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1. Introduction

This document presents the RF requirements for energy upgrades of the Thomas Jefferson National Accelerator Facility’s two superconducting radio−frequency (SRF) electron accelerators:

- the Continuous Electron Beam Accelerator Facility (CEBAF) accelerator, which was designed for an energy of 4 GeV (billion electron volts), operates at nearly 6 GeV, and is planned for upgrading to 12 GeV, and

- the Jefferson Lab IR Demo Free−Electron Laser’s (FEL) 42 MeV (million electron volts) driver accelerator, which is planned for upgrading to 160 MeV.

The requirements have also been formulated with due mindfulness of the possible application of Jefferson Lab SRF accelerator technology in other accelerator efforts as well.

1.1 Background: SRF Accelerators at Jefferson Lab

Readers already familiar with the overall Jefferson Lab technical context might choose to skip this section, which gives general, context−setting thumbnail sketches of the two SRF accelerators to be upgraded.

1.1.1 CEBAF. The CEBAF accelerator and its three experiment halls constitute the world’s leading research facility for electromagnetic nuclear physics, the study of the atom’s nucleus using electron beams as probes. Figure 1−1 is the entire CEBAF accelerator complex as seen from the air, with Figure 1−2 the corresponding accelerator schematic. Figure 1−3 shows the present five−cell SRF accelerating cavity as paired for use in the present cryomodules (Figure 1−4) arrayed in each of the twin linear accelerators (linacs), with four pairs per cryomodule. Typical magnets for transporting the beam appear in Figure 1−5. Figure 1−6 is a photograph of key components within the Central Helium Liquifier (CHL), which supplies liquid helium at 2 K for the superconducting operation of both CEBAF and the FEL driver accelerator.

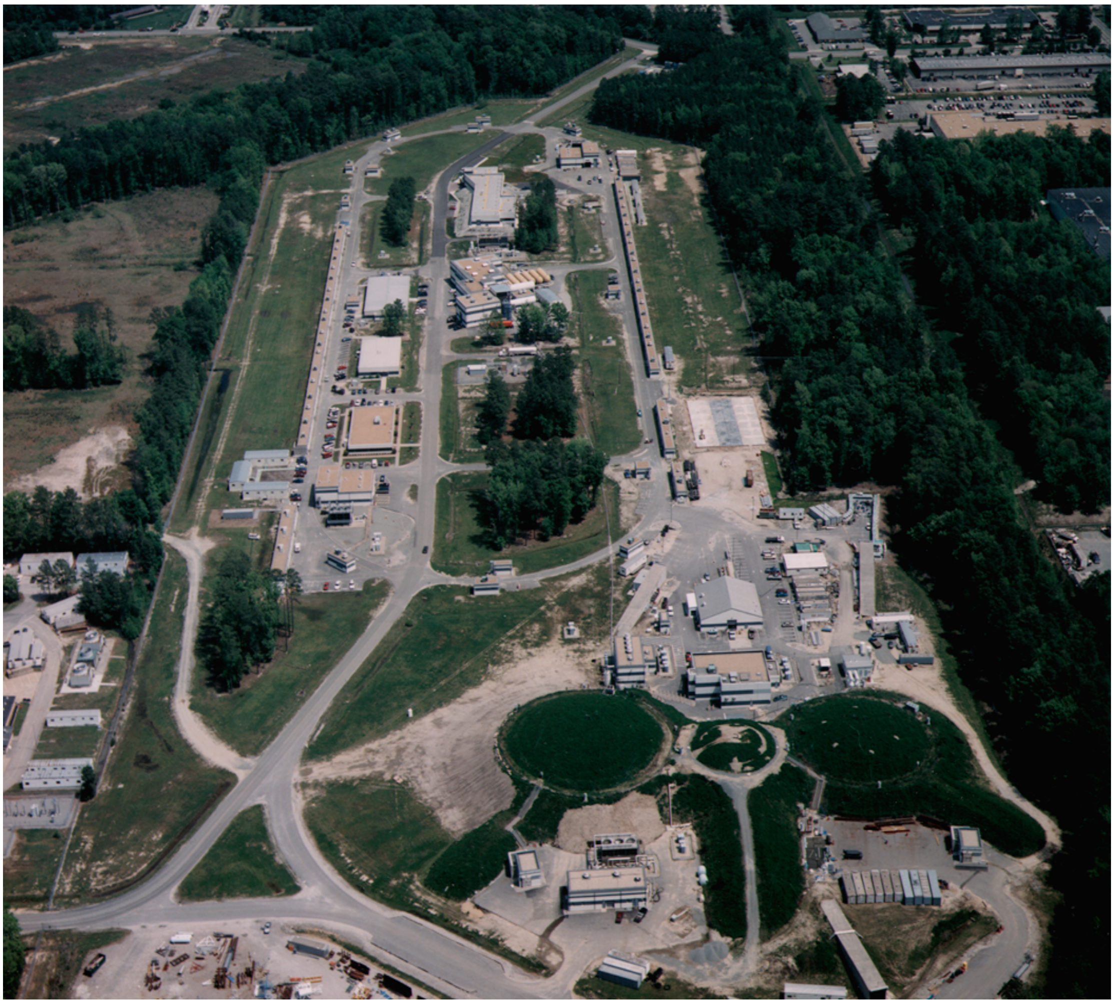

Figure 1−1. Aerial view of the CEBAF accelerator complex. CEBAF's nuclear physics users conduct their experiments in the earthen−topped, domed, semi−underground structures in the foreground —from left to right, Experiment Halls A, B, and C. Above−ground service buildings and a service road trace the underground accelerator's racetrack shape. RF power reaches the accelerating components of each linear accelerator (linac) from within the long service buildings above the linac "straightaways." The service buildings above the recirculation arcs that interconnect the two linacs house DC power supplies for the magnetic transport lines that guide the electron beam from one linac to the other for multiple−pass acceleration.

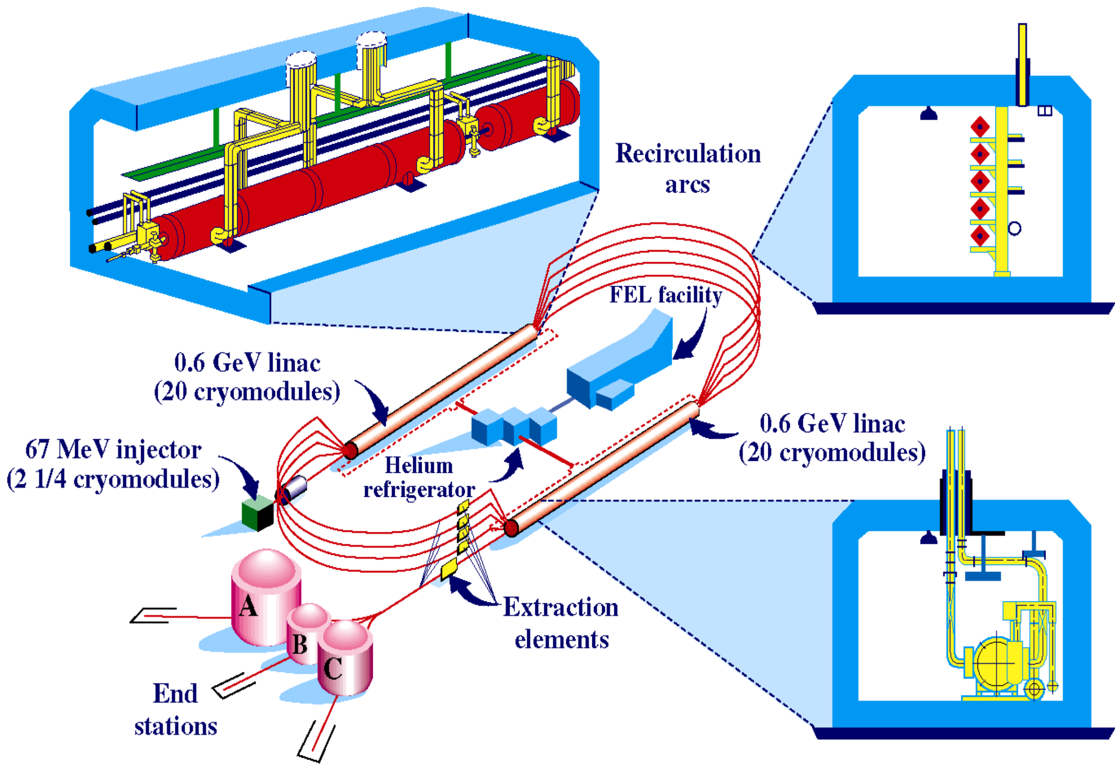

Figure 1−2. The CEBAF SRF recirculating electron accelerator. Inside each cryomodule (detailed views, upper left and lower right) are four pairs of five−cell, 1497 MHz SRF accelerating cavities (see Figure 1−3). Arrays of vertically stacked beam−transport magnets constitute a total of nine beamlines in the recirculation arcs that interconnect the two linacs, allowing up to five full acceleration passes through the machine before beams are directed to the three experiment halls, also called end stations.

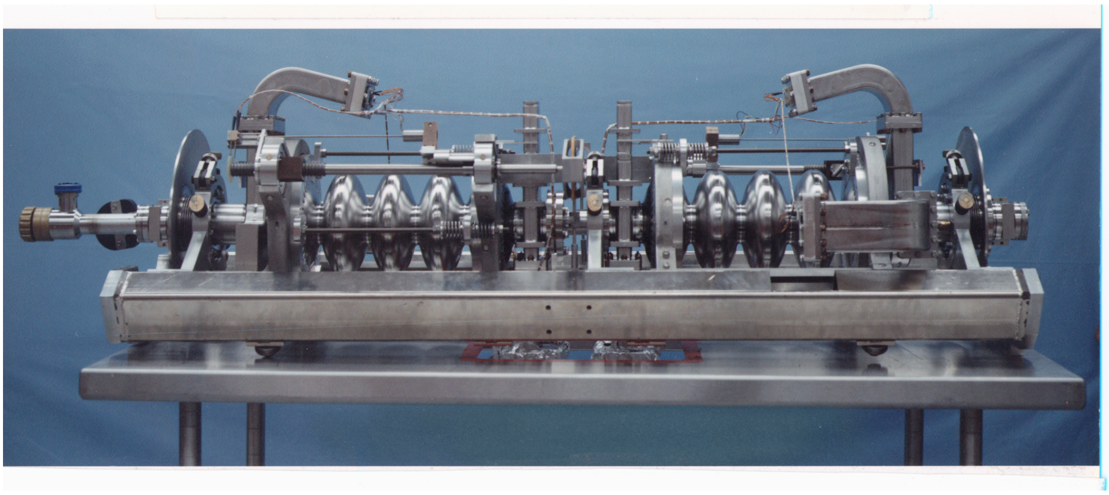

Figure 1−3. A CEBAF SRF accelerating cavity pair. These five−cell, 1497 MHz cavities operate superconductively at 2 K. Each cryomodule (Figure 1−4) contains four hermetically joined pairs like this one. In the standard, pre−upgrade cryomodule configuration, interconnections bridging from one pair to the next take up a substantial portion of the cryomodule length available for accelerating structures.

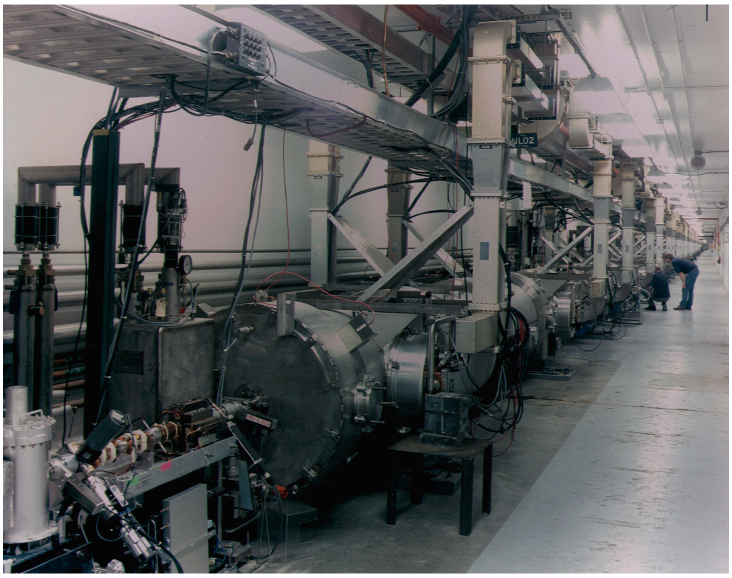

Figure 1−4. Cryomodules in CEBAF's South Linac (the right−hand racetrack "straightaway" in Figures 1−1
and 1−2). RF power waveguides descend to the cryomodules from service buildings at ground level.

Figure 1−5. Beam transport magnets in the recirculation lines of CEBAF's east arc. With the present five−pass
recirculation, CEBAF uses more than 2200 beam transport magnets overall.

Figure 1−6. The 2 K and 4 K cold boxes in CEBAF's 4.8 kW Central Helium Liquifier (CHL), which represents the world's largest 2 K cryogenics capacity.

