3.0×10^{-3}
$0 - 10^3$	4.1×10^{-5}	4.6×10^{-3}
$0 - 10^4$	5.5×10^{-5}	7.0×10^{-3}
$0 - 10^5$	7.0×10^{-5}	1.6×10^{-2}
$0 - 10^6$	7.5×10^{-5}	

The RF control system meets the noise specification for uncorrelated noise. This is true for noise frequencies above 1 kHz. The low frequency microphonic noise shows some correlation but certainly does not have the same phase for all cavities. This is due to the complex nature of the mechanical excitation of the cavities which have different mechanical eigenfrequencies. Below 1 kHz, the dominating noise source is 60 Hz noise which is correlated and therefore a factor of three to high.

CONCLUSION

The CEBAF RF control system has to regulate RF amplitude and phase fluctuation to a high degree of accuracy. Presently 25 MeV of the 45 MeV injector are installed and operational. It has been shown that 10 superconducting cavities are controlled simultaneously meeting specifications for uncorrelated errors. The dominating correlated noise is introduced through ground loop at 60 Hz. Proper grounding and choice of line phases will reduce it to an acceptable level.

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