1.1.2 Free−Electron Laser. The Jefferson Lab Infrared Demonstrator Free−Electron Laser—the IR Demo FEL, Figure 1−7—represents scientifically and technologically beneficial leveraging of CEBAF's SRF electron−accelerating technology. Unlike the monochromatic, coherent light from most conventional lasers, an FEL's light can be tuned through a range of wavelengths, since an FEL extracts its optical energy not from bound electrons but from free electrons in an accelerated electron beam. Thanks to various technical advantages inherent in SRF beam−acceleration technology, the IR Demo FEL operates in the kilowatt range, two orders of magnitude higher than the average power of previous FELs. Its light has multiple uses for both basic and applied research, with numerous prospects for eventual practical application in manufacturing and national defense. The Jefferson Lab FEL User Facility, which appears near the inside top of the racetrack in Figures 1−1 and 1−2, houses the FEL.

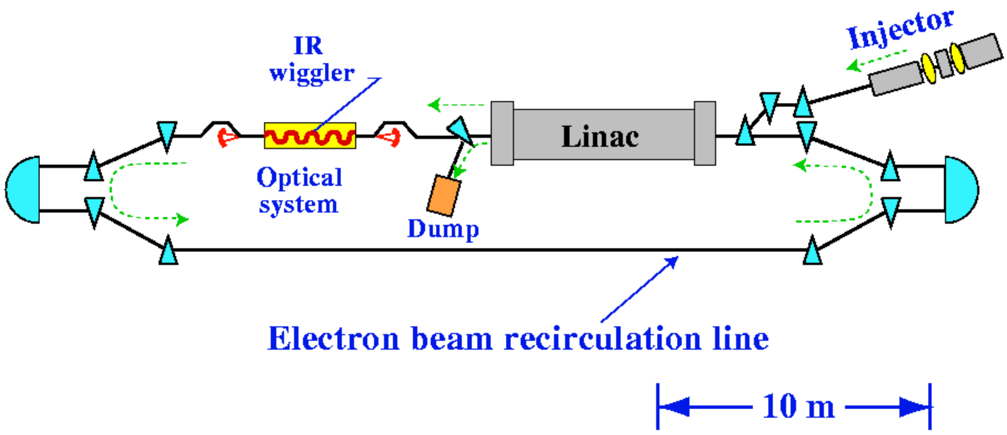

Figure 1−7. In the Jefferson Lab IR Demo FEL, a "wiggler" magnet extracts optical energy from an electron beam produced in an SRF accelerator. Unspent electron beam energy is recaptured in an energy−recovery process involving electron beam recirculation and deceleration.

1.2 Summaries of Accelerator Upgrade Plans

CEBAF's nuclear physics users began experiments in the mid−1990s. The IR Demo FEL's users began experiments in 1999. Both user communities now need upgrades ~~to~~ 12 GeV energy for CEBAF, and, for the FEL, to 10 kW average power based on a 160 MeV electron beam.

1.2.1 CEBAF Upgrade Plans. Figure 1−8 shows the key elements of the 12 GeV CEBAF upgrade. The higher energy will be attained by adding ten new, higher−voltage cryomodules (five per linac, making use of available cryomodule slots) and by replacing six of the old cryomodules (three per linac). The new cryomodules are being developed based on SRF technology improvements achieved over the last decade. To increase the voltage provided by a cryomodule of given length requires increasing the cavity accelerating gradient, or increasing the effective accelerating length within the cryomodule, or increasing both. However, maximizing the accelerating length involves less technical risk and, for CW operation, has the added advantage of lowering the dynamic refrigeration load. So the upgrade cryomodule will contain eight seven−cell cavities (Figure 1−9), as opposed to the four distinct pairs of five−cell cavities (Figure 1−3) in the existing configuration. Since the cell design itself has not been changed for the upgrade, this means 8 × 70 cm of active length per cryomodule, rather than the previous 8 × 50 cm. To accommodate the increased cavity length within an unchanged cryomodule length, the upgrade cryomodule has been redesigned to exclude the pair−to−pair bridging sections formerly needed. With gradients exceeding 12 MV/m routinely available from

CEBAF SRF cavity technology in the late 1990s, 65 MV has been conservatively specified for the upgrade cryomodule. A cavity quality factor Q of 6.5×10^9 at an accelerating gradient of 12.5 MV/m has been specified for the seven−cell cavities, and has been met in tests of a seven−cell prototype.

Besides the RF system addressed in the present document, changes must also be made to other accelerator subsystems to accommodate the higher energy. A tenth arc beamline will be added so that a beam can be accelerated in a sixth pass through the north linac, for a total of 5.5 passes through the entire machine, yielding 12 GeV and allowing generation of a photon beam to a fourth experiment hall to be constructed, Hall D. Changes in DC power supplies and spreader/recombiner magnets represent the upgrade's other main effects in the recirculation arcs. The upgrade also necessitates an increase in refrigeration capacity from 4.8 kW to 8.5 kW.

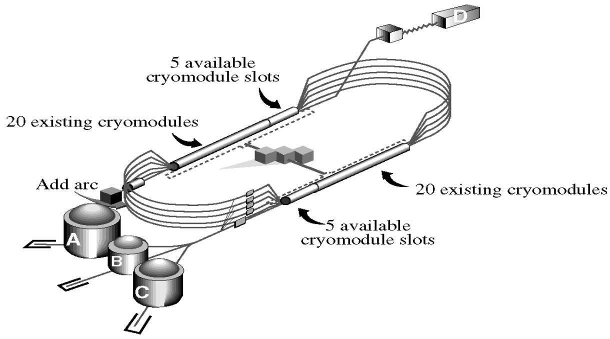

Figure 1−8. Cryomodule slots available for upgrading the existing CEBAF accelerator to 12 GeV. With
an added recirculation arc, electrons will make five and a half passes through the
upgraded machine with its added Experiment Hall D.

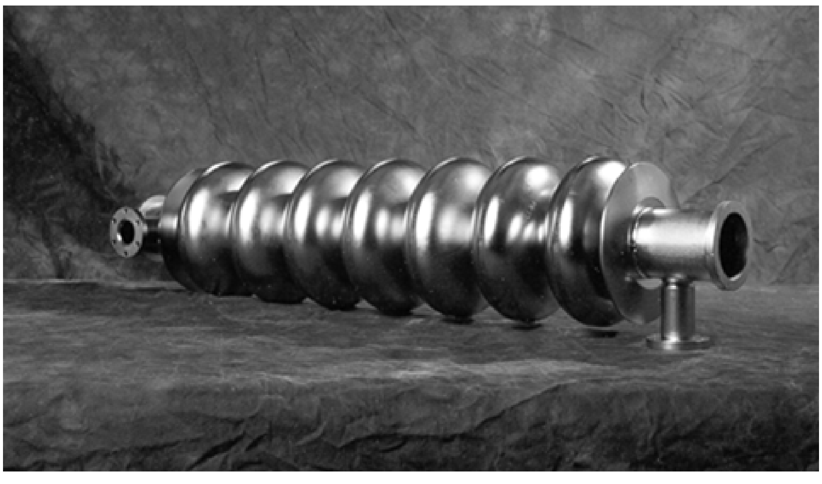

Figure 1−9. Prototype seven−cell, 1497 MHz CEBAF SRF accelerating cavity for use in accelerator upgrades. (Compare to the five−cell cavities shown in Figure 1−3.)

1.2.2 FEL Upgrade Plans. Figure 1−10 shows the upgraded FEL with its three−cryomodule, 160 MeV SRF driver accelerator. Plans are for the upgraded FEL to reach 10 kW in the infrared, with a 1 kW ultraviolet capability to be added. The upgraded FEL's RF system will have to accommodate high beam loading in the injector, energy recovery in the linac, and the need for tight control of microphonic noise.

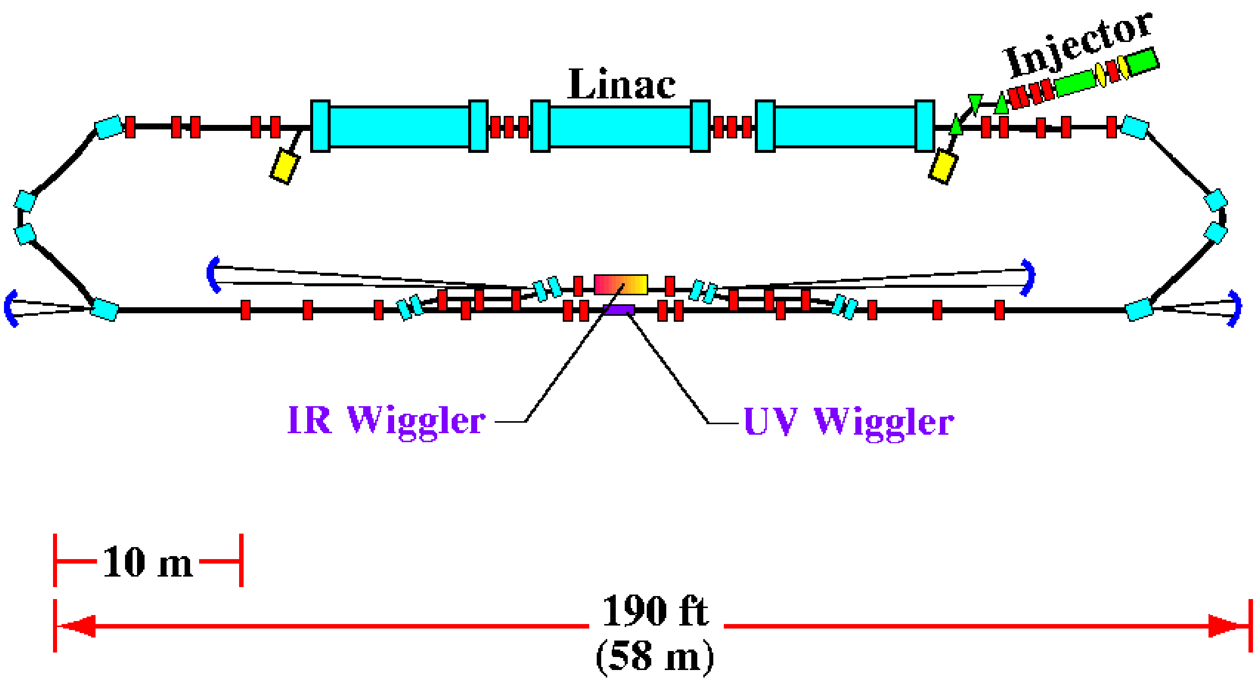

Figure 1−10. Upgrade of the Jefferson Lab FEL. Seven−cell SRF cavities will be used in the driver linac's middle cryomodule.

1.3 Existing RF Systems

Because the present cryomodules containing pairs of five−cell cavities will continue as important components of both upgraded accelerators, the existing RF systems remain an important consideration in establishing the RF requirements for both accelerator upgrades. The later chapters of this document report the requirements for RF power distribution, control, and monitoring for both the five−cell and seven−cell cavities.

The present section sketches the existing CEBAF RF system. For introductory purposes, this sketch applies also to the FEL driver accelerator, even though certain key aspects of FEL operation differ from CEBAF operation, as reflected in later chapters. Figures 1−11, 1−12, and 1−13 are, respectively, photographs of the existing CEBAF RF control module, RF control rack, and klystrons.

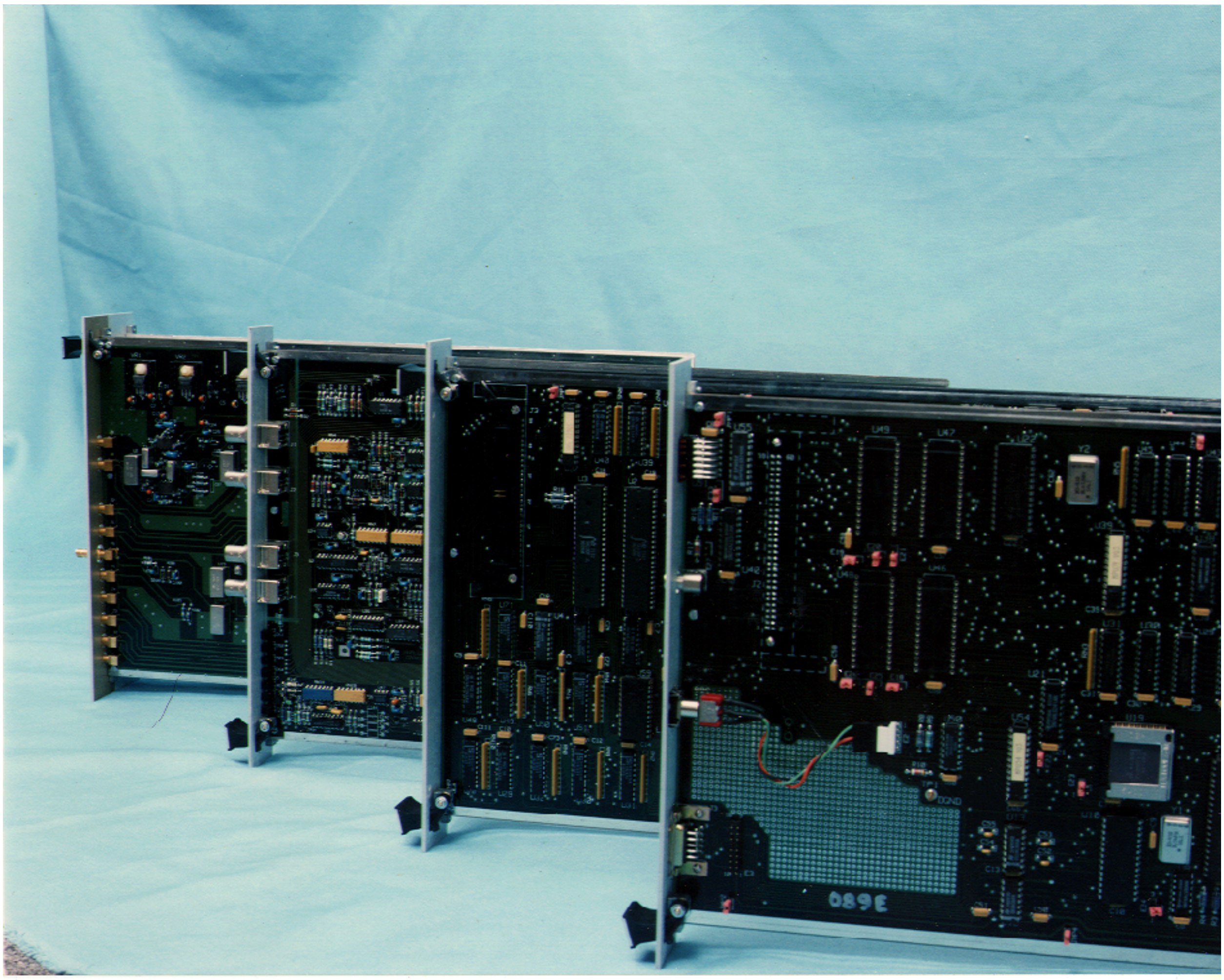

Figure 1−11. A CEBAF RF control module.

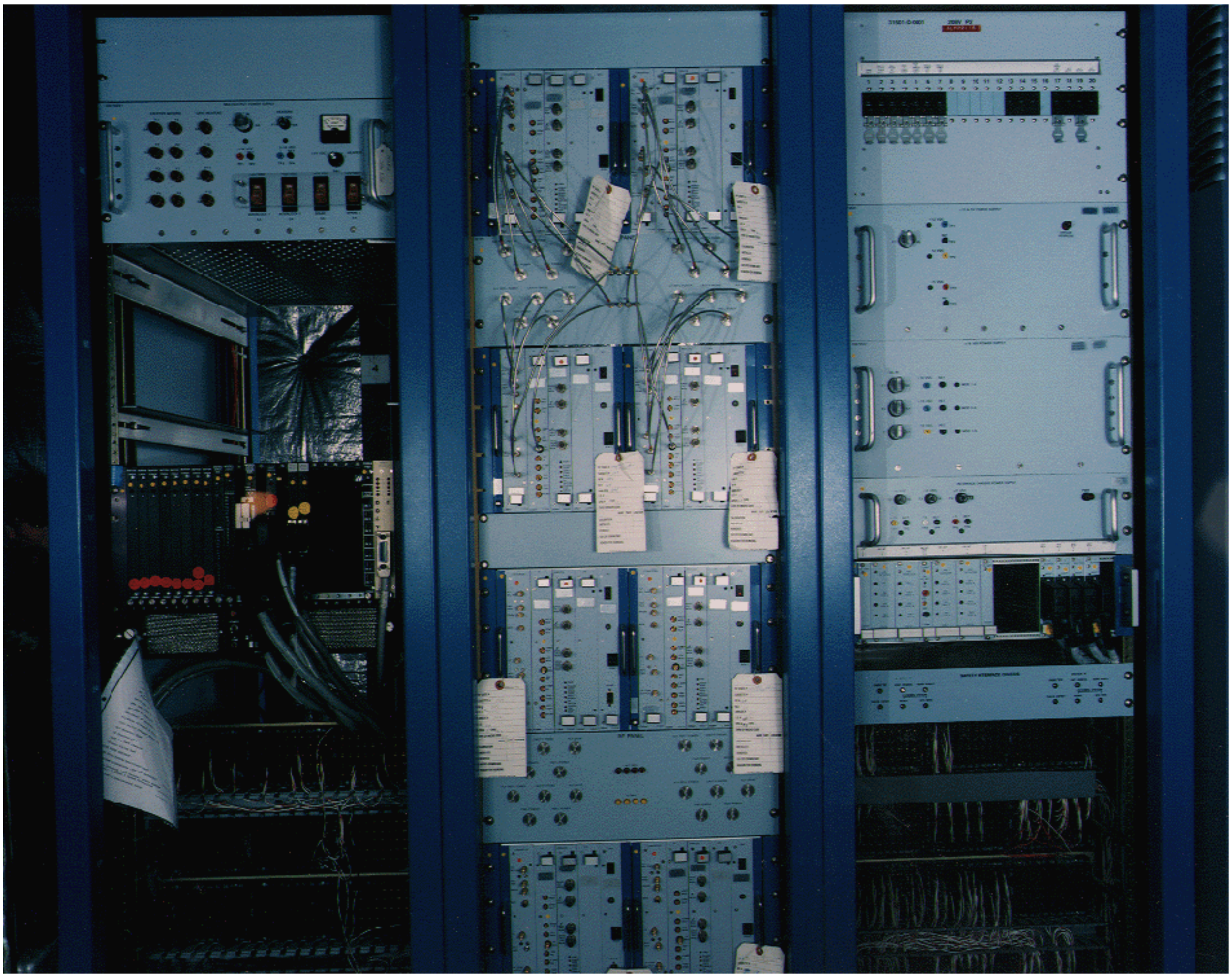

Figure 1−12. A CEBAF RF control rack.

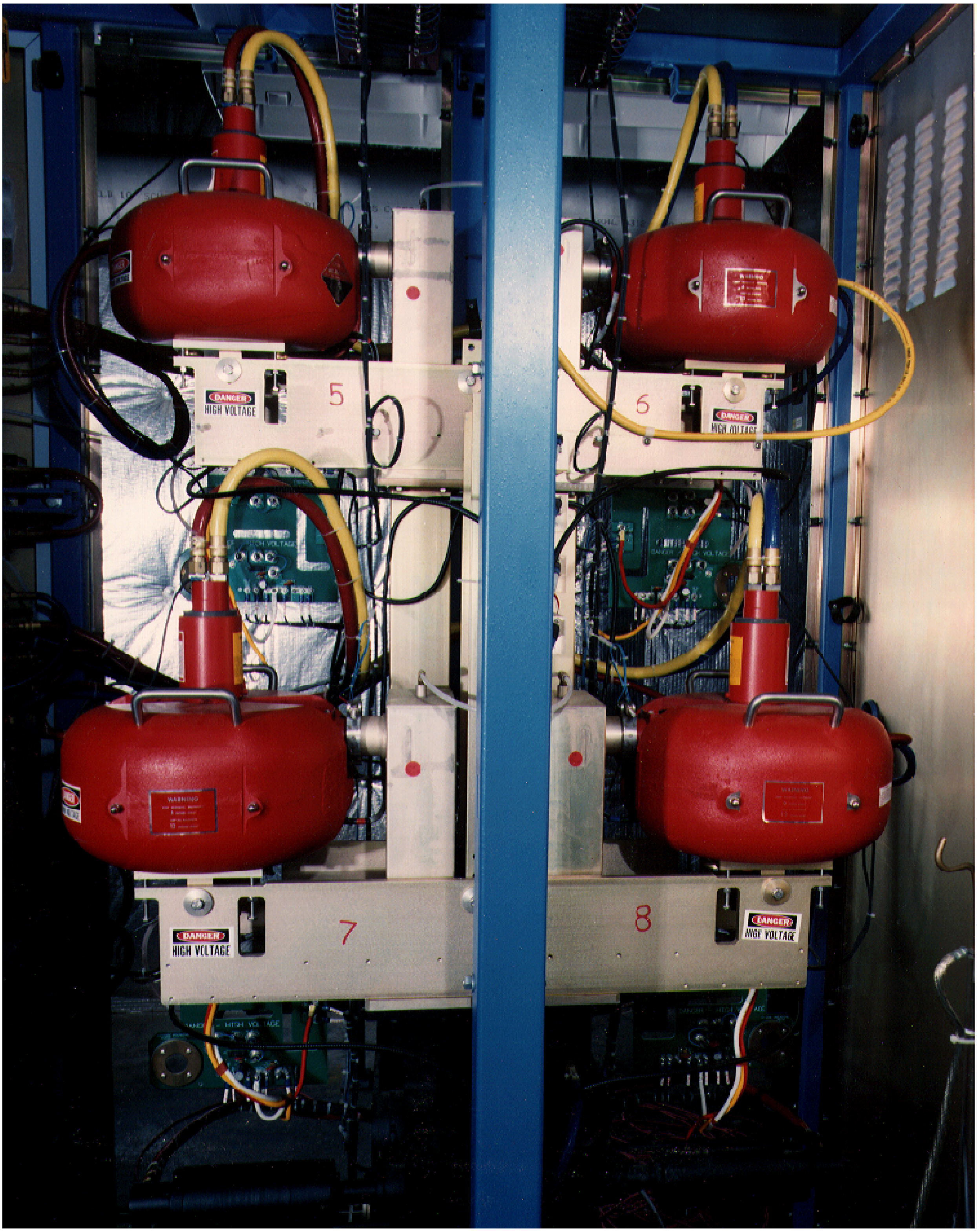

Figure 1−13. Four klystrons of the kind found in the existing CEBAF accelerator.

The primary function of the RF system in either accelerator is to develop the RF required for acceleration of the beam. The high−power elements provide the raw RF power, while the low−level systems monitor and adjust the amplitude and phase of the RF delivered to each cryomodule. The RF control module also monitors numerous signals to ensure proper operation and terminate RF to prevent damage to personnel or systems in the event of abnormal conditions.

The present CEBAF RF system consists of an injector (warm−temperature capture, quarter−cryomodule, two full cryomodules) plus two linacs of 20 cryomodules each. A total of 42 eight−cavity cryomodules are powered by 42 identical RF systems. The RF system used for the capture section consists of a modified standard RF zone. Each zone comprises both low−level RF control and high−power RF equipment located in the service buildings above the tunnel.

The key to this regulation is the RF control module. This multi−card block contains a CPU card with I/O, frequency up−converter and down−converter, plus analog and IF control systems. The developed signal is applied to a preamplifier producing up to 2 W at 1497 MHz, the output of which is then fed to a single klystron for amplification to a maximum of 5 kW. Each zone contains one cryomodule with eight cavities. The RF zone is designed to provide the RF required and includes eight klystrons in a single HPA (high−power amplifier), eight control modules, plus ancillary systems. The klystron is followed by a coax−to−WR650−waveguide transition. The waveguide path includes a circulator, directional couplers, and an HOM filter. The circulator protects the klystron from excessive reflected RF power, the directional couplers allow monitoring of the forward and reflected power levels, and an HOM filter attenuates harmonics to and from the cavity. The eight klystrons in a zone are powered by a common cathode power supply (CPS) (11.6 kV). Individual filament and modulating anode power supplies and instrumentation are included with each HPA.

The initial purchase of 350 klystrons was by multiyear contract with Varian (now CPI). Replacement tubes were procured from Litton Electron Devices. The tube was designed for 5 kW CW operation at 1497 MHz. Extended testing has shown these tubes capable of higher power levels when operated with increased voltages and additional cooling. The most recent replacements from Litton have been tested to 8 kW and are certified by Litton for operation at that power level. The only change made was a change in window material. A selected group of the Varian tubes can be operated at 8 kW. Many more can be operated at power greater than 5 kW, though likely not reliably as high as 8 kW.

1.4 Purpose, Scope, and Method

1.4.1 Purpose. The purpose of this report is to document a set of requirements for the RF system for the energy upgrades of CEBAF and the FEL driver accelerator. In addition, Appendix 1 evaluates the present system against this set of requirements.

1.4.2 Scope. The right side of Figure 1−14 shows the existing CEBAF approach to subsystem segmentation. As a practical matter, it has been decided to continue this approach in the upgrades. Thus the phrase *RF system* refers to Low Level RF Control System, the high−power amplifier/cathode power supply (HPA/CPS) system, and their interfaces to accelerator systems. Accordingly, the RF system requirements address the following:

- RF controls
- HPA/CPS controls
- Diagnostic tools

- Integration into existing accelerator systems, including high−level applications
- Backward compatibility (control of the present cavities)

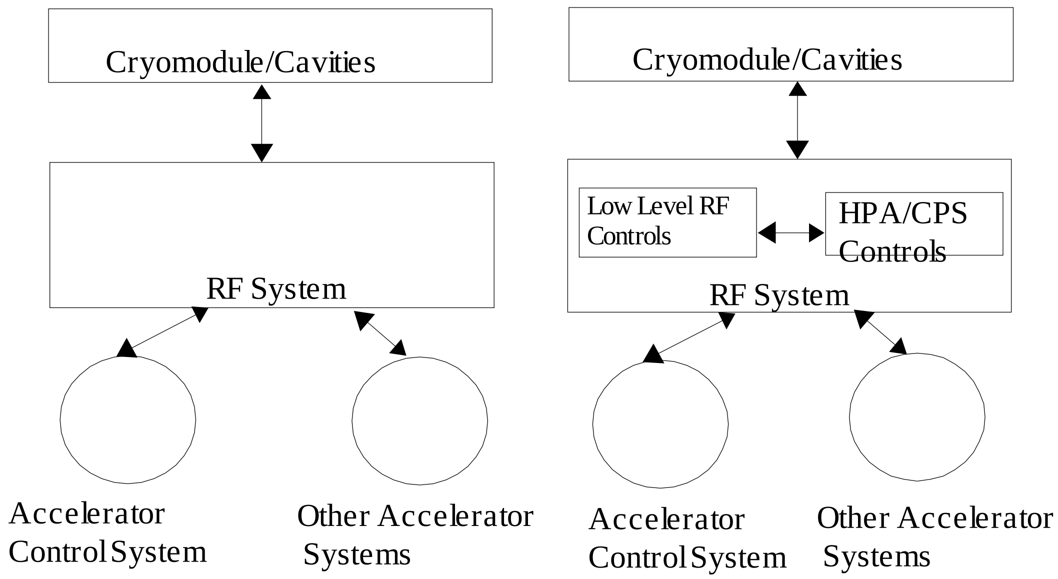

Figure 1−14. Each accelerator requires an RF system, but various approaches can be used to segment it. Jefferson Lab will continue the existing segmentation approach (*right*), as originally chosen for CEBAF.

1.4.3 Method. The requirements were arrived at from the user's standpoint, subject to institutional constraints. The key users are the nuclear physics experimenters who use CEBAF and the light−source users who use the FEL. However, the interests of three additional stakeholder groups have been integrated as well: those who operate the accelerators, those who maintain them, and those who prescribe and administer accelerator−related EH&S (environment, health, and safety) programs. With due mindfulness of the needs of the primary users and the additional stakeholders, the requirements have been formulated to meet the following criteria:

- Specificity, which demands that each requirement statement be unambiguous.
- Measurability, which facilitates design evaluation.
- Reasonable achievability, which precludes inconsistent requirements.
- Traceability, allowing identification of the source or reason for each requirement.

The requirements have also been categorized as to whether they are mandatory or preferred. *Mandatory* means not only essential but necessary for an operable system. *Preferred* means value−adding but not essential. The cost/benefit analysis concerning a preferred requirement is a design question beyond the scope of the present effort. The word *shall* refers to mandatory requirements; the word *will* refers to a statement of fact; the word *should* refers to a preferred requirement.

Audiences defined for this requirements document are:

- System designers
- Accelerator physicists
- Hardware and software engineers

- Cavity developers
- Operations group
- Maintenance group
- Nuclear physics and FEL users
- Safety groups
- Management
-

Appendix III defines key terms, local terminology, and acronyms. References are listed at the end of the document, with copies of selected key references included.

2.0 User Requirements

2.1 Introduction

The Physics Users request the following from Accelerator Operations, which have direct bearing on the RF System.

1. A range of beam energies,
2. A range of beam currents*,
3. Low beam energy spread,
4. Low beam energy jitter,
5. Stable beam position at the target* and
6. High beam availability .

* Beam current and position stabilities have sources which are beyond the scope of this document.

When operating below 5 GeV, the users require that the energy upgraded accelerator reproduce the presently available beam characteristics.

The FEL Users require

1. High beam current,
2. Low beam energy spread,
3. Low beam energy jitter and
4. High beam availability .

2.2 Beam Characteristics (Physics)

2.2.1 The RF System shall satisfy the parameters listed in Table 2.1

Table 2.1

Parameter	***Value***
No. of Passes	1, 2, 3, 4, 5, 5.5
Max. Design Energy	⩾12.1 GeV @ 5.5 Pass
Energy range for 1 Pass beam	0.55 GeV to ⩾2.2 GeV
RMS Energy Spread	See Figure 2.2
Beam Current @ 5.5 Pass (Hall D)	100 pA $\leqslant I_{beam} \leqslant$ 2 mA
Beam Current @ 1, 2, 3, 4 & 5 Passes (Hall B)	100 pA $\leqslant I_{beam} \leqslant$ 1 mA
Max. Beam Current @ 1, 2, 3, 4 & 5 Passes (Halls A, C)(1)	180 mA See Figure 2.1
No. of Beam interruptions due to RF System Faults(2)	⩽ 10 faults/8 hr. shift

(1) For each of the Halls A and C, the beam dump power limit is 800 KW. Maximum current limit to any hall is 180 mA. Each hall can receive a different beam current in the allowed range at a given pass.
(2) This applies to FEL also.

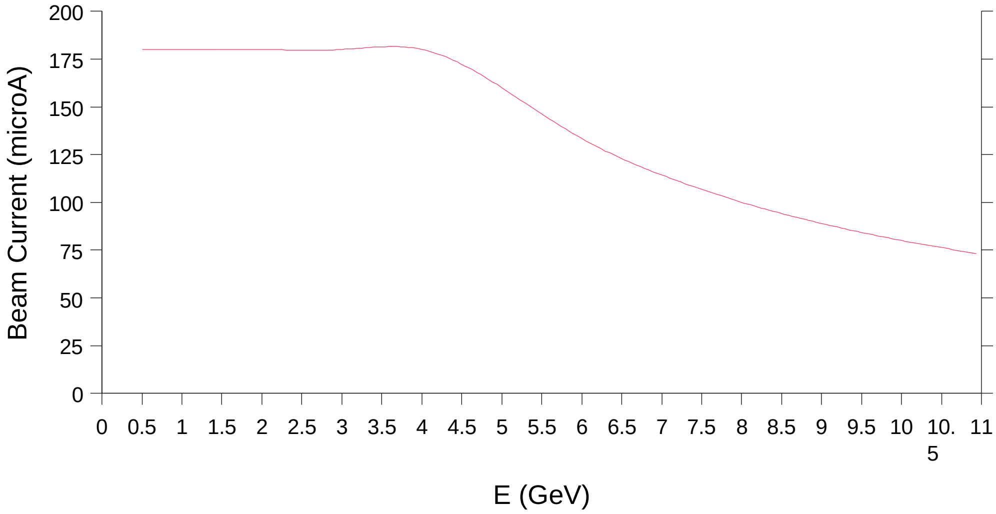

Figure 2.1 Allowed Beam Current as a function of Beam Energy

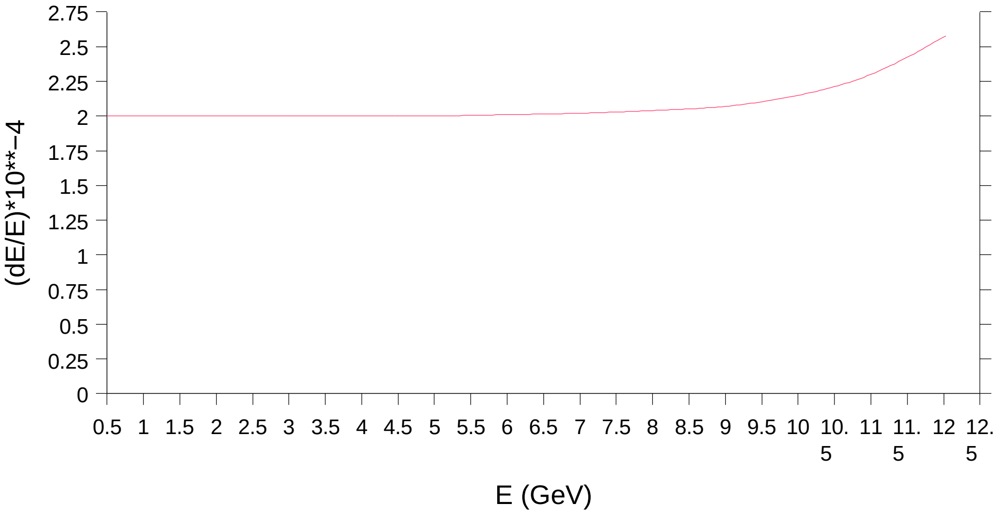

Figure 2.2. RMS Beam Energy Spread as a function of Beam Energy

2.3 Beam Characteristics (FEL)

2.3.1 The RF System shall satisfy the parameters listed in Table 2.2

Table 2.2

Parameter	***Value***
Max. Design Energy	$\geqslant$ 150 MeV
RMS Energy Jitter	$4.4 * 10^{-4}$
Beam Current	$\geqslant$10 mA

2.4 Beam Availability

2.4.1 During scheduled beam delivery, the average beam availability shall exceed 95%.

3.0 Low Level RF Control System Requirements

3.1 Introduction

The Low Level RF Control System has to control both 5−cell and 7−cell superconducting cavities of the CEBAF (max. beam current 1 mA @ 4 GeV) and FEL (max. beam current ⩾ 10 mA) accelerators. Table 3.1 lists the design specifications for both types of cavities. Since it is very likely that the implementation of the upgraded system occurs in stages, the Low Level RF Control System must interface to the existing as well as the upgraded HPA/CPS system. In order to avoid confusion during operations, the user interface for all configurations should be the same.

The Low Level RF Control System has interfaces to the following accelerator systems:

1. The Accelerator Control System (EPICS),
2. The Accelerator's Safety Systems, both equipment and personnel protection,
3. The HPA/CPS system,
4. Systems implementing high level applications (Fast Feedback, Master Oscillator Modulation, etc.)

Figure 3.1 shows the block diagram of the Low Level RF Control System.

The user demand is for the accelerator to provide beam in Continuous Wave (CW). Mode. For reasons of equipment protection, the setup (tuning) of the accelerator is in pulsed beam mode (about 1% duty factor). These two modes present require different transient responses from the RF system.

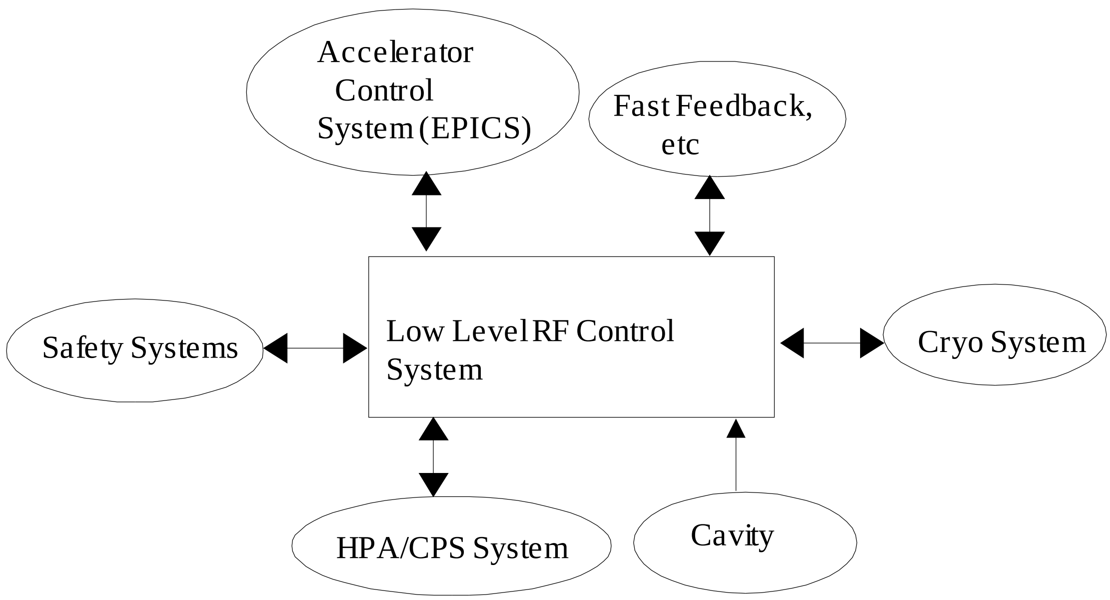

Figure 3.1

Table 3.1: Design Specifications of 5−cell and 7−cell cavities

	CEBAF		FEL Injector	FEL Linac
	5−Cell Cavities	7−Cell Cavities	5−Cell Cavities	7−Cell Cavities
Parameter	Value	Value	Value	Value
Frequency	1497 MHz	1497 MHz	1497 MHz	1497 MHz
Gradient	5 MV/m(1)	12.5 MV/m	5 MV/m	12.5 MV/m
Q_0	$2.4 * 10^9$	$6.5 * 10^9$	$2.4 * 10^9$	$6.5 * 10^9$
Q_{ext}	$6.6 * 10^6$	$2.2 * 10^7$	$6.6 * 10^6$ (2)	$4 * 10^6$
R_S	960 Ohms/m	960 Ohms/m	960 Ohms/m	960 Ohms/m
Lorentz Detuning Coefficient	$2\ Hz/(MV/m)^2$	$2\ Hz/(MV/m)^2$	$2\ Hz/(MV/m)^2$	$2\ Hz/(MV/m)^2$
Detuning limit due to microphonics(3)	50 Hz	25 Hz	25 Hz	25 Hz
Cavity Cross −talk	60 dB	60 dB	60 dB	60 dB
Probe Transmitted Power (4)	20 dBm	20 dBm	20 dBm	20 dBm
Tuning Accuracy	10 Hz	2 Hz	10 Hz	2 Hz
Range of Mechanical Tuner	200 KHz	400 KHz	200 KHz	400 KHz
Resolution of Mechanical Tuner	10 Hz	100 Hz	10 Hz	100 Hz
Range of Piezo Tuner	N/A	2 KHz	NA	2 KHz
Resolution of Piezo Tuner	N/A	2 Hz	NA	2 Hz

(1) *Some 5−cell cavities operate at 10 MV/m.*

(2) *Average value of FEL 5−cell cavities is* $4.0*10^6$

(3) *At klystron power of 5 KW.*

(4) *At 12.5 MV/m*

3.2 Performance Requirements

<u>Field Control</u>

3.2.1 The Low Level RF Control System shall satisfy the parameters of Tables 3.2a and 3.2b.

Table 3.2a

	CEBAF		FEL Injector	FEL Linac
	5−Cell Cavities	7−Cell Cavities	5−Cell Cavities	7−Cell Cavities
Parameter	Value	Value	Value	Value
Gradient Control Range (step size?)	0.5 − 12 MV/m	0.5 − 25 MV/m	0.5 − 12 MV/m	0.5 − 25 MV/m
Gradient Stability (CW)	See Table 3.2b	See Table 3.2b	$4.4 * 10^{-4}$	$2.8 * 10^{--4}$
Gradient Stability (Beam Pulsed Mode)	3%	3%	3%	3%
Gradient Calibration			2% [2]	1% − 2% [3]
Gradient Resolution	10^{-4}	10^{-4}	10^{-4}	10^{-4}
Gradient Reproducibility	10^{-3}	10^{-3}	10^{-3}	10^{-3}
Phase Control Range (step size = 0.1^0)	$0 - 360^0$	$0 - 360^0$	$0 - 360^0$	$0 - 360^0$
rms Phase Stability(CW)	See Table 3.2b	See Table 3.2b	0.09^0	0.09^0
Phase Stability (Beam Pulsed Mode)	See Table 3.2b	See Table 3.2b	7%	
Phase Calibration[1]	2^0	2^0	2^0	2^0

(1) *With respect to the Master Oscillator.*
(2) *With beam, In the gradient range 8 MV/m to 12.5 MV/m. Without beam 10%*
(3) *In the gradient range 6 MV/m to 12.5 MV/m*

Table 3.2b

	Fast (< 1 sec)	***Slow (> 1 sec)***
rms Phase Stability (correlated)	0.24^o	infinite
Phase Stability (un−correlated)	0.5^o	3.0^o
Amplitude (correlated)	$2.2 * 10^{-5}$	
Amplitude (un−correlated)	$4.5 * 10^{-4}$	

Resonance Control

3.2.2 Autotune: The Low Level RF Control System shall be able to tune the cavity from at least 20 bandwidths away from resonance (one button action).

Speed: < 1 minute
Accuracy: within 3° of resonance

3.2.3 Manual tune: The Low Level RF Control System shall allow manual

a) stepping of the mechanical tuner (minimum step size 10 Hz) in both directions,
b) adjustment of the voltage of the Piezo tuner (minimum step size 2 Hz).

Loop Gain & Control

3.2.4 The Low Level RF Control System shall control loop gains, with a minimum step size of 1 dB. This applies to both gradient and phase control loops, whether implemented as separate loops or together as a single loop.

3.2.5 Variable loop filter, if implemented, shall be available to the operator.

Open Loop Operation

3.2.6 The Low Level RF Control System shall be able to control phase and amplitude in an open loop configuration with no feedback.

3.2.7 If the implementation uses two loops, the system shall allow the operator to turn off any one loop or both loops.

Pulse/Synch Input

3.2.8 The Low Level RF Control System should operate the accelerator in pulsed RF mode, in response to an input signal with the following characteristics.

Repetition rate: < 1 KHz
Duty Cycle: Variable 1 % − 100 %
Lock up time: < 250 msec
Open Loop Duty cycle: > 10 %
Input Impedance: 10 kW

Calibration

3.2.9 The detectors which measure the forward and reflected power shall have no more than 10 % deviation from each other.

3.3 Operational Requirements

Controls

3.3.1 The Low Level RF Control System's hardware shall interface to the Accelerator Control System's IOC (EPICS IOC).

3.3.2 Once started,

a. Losing EPICS communications shall NOT terminate the Low Level RF Control System operation.
b. Only interlock faults shall terminate the operation of the Low Level RF Control System.

3.3.3 The Low Level RF Control System shall have a heartbeat signal, the loss of which terminates the Low Level RF Control System operations.

Note: Termination of operation means the removal of all permits and drive signals. (refer to fig 3.2)

3.3.4 The Low Level RF Control System shall provide the following monitoring signals to the EPICS system.

a) Cavity Gradient (0.000 to 25.000 MV/m)
b) RMS noise on the Cavity Gradient
c) Gradient Error FFT (0 to 100 kHz, 16000 points)
d) Cavity Phase (0.0^o to 360.0^o)
e) RMS noise on the Cavity Phase
f) Phase Error FFT (0 to 100 kHz, 16000 points)
g) Cavity Detuning Angle/Frequency (degrees/Hz)
h) Q_{ext} of the cavity
i) Clipping and Railing of Control Loops
j) Gradient Drive Signal
k) Phase Drive Signal
l) Forward Power to the Cavity(0.00 to 10.00 kW, 10 W resolution)
m) Reflected Power from the cavity(0.00 to 20.00 kW, 10 W resolution)
n) Read backs from the mechanical and piezo tuners. (resolution step size quivalent of 100 Hz for the mecahnica tuner and 2Hz for the piezo tuner)

3.3.5 The Low Level RF Control System shall respond to the following control signals from the EPICS system.

a) Turn RF On/Off
b) Bypass a selected cavity
c) Bypass a selected cryomodule
d) Bypass a selected zone.
e) Amplifier Permit: On/Off
f) CPS Permit: On/Off
g) Gradient Set point: 0.000 to 25.000 MV/m (resolution?)
h) Phase Set point: 0.0^o to 360.0^o, continuous (0.1^0)
i) Gain Controls: 0 to 100 dB, increments of 1.0 dB

j) Loop Filter Controls: 0.1 Hz to 1 kHz (if implemented)
k) Loop Controls: Open/Closed (both loops)
l) Open Loop Gradient Control: 0 to 8 kW for each cavity (can be arbitrary i.e. 0.0 to 10.00 vdc)
m) Open Loop Phase Control: 0.00º to 360.00º, continuous (0.1^0)
n) Autotune: Automode or Manual mode
o) Mechanical Tuner Controls: Step size, speed.
p) Piezo Tuner Controls: Voltage

Interfaces

3.3.6 The Low Level RF Control System shall adjust the cavity gradient in response to an input signal from the Fast Feedback System. This signal has the following characteristics.

Bandwidth: 1 MHz
Voltage: −10 to 10 Vdc, corresponding to gradient adjustment of −2 MV/m to +2 MV/m from the set point.
Input Impedance: 10 kW

3.3.7 The Low Level RF Control System shall output a signal to support feed forward compensation. This signal shall have the following characteristics.

Bandwidth: 1 MHz
Voltage: −10 to 10 Vdc, corresponding to gradient adjustment of −2 MV/m to +2 MV/m from the set point.
Input Impedance: 10 kW

3.3.8 The Low Level RF Control System shall interface to the HPA/CPS system, using the signals in Figure 3.2.

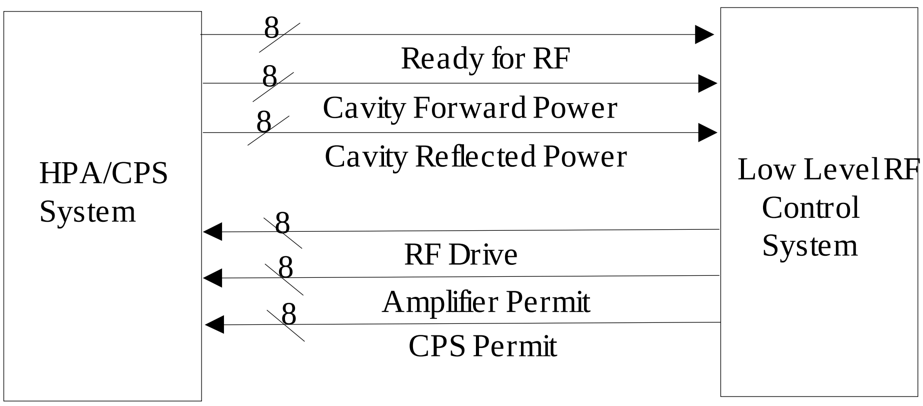

Figure 3.2

Ready for RF: Indicates HPA/CPS System's status
Cavity Forward Power: One RF signal for each klystron/cavity. Cable is ¼ inch heliax
Cavity Reflected Power: One RF signal for each klystron/cavity. Cable is ¼ inch heliax
RF Drive: RF input to the (2.5W) 5 Watt amplifier. There will be one signal for each klystron/cavity. Cable is ¼ inch heliax

Amplifier Permit: This is a permit signal to each individual 5 watt amplifier. Removing the permit interrupts the DC power to the 5 watt amplifier.
CPS Permit: This signal enables the CPS to go to High Voltage ON. 8 outputs are summed to one input.

3.3.9 The Low Level RF Control System shall receive one Permissive per cryomodule in order to send RF power to the cavities.

3.3.10 The RF system shall send the following data to the Cryo Systems.

a) The RF heat load in watts for every cryomodule (better than 20% accuracy)
b) Additional data exchange TBD (e.g. Information from cryo systems such as liquid level).

3.3.11 The following data transmission options shall be available,

a) Selectable rate between 1 − 10 Hz
b) Transmission only on change of data.

3.3.12 The RF system should be compatible with the presently distributed frequencies (1427 Mhz, 70 Mhz, 10 Mhz).

3.4 Maintenance Requirements

3.4.1 The Low Level RF Control System shall store the state and history of the cavities on the occurrence of.

a) any fault
b) user provided TTL signal

3.4.2 The duration over which the system preserves the state and history of the cavities is user configurable from 0 − 10 msec.

3.4.3 The time resolution of the Data Acquisition shall be at least 1 ms.

3.4.4 The system shall be able to acquire user specified data on the cavities on software command.

3.4.5 It shall be possible to communicate with the Low Level RF Control System while the accelerator/FEL is in any PSS access.

3.5 Integration

Functional Integration

3.5.1 The Low Level RF Control System shall have separate inputs for accepting signals from fast feedback and fast forward systems.

3.5.2. The Low Level RF Control System shall interface to the existing HPA/CPS system as well as the upgraded HPA/CPS System.

Physical Integration

3.5.3 The Low Level RF Control System shall fit in the existing space in the Service Buildings.

3.5.4 The Low Level RF Control System shall use forced air cooling.

3.5.5 The Low Level RF control System shall use 120 VAC, 60 Hz, Single phase power.

3.6 System Safety Requirements

Equipment Protection

3.6.1 The Low Level RF Control System shall satisfy the Interlock requirements set in Table 3.3.

3.6.2 The Low Level RF Control System shall signal the EPICS system when the stepper motor of the mechanical tuner exceeds 50000 steps.

Table 3.3

Cause	*Maskable FSD*	*Response time*	*Notes*
CHL Permissive to the cryomodule.	See Notes	< 1 s.	Must be present to turns RF on to the cryomodule. Fault turns RF Off and generates FSD. If RF is already off, does not generate an FSD(1)
Cavity Forward Power exceeds TBD limit	Yes	< 100 ms.	Maskable during cavity tuning
Cavity gradient falls below TBD limit	Yes	< 100 ms.	Maskable during cavity tuning
Cavity Window Arcing	No	< 100 ms.	
Cavity Window Heating	Yes	< 1 s.	Maskable for high current Operations
Cavity Quench	No	< 100 ms.	

Cause	*Maskable FSD*	*Response time*	*Notes*
Cavity has Forward Power in HV state	Yes	< 1 s	The high voltage is on, but no RF drive from the Low Level RF Control System, in which case there should be not Forward Power.
Thermal Interlocks	No FSD	1 s.	There should be a warning when the air temperature in the exceeds 55^0 C

(1) Low Level RF Control System may generate FSD faults under certain conditions, e.g. Improperly bypassed cavity measuring beam induced power.

4.0 HPA/CPS System Requirements

4.1 Introduction

This section describes the requirements for the High Power RF Amplifier portion of the RF System Upgrade for Jlab's CEBAF and FEL accelerators. The High Power Amplifier drives the superconducting cavities which accelerate the electron beam. The main technical requirement for a High Power Amplifier is the need for eight, 8 kW, CW RF amplifiers operating at a frequency of 1497 MHz to drive a cryomodule. Input to the High Power section comes from the Low Level RF Control System. The eight outputs from the amplifier assembly drive the cavities in a cryomodule. An RF Amplifier (one zone) consists of two elements; a high voltage Cathode Power Supply, and eight Klystron amplifiers located in a common enclosure designated as the High Power Amplifier cabinet, or HPA.

For reasons of backward compatibility with existing RF system, the components of the upgraded RF system should use as much of the existing engineering and equipment as possible. The upgraded system will preserve the proven usefulness of the present system's modularity. Other considerations for the upgrade are the ease of maintenance, personnel training and reduction of spares inventory. These features combined with new technical requirements of the upgraded system will drive the HPA design.

The major design revisions will be in the controls interface and integration. Functional interfaces to other accelerator systems will stay unchanged.

The two major elements of the HPA system are the Cathode Power Supply (CPS) and the HPA. Each of the eight HPA amplifier output channels consist of two stages of amplification− a 5 Watt RF pre−amplifier stage and an 8 kW klystron stage. The HPA shall provide all support power supplies, controls, monitoring and interlocking required to operate the amplifier channels. Figure 4.1 shows the system block diagram of the HPA/CPS System.

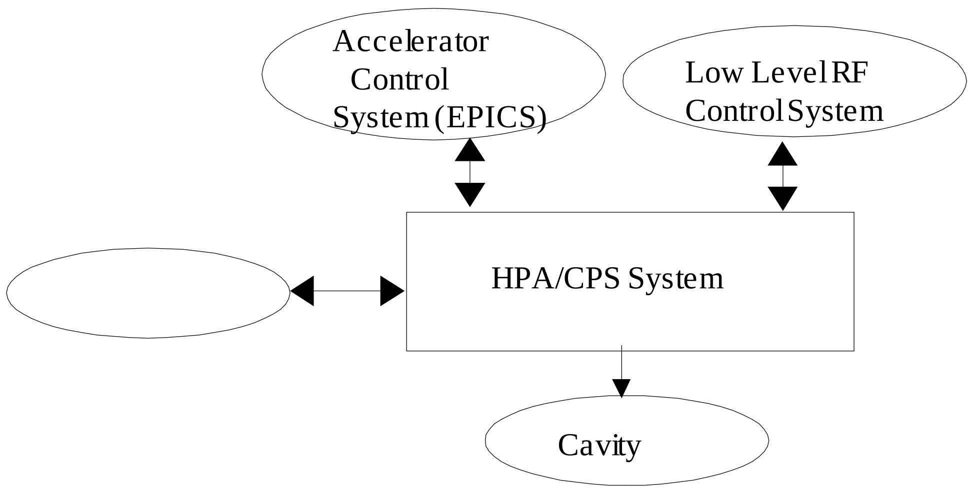

Figure 4.1

4.2 Cathode Power Supply

4.2.1 Performance Requirements

<u>*Outputs*</u>

4.2.1.1 The output of the CPS shall be a variable negative, DC voltage capable of simultaneously operating 8 klystron amplifiers at 8 kW (RF power) each.

4.2.1.2 The CPS shall optionally be able to operate each amplifier to 10 kW output. *Note: The actual CPS voltage and current needed will depend on the klystron chosen and its efficiency.*

4.2..1.3 Output voltage ripple shall be less than 0.1% of maximum full−scale voltage, peak to peak, at all output settings.

<u>*Reliability*</u>

4.2.1.4 The minimum MTBF of the CPS shall be greater than 50,000 hrs.

4.2.2 Operational Requirements

<u>*Control*</u>

4.2.2.1 It shall be possible to operate the CPS in either local or remote mode (selectable).

4.2.2.2 The output voltage from the CPS shall be adjustable both locally and remotely.

4.2.2.3 The 8 high voltage DC outputs shall each have an individually controlled connect/disconnect switch for each individual klystron.

4.2.2.4 The switch shall be able to isolate the output voltage from a klystron.

4.2.2.5 The switch shall be operable via local or remote control only when the CPS high voltage is off.

Note: The switch is not for isolation of high voltage for personnel safety purposes.

4.2.2.6 CPS On/Off/Reset functional control shall be available at the equipment location.

4.2.2.7 The CPS shall have an interface to the Accelerator control System (EPICS) to allow full functional remote control of On/Off/Reset operations.

4.2.3 Maintenance Requirements

4.2.3.1 The inside of the enclosure shall have internal lighting to facilitate easy visibility for inspection and repair.

4.2.3.2 The interior walls of the enclosure shall be white.

4.2.3.3 The CPS shall have local, stand−alone controls to facilitate commissioning, diagnostics and maintenance.

4.2.3.4 The CPS shall have provisions for monitoring and storing operational, fault and parameter history. *Note: The exact parameters are TBD at design time.*

4.2.3.5 Operation of the CPS in local mode shall not require the presence of Low Level RF Control system or communication to higher level controls (EPICS).

4.2.3.6 While in local mode, it shall not be possible to operate the CPS remotely.

4.2.3.7 Returning control to remote operation shall not change the CPS state or output voltage.

4.2.3.8 The CPS shall provide the capability for both remote and local monitoring of the status of interlocks and operational parameters.

4.2.3.9 On demand, CPS shall generate Miram curves to find the optimum filament voltages for a set of CPS voltage settings.

4.2.3.10 The CPS shall allows the user to monitor the magnitude of CPS voltage with an accuracy of 0.1%.

4.2.3.11 The CPS shall allow the user to monitor the ripple on the CPS voltage.

4.2.3.12 The CPS shall allow the user to monitor the CPS current with an accuracy of 1%.

4.2.4 Integration

Functional Integration

4.2.4.1 The CPS shall require a CPS Permit signal from the Low Level RF Control System in order to turn on.

4.2.4.2 There shall be 8 CPS permits per RF zone, corresponding to 8 cavities. *Note:The 8 permits may be summed to provide one CPS Enable.*

Physical Integration

4.2.4.3 AC input power shall be at 480 VAC, +/−10%, 3−phase, 60 Hz for generating the DC voltage.

4.2.4.4 AC input power shall be at 120 VAC single phase, 60 Hz for control, lighting and service power.

4.2.4.5 The design shall determine the use of Low Conductivity Water cooling. *Note: The characteristics of the LCW supply are: a) Supply pressure:125 PSIG, b) Return Pressure: 40 PSIG And c) Inlet temperature 35° C.*

4.2.4.6 The temperature rise of the out flowing LCW shall not exceed 15° C.

4.2.4.7 The LCW flow rate shall not exceed 10 GPM.

4.2.4.8 There shall be forced air cooling, which vents the heat to outside of the building.

Note: The power supply operates in the air−conditioned Linac equipment gallery. The nominal temperature is 25−35° C. Use of ducted outside air for cooling should be considered. Ambient outside air temperature is in the range –10 to +40° C with 10−90% relative humidity.

4.2.4.9 The CPS enclosure shall fit into a space of XxXxX, LxWxH.

4.2.4.10 It shall be possible to upgrade the existing RF zones to the new system zones without impacting equipment already in place. (Do we need this?)

4.2.5 System Safety Requirements

Equipment Protection

4.2.5.1 The CPS shall have an electronically triggered crowbar circuit on the output DC voltage to remove voltage from the klystrons under fault conditions. (< 10 microseconds or as determined to be required for klystron protection).

4.2.5.2 The following interlocks shall exist.

a) AC overload,
b) DC overload,
c) Phase Imbalance,
d) Temperature,
e) Air Flow,
f) Water Flow and
g) Over voltage.

Note: The design may implement additional interlocks.

4.2.5.3 Failure of any of the above interlocks shall generate an FSD fault.

4.2.5.3 Resetting the FSD fault shall require operator intervention.

<u>*Personnel Safety*</u>

4.2.5.4 The CPS shall turn on ONLY when the PSS system provides permit. (24 V loop? Or 625 Khz oscillation?)

4.2.5.5 Removal of the permit shall cause the CPS to turn off.

4.2.5.6 The CPS shall provide on/off status of the CPS to the PSS system for monitoring.

4.2.5.7 Access to the CPS shall be through doors on the front and rear.

4.2.5.8 All doors shall have interlocks which will remove high voltage and discharge stored energy when opened.

4.2.5.9 The CPS shall have an Emergency shutdown button that turns the high voltage power off and removes stored energy.

4.2.5.10 The CPS shall have UL approved grounding hooks at each access point for safely discharging any residual stored energy within the CPS.

4.2.5.11 The CPS shall not turn on when the ground hook is not in its proper place.

4.2.5.12 There shall be locally and remotely accessible indicators to inform whether the ground hook is in its proper place.

4.2.5.13 The AC Power distribution to the CPS shall have lockable disconnects conforming to Jlab's LOTO policies.

4.3 High Power Amplifier

4.3.1 Performance Requirements

<u>*Outputs*</u>

4.3.1.1 There shall be 8 independently controlled output channels in an HPA.

4.3.1.2 Each channel shall have an 8 kW RF output power capability.

4.3.1.3 The power gain shall be 35 dB, +/−3 dB at 1497 MHz

4.3.1.4 There shall be no modulating anode.

Note: The new RF system does not use modulating anode for reasons of reliability (The present system does). Older style klystrons will continue to power many RF zones for some time. Therefore at design time, it is necessary to evaluate the backward compatibility of the new HPA design and possible use of older tubes in new zones (or vice versa) and determine modulating anode support requirements. Specification Number HP002 shall be the basis for a new tube specification.

<u>*Reliability*</u>

4.3.1.4 The MTBF of the HPA shall be greater than 6000 hrs. (including klystron life time).

4.3.2 Operational Requirements

<u>*Control*</u>

4.3.2.1 The HPA shall provide the following RF monitors to the Low Level controls for each channel:

a) Cavity forward power and
b) Cavity reflected power.

4.3.2.2 The HPA shall provide the the above signals to the Accelerator Control System (EPICS).

4.3.2.3 The HPA shall have an interface to the Accelerator Control System (EPICS) to allow full functional remote control of On/Off/Reset operations.

4.3.2.4 The HPA shall have both local and remote control modes(selectable).

4.3.2.5 The HPA shall have remote controls to allow

a) setting,
b) controlling.
c) reading out of all parameters and
d) trip limits.
that facilitate commissioning and diagnosis of problems.

4.3.2.6 Selecting local control mode shall inhibit remote control of the HPA.

4.3.2.7 Selecting local control mode shall not affect remote status monitoring.

4.3.2.8 Selection of the remote control mode shall disable local controls.

4.3.2.9 Selecting remote control mode shall not affect local status monitoring.

4.3.2.10 Once started, the loss of communications with the Accelerator Control System (EPICS) should not cause the HPA/CPS System to cease operations.

Interfaces

4..3.2.11 Output waveguide from the HPA shall be WR650.

4.3.2.12 There shall be the following interconnections between the Low Level RF Control System and the HPA:

a) RF Drive – This signal shall be the output of the Low Level RF Control System and the RF input to the 5 Watt amplifier. There shall be one signal for each klystron/cavity. Cable shall be ¼ inch heliax.

b) CRFP− Cavity forward power signal to Low Level RF Control System. There shall be one RF signal for each klystron/cavity. Cable shall be ¼ inch heliax.

c) CRRP− Cavity reflected power signal to Low Level RF Control System. There shall be one RF signal for each klystron/cavity. Cable shall be ¼ inch heliax.

d) Amplifier Permit – This shall be a permit signal, that originates in the Low Level RF Control System, to each individual 5 watt amplifier. Removing the permit shall interrupt the DC power to the 5 Watt amplifier.

Note:4.3.2.12 is a repetition of Requirement 3.3.8

4.3.2.13 The HPA shall connect to the CPS output voltage through a UL rated HV cable connection.

4.3.3 Maintenance Requirements

4.3.3.1 There shall be a non−interlocked section of the HPA cabinet containing all hardware that does not require high voltage isolation for personnel for safety reasons. This shall include the 5 Watt amplifiers and other interlocks for utilities such as water, air, or waveguide pressure.

4.3.3.2 Field replaceable parts should have easy access such that they do not require disassembly of other power supply components to allow service or removal.

4.3.3.3 The HPA shall have local controls to allow

a) setting

b) controlling
c) reading out of all parameters
d) trip limits.
that facilitate commissioning and diagnosis of problems.

4.3.3.4 The HPA shall have a local diagnostic capability that allows the automated performance of

a) calibration measurements
b) data logging
c) fault logging
e) or other diagnostic functions as determined to be needed, during the system design.

4.3.3.5 The diagnostic capability shall be available via both local and remote control.

4.3.3.6 The state of the HPA and the states of all interlocks that can inhibit operation shall be available locally.

4.3.3.7 The state of the HPA and the states of all interlocks that can inhibit operation shall be available remotely.

4.3.3.8 Local monitoring of important analog values shall be provided as determined necessary by the design.

4.3.3.9 Read back of the power output of the 5 W amplifier shall be available (accuracy of 0.1%)

a) locally and

b) remotely.

4.3.3.10 Read back of the power output of the klystron shall be available (accuracy of 0.1%) remotely.

4.3.3.11 There should be an automatically kept record of the cumulative hours of operation of each klystron, even if a klystron's location changes.

4.3.3.12 The waveguide pressure reading shall be available remotely.

4.3.4 Integration

<u>Functional Integration</u>

4.3.4.1 RF input power to the 5 Watt amplifier shall be provided by the Low Level RF Control System.

Note: Specification Number xx defines the input requirements to the 5 Watt amplifier and the output requirements available to drive the klystron.

4.3.4.2 The 5 Watt amplifier shall have an output power monitor to verify proper operation.

4.3.4.3 The 5 Watt amplifier shall have an enable input to gate RF output power.

<u>*Physical Integration*</u>

<u>*Utilities*</u>

4.3.4.4 The HPA shall use 208 VAC, 3−phase and 120 VAC, single phase to derive all necessary control power.

4.3.4.5 The HPA shall use a klystron amplifier with the same form, fit and function as used in existing HPAs.

4.3.4.6 The HPA enclosure shall be the same size as the existing HPA enclosures

4.3.4.7 The waveguide shall use the existing tunnel penetrations to the cavities.

4.3.4.8 The HPA enclosure shall be the same size as the present enclosure (dimensions??)

4.3.4.9 For cooling, the HPA shall use Low Conductivity Water with the following characteristics.

a) Inlet temperature: 35° C
b) Supply pressure: 125 PSIG;
c) Return Pressure: approximately 40 PSIG.

4.3.4.10 The temperature rise of the out flowing LCW shall not exceed 15° C.

4.3.4.11 The LCW flow rate shall not exceed 70 GPM.

4.3.5 System Safety Requirements

<u>*Equipment Protection*</u>

4.3.5.1 There shall be an RF circulator and load to isolate the klystron from power reflected from the cavity.

4.3.5.2 The circulator load shall be capable of absorbing 8 kW of reflected RF power without damage.

4.3.5.3 The HPA shall use its reflected power signal to protect the klystron in case of an RF circulator failure.

4.3.5.3 Equipment protection interlocks shall take the state of the HPA to the lowest level consistent with the specific protection of the hardware.

4.3.5.4 Summed HPA interlocks, (as determined necessary by design), shall provide a CPS Permit.

4.3.5.5 There shall be filament interlocks to protect the klystron.

4.3.5.6 The interlock shall turn off the CPS and/or the filament power supply.

4.3.5.7 There shall be thermal (air temperature or other heat sink temperatures) interlocks to protect the HPA.

4.3.5.8 There shall be a reflected power interlock to protect the Klystron. The interlock shall inhibit RF power and/or high voltage.

4.3.5.9 A klystron body over current interlock shall inhibit the CPS.

4.3.5.10 A klystron cathode over current shall inhibit the CPS

4.3.5.11 A water flow interlock shall protect the HPA against loss of cooling water flow.

Personnel Safety

4.3.5.11 The HPA design shall conform to the Jefferson Lab Personnel Safety System as defined in xxxxx

4.3.5.12 The AC Power distribution to the HPA shall have lockable disconnects conforming to Jlab's LOTO policies.

4.3.5.13 In order to ensure that the wave guides have no leaks, all waveguide shall be pressurized to approximately 1 PSIG with dry air or nitrogen.

4.3.5.14 There shall be a loss of pressure interlock signal to the PSS.

Note: The PSS will ensure neither beam generated RF nor klystron generated RF can be injected into an open waveguide, when this interlock fails.

4.3.5.15 The HPA shall have UL approved grounding hooks at each access point for safely discharging any stored energy

4.3.5.16 The HPA shall not turn on when the ground hook is not in its proper place.

4.3.5.17 There shall be locally and remotely accessible indicators to inform whether the ground hook is in its proper place.

4.3.5.18 Valves controlling LCW cooling shall be external to any high voltage compartment.

4.3.5.19 All doors shall have interlocks which will remove high voltage and discharge stored energy when opened.

5.0 Global System Requirements

5.1 Introduction

This section describes requirements that apply to the entire RF system upgrade including Jlab's safety standards and documentation.

5.2 Operational Requirements

Startup Time

5.2.1 From the time the operator starts the RF system, it shall not take more than 2 hrs. for the RF system to be ready for beam.

One Button Operation

5.2.2 Starting the RF system for

a) the entire accelerator.
b) any linac.
c) any cryomodule, or
d) any cavity
should require only one action from the operator (e.g. push button).

RF Fault Recovery

5.2.3 Automatic fault Recovery

5.2.4 The system shall have the capability of automatically resetting RF faults that trigger the FSD system trips (auto recovery).

5.2.5 The auto−recovery shall be an operator selectable option.

5.2.6 The default shall be manual reset of the FSD trip.

5.2.7 Every auto recoverable fault shall have a an operator settable limit associated with it.

5.2.8 Exceeding the auto recovery fault limit shall require operator intervention.

5.2.9 When auto recovery is active, the average time from a fault to the commencement of beam delivery shall not exceed 10 secs. (assumes that the cavity is in tune or not more than a few bandwidths away).

Controls

5.2.10 Loss of communications to the EPICS control system shall not cause the RF system to stop functioning or change state. (.i.e. The Low Level RF Control System and the HPA/CPS system shall continue functioning).

Availability

5.2.10 The availability, over one year, of the RF system for both CEBAF and FEL accelerators shall be at least 96%.

5.3 Maintenance Requirements

Documentation

5.3.1 The designers shall provide a complete set of documentation for the RF system. The documents are:

a) Design documents of RF controls including interfaces,
b) Design documents of HPA/CPS including interfaces,
c) Schematic drawings of all modules,
d) Users manuals for the RF System,
e) Troubleshooting guides for the RF system and modules.

5.3.2 The RF System documentation shall identify

a) the electrical hazards associated with the operation of the system.
b) the radiation hazards associated with the operation of the system.

5.3.3 The RF system documentation shall include SOPs for safe

a) troubleshooting of the system.
b) commissioning of the system.
c) maintenance of the system.

Controls

5.3.4 There shall be provisions to enable operation of portions of the HPA/CPS system, including full power RF output into waveguide shorts, without requiring the presence of the Low Level RF Control System.

5.4 Integration

Functional Integration

5.4.1 The upgraded RF system should run existing high level applications (e.g. LEM++).

5.5 System Safety Requirements

Safety Standards

5.5.1 The RF System must comply with Jefferson Lab's electrical safety policies. (Ref. Z, Chapter X, Section Y).

5.5.2 The RF System must comply with Jefferson Lab's Beam Containment Policy (Ref. Z, Chapter X, Section Y).

5.6 Security Requirements

5.6.1 The communication scheme shall implement security features to prevent unauthorized access to the RF controls.

6.0 Justifications for Requirements

6.1 User

Physics User: Beam Energy, Dynamic Range in Energy, Energy Spread

Rationale: The near term Institutional plan calls for a 12 GeV accelerator at 5.5 Passes. However, there still will be experiments at lower energies which demand the present machine's capabilities of energy spread and maximum current..
Source(s): Jefferson Lab Institutional Plan FY2000−2004, Physics Division
Traceable to:
Derivable(s): Accelerating Gradient, Gradient and Phase Control
Compatibility:
Conflicts:
Validated by Source(s):
History: Created on: Aug. 4, 2000 Revised:

Physics User: Beam Current, Beam Availability

Rationale: The beam dumps in the experimental halls limit the maximum current at any energy. Efficient Data taking requires that during scheduled operations, beam stays on for extended periods prior to a trip.
Source(s): Physics Division
Traceable to:
Derivable(s): MTBF of Low Level RF Control System and HPA/CPS system
Compatibility:
Conflicts:
Validated by Source(s):
History: Created on: Aug. 4, 2000 Revised:

FEL User:

See Appendix I: (Extracted from RF Requirements for the IR FEL Upgrade Project by Lia Merminga)

Appendix I: RF Requirements for the IR FEL Upgrade Project

1.0 Injector RF System

Energy Stability (rms) (4.4×10^{-4}): This is the amount of allowed jitter of the energy centroid. It is derived from the energy and timing jitter requirements at the wiggler, transported back to the injector. It is applicable for noise frequencies of 2 kHz.

Phase Stability (rms) (0.09º): The rms relative energy stability requirement at the wiggler of 4×10^{-4}, and the rms timing jitter requirement of $10^{-9}/f_m$ where f_m is the frequency of the noise, transported back to the injector, give a permissible phase 3 stability of 0.135 º for f_m = 2 kHz. Assuming that 2/3 of this value actually originates from the injector, we obtain the quoted value. The linac phase is assumed to be −10º.

Gradient Stability in Pulsed Mode (3%): Pulsed beam mode is used frequently during machine setup, and may also be used for pulsed lasing applications. The requirement on gradient stability in pulsed mode is driven by the RF fluctuations due to transient beam loading and the energy aperture of the beam transport to the linac. Given that the energy aperture from the injector to the linac is ±3%, voltage fluctuations should be within this range. For typical RF low−level parameters, 10 MV/m gradient and $Q_L=2\times10^6$, 1.875 mA average current in the macropulse causes $\Delta V/V \sim 3\times10^{-3}$. Therefore fluctuations due to average current as high as 10 mA are still within the energy aperture of the transport. However, if one requires that RF not occupy the entire aperture, then feedforward can be invoked to reduce the magnitude of the fluctuations both in gradient and phase.

Phase Stability in Pulsed Mode (±7º): This requirement is driven by the energy aperture of the transport to the linac (±3%) times the momentum compaction from the exit of the cryounit to the entrance of the linac, $M_{56}^{inj} = -0.13$ m.

Gradient Calibration (2% from 8 MV/m to 12.5 MV/m): This requirement is driven by the desire to set the overall energy to approximately 1% to ease the setup process, and allow for more accurate comparisons between machine performance and PARMELA simulations. ¾ Phase Calibration (2º w.r.t. MO): The only driver here is ease of operations.

Gradient Resolution (10^{-4}): Current specification.

Gradient Reproducibility (10^{-3}): Determined by operational convenience. Also magnets can be set to better than 10^{-3}.

Operating Range

Gradient (Cavity 4 Eacc=12.4 MV/m, Cavity 3 Eacc=9.55 MV/m): The IRFEL injector has been operating at these gradients. Below 8 MV/m RF specs may not be met.

Accelerating Phases(f_4=0º ± 0.1º, f_3=−20º ± 0.1º): The IRFEL injector has been operating at these phases, set by PARMELA simulations. Note that these phases are optimized for 60 pC per bunch and may be different at 135 pC/bunch.

Detuning Angle (δ_4=0º, δ_3=−34.2º): The existing tuning algorithm ensures the optimum tuning condition for off−crest operation, which for cavity 3 is at a detuning angle of − 34.2º. For bunches accelerated on or near the crest of the RF wave, the optimum power requirement occurs on resonance.

Accelerating System

Loaded Q of Cavities (Cavity 4 Q_L=1.4×10^6 , Cavity 3 Q_L=1.98×10^6): These are the measured values of the external Q's of the IRFEL injector cavities. They closely approximate the specification of 2×10^6 , which was derived as a result of an optimization with respect to beam loading of 5 mA and 100 Hz amplitude of microphonics. At 10 mA and 80 kW klystron power, the maximum amplitude of microphonics the cavities can handle with the present coupling is between 600 Hz and 700 Hz. If we were to reoptimize the coupling for maximum allowed microphonics, the optimum Q_L values would be 0.82×10^6 for cavity 4 and 0.42×10^6 for cavity 3, and the amplitude of the noise would be 710 Hz for cavity 4 and 1600 Hz for cavity 3. In both cavities these amounts of detuning correspond to about 40º of phase noise.5

External Q for Probe Coupler (5.2×10^{11}): It is determined by the need to direct 100 mW of power out of a cavity to the control module for measurement of gradient detector and other cavity signals. At a gradient of 10 MV/m, the value of Q of the probe is 5.2 ×10^{11} .

Microphonic Noise Level (Amplitude) (df = 600 Hz to 700 Hz): This requirement is based on the maximum amplitude of noise the present cavities with upgraded klystrons but existing coupling can tolerate. Microphonic noise has been measured in the IRFEL injector cavities to be about 1.5º which corresponds to 10 Hz for cavity 3 and 14 Hz for cavity 4. These measurements were taken with no beam. With cw beam in the cavities we expect higher noise levels because the HOM loads in the FEL cavities are directly connected to the shield and cryogenic flow through the shields may induce vibrations in the cavities. We plan to measure the magnitude of the noise as function of beam current, however our experience with the IRFEL is that microphonics has not been an operational problem.

2.0 Linac RF System

RF Control

Gradient Stability (rms) Steady−State (2.8×10^{-4}): It is determined by the energy jitter at the wiggler, and assumes 3.7×10^{-4} rms injector error. It also assumes that the remaining error, which is due to the linac RF, is split equally between phase and amplitude (with the appropriate weighting), and that errors are correlated.

Phase Stability (rms) (0.09º): It is calculated similarly to the gradient stability. Assumes that bunches in the linac are accelerated −10º off crest. Both specifications are valid for noise frequencies of 2 kHz.

Gradient Calibration (1% to 2% from 6 MV/m to 12.5 MV/m): This requirement is driven by the desire to set the overall energy to approximately 1%. It will also ease the setup process, and ensure that beam energy is within the energy aperture of the arc

(±5%).

Phase Calibration (2º w.r.t. MO): The only driver here is ease of operations.

Gradient Resolution (10^{-4}): Current specification.

Gradient Reproducibility (10^{-3}): Determined by operational convenience.

Operating Range

Gradient (6 MV/m to 12.5 MV/m): This is the range of required gradients in order to meet the total linac energy gain requirement of 150 MeV.8

Accelerating Phases (−10º for accelerating beam and 170º for decelerating beam): The accelerating phase is determined by longitudinal dynamics and set operationally by bunch length minimization at the wiggler and laser optimization. The decelerating phase is set so that the two beam current vectors cancel each other.

Detuning Angle(0º): In the energy recovery mode beam loading is ideally zero, and so is the detuning angle.

Accelerating System

Loaded Q of Cavities (Standard CEBAF cryomodule: 4×10^{6}, Upgrade cryomodule: 8×10^{6}): The arguments were presented earlier.

External Q for Probe Coupler (3.3×10^{11} to 1.1×10^{12}): It is determined by the need to direct 100 mW of power out of a cavity to the control module for measurement of probe and other cavity signals. For the standard CEBAF cavities at a gradient of 8 MV/m, the value of Q_{probe} is 3.3×10^{11} , and for 12.5 MV/m it is 8.1×10^{11} . For the CEBAF Upgrade 7−cell cavities at a gradient of 12.5 MV/m, $Q_{probe} = 1.1\times10^{12}$.

Microphonic Noise Level (Amplitude) (df=128 Hz for standard CEBAF cryomodule, 90 Hz for the Upgrade cryomodule): Arguments were presented above.

Lorentz Force Detuning (200 Hz): This requirement is based on operational experience with the IRFEL linac cavities. The measured Lorentz force coefficients in these cavities vary from −1.5 to −3.6 $Hz/(MV/m)^2$. Although smaller Lorentz force coefficients would definitely be desirable, at gradients varying from 8 MV/m to 11 MV/m, ponderomotive force detuning did not present an operational challenge. However, the combination of higher gradients, close to 12.5 MV/m, and narrower cavity bandwidths, will require attention.

Master Oscillator and Distribution

Frequency Stability (3.8×10^{8}): This is a top−level requirement. The optical cavity in an RF linac based FEL must have its round trip travel time precisely matched to the arrival time of the electron bunches so that the previously emitted bunches overlap the new electron bunches. This requirement imposes the constraint on the optical cavity length to remain constant to 1.2 µm peak to peak. The arrival time must be kept constant to the same precision. This implies that a change in the frequency of the pulses, df/f, must remain within 3.8×10^{8} . This level of accuracy is already achieved in the CEBAF master oscillator.

HOM Damping

Transverse Modes: Detailed studies of the effect of transverse Higher Order Modes on the beam stability depend on the accelerator parameters, and therefore are still in progress, however it is safe to say that transverse modes should be damped to Q's less than 10^6 , and possibly 10^4 , in order for multipass Beam Bunch breadUp threshold current to remain safely above the operating current.

Longitudinal Modes: The power that needs to be extracted per cavity, assuming a 7−cell cavity with loss factor equal to 13.6 V/pC [5], 135 pC/bunch and 10 mA is about 40 Watts.

Appendix II: Resonance Control for Super Conducting Cavities

1.0 Introduction

Resonance control for super conducting (sc) cavities is vastly different than for normal conducting cavities. Typically for normal conducting cavities a cooling water control loop is used to keep the cavity on resonance. The loop has a bandwidth of a few Hz and compares either the reflected power or transmitted power to the forward power. Given that Q_{ext} are typically between 10,000 and 100,000, bandwidths are large allowing the water control loop to be rather slow and coarse. In the case of the sc cavities they are kept at liquid He temperatures so it is not practicable to control resonance with temperature. In addition the large Q_{ext} (1 to 10 million +) does not lend itself to a coarse water control, a more precise form of control is needed. Resonance control has typically been accomplished by mechanically squeezing the cavities along the z−axis. In the case of CEBAF a stepper motor controls the cavity length and hence the resonance frequency. As Q_{ext} increases beyond 10 million then a faster more precise control is needed and this has been accomplished with magnitostrictive or Piezo electromechanical control in addition to the stepper motor.

Resonance control includes many different scenarios or exceptions depending on operations and fault conditions. Most of the time the cavity is operating and the stepper motor will need to be adjusted maybe 2 or 3 times a week and only a small amount (~100 Hz). If the cryogenic refrigerator faults then He bath pressure will change dramatically forcing the cavities resonance to change with it. In this case the cavity will need to be tuned possibly from as far away as the 5 kHz. A control system must be prepared to accommodate this happening approximately every 2 months. Lastly there are times when a cavity is tuned away from the master reference for operability reasons. In the final case the control system may not be able to bring it back to master reference and the cavity may have to be manually tuned.

2.0 Principle of Resonance Control

An accelerating cavity can be describe using a second order differential equation and in circuit theory is essentially an LRC circuit (L, inductance; R, Resistance; C, Capacitance). As with any LRC circuit it will have a frequency dependant transfer function (a comparison of the forward power to transmitted power of the cavity) where at some point that circuit/cavity resonates. This is at the point that the inductance and capacitance of the circuit cancel each other out and you are left with only the resistive losses. This is exactly analogous to the audio resonance that you may have experience in the shower that seems to become louder. Figure 1 shows the transfer function of an LRC circuit (cavity model) for phase. Notice how the phase goes from 90^o to 0^o at resonance and then to -90^o. For close in resonance control one simply needs to monitor the phase of the circuit/cavity and then adjust the cavity accordingly. The idea being to keep the cavity tuned around 0^o phase. The sign of the phase tells the controls which direction to tune. This method is fine for keeping the cavity on or near resonance (with in a bandwidth $\sim F_o/Q_{ext}$). Beyond a couple of bandwidths though the transmitted signal become small and the phase slope flattens out making it difficult to get accurate information concerning the distance from resonance.

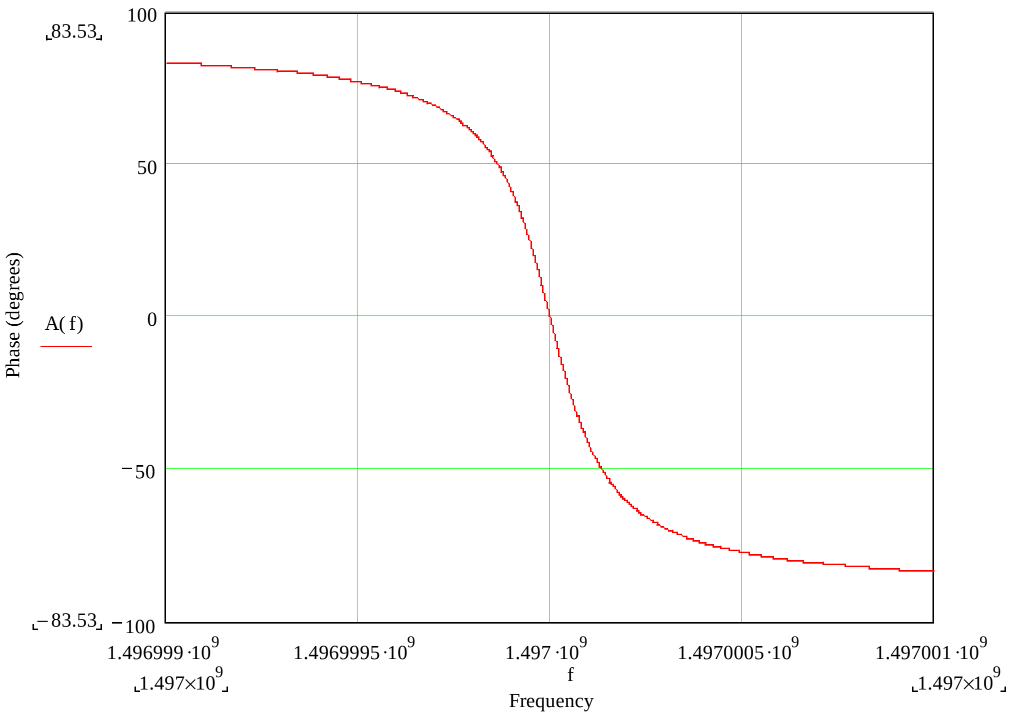

Figure 1 Cavity Transfer Function (Phase)

As stated above the present CEBAF system uses only a stepper motor to keep the cavity within 10 Hz of the master reference. For the energy upgrade cavity the Q_{ext} is a factor of three higher making the cavity more susceptible to detuning. In this case it has been proposed to use a Piezo tuner in conjunction with the stepper motor to keep the cavity within 1 Hz of the master reference.

To determine the resonance of a cavity that is well away from the master reference a different technique is used. The easiest method is to sweep a side band away (on both sides) from the master reference to determine the distance away. Another method is to generate a white noise and modulate the master reference in this way the resonance frequency can also be determined. Using these methods gives both the frequency delta from the master reference and the direction (above or below) or sign. This information is then given to the stepper motor and the cavity is tuned so many thousand steps back towards the reference. The process is repeated until the cavity is close enough to use the transfer measurement to maintain the resonance and round the master reference.

Lastly, a cavity can be tuned by manually using a network analyzer and sweeping the frequency to determine resonance. By locally controlling the stepper motor by hand and observing the transfer function displayed by the analyzer one can tune the cavity back to the master reference.

Appendix III: Evaluation of the Present System

The evaluation of the present RF system consists of an overview of the present system limitations, and an estimate of the needed modifications for the control of the new 7−cell cavities.

1.0 Present System Limitations

1.1 Lorentz Detuning

The 7−cell cavities will have bandwidths of ≃70 Hz. The Lorentz force on the cavity at 15 MV/m detunes the cavity up to 6 bandwidths away from resonance. The present RF systems cannot operate beyond 1 cavity bandwidth (hardware limitation). This is a problem when going quickly from zero gradient to full gradient in the cavity. Should the need arise for RF pulsed operation, this problem worsens (Low Level RF Control System Requirements 3.x.x).

Refer to section on Low Level RF Control System (Low Level RF Control System Requirements 3.x.x)for tuning.

1.2 Gradient Dynamic Range

The present system, designed for gradients of 10 MV/m may saturate when operating the 7−cell cavities, with a design gradient of 12.5 MV/m. (Low Level RF Control System Requirements 3.x.x. The 7−cell cavities are likely to sustain gradients well above the design specification of 12.5 MV/m).

At present, adding attenuation to the cavity probe cables has allowed operations above 10 MV/m. Unfortunately this solution has the drawback of not having constant gain over the gradient range. This results in poorly regulated cavity fields at lower gradient, which becomes a problem for low energy operations. (Physics User Requirements 2.x.x).

1.3 Piezo Tuner

The present system only supports a mechanical stepper motor tuner. The new cavities will have both a mechanical and Piezo tuner (Low Level RF Control System Requirements 3.x.x). This necessitates the development of an add−on subsystem.

1.4 System Flexibility

A major drawback of the present system is its inability to allow changes to some basic system concepts concerning feedback (e.g. self−excited loop), which will make it easier to operate the high gradient cavities.

1.5 HPA/CPS Control Interface

In the present system, the HPA/CPS interfaces to EPICS through the RF interface. This dependency hinders the stand alone commissioning and maintenance of the HPA/CPS Controls. (HPA/CPS System Requirements

4.x.x)

1.6 Control System Interface

The present system's interface to the control system satisfies Low Level RF Control System Requirement 3.x.x through a CAMAC interface. This interface is neither direct nor robust and definitely needs a redesign for a system whose lifetime should be longer than 10 years.

1.7 Maintenance

The present system uses custom in−house designed processor. The software maintenance of such a non−commercial component requires specialized talent and is not easily shareable among the general software population. (General Requirements 5.x.x Use commercial processors). The use of non−commercial components also requires specialization in hardware maintenance and demands talented labor.

The present system does not allow online maintenance. It is possible to bypass a cavity, but it is not possible to debug or repair the RF controls without removing the modules from the chassis (General Requirements 5.x.x).

1.7 System Life Span and Parts Availability

The present system is 10 years old and is rapidly approaching the middle of its useful design life span of 20 years. Parts for the system are becoming harder to find and consequently becoming expensive. This fact prompted a redesign of one sub−system, the RF Converter module, which reduced the component cost. It is possible to take a similar redesign of other sub−systems. Section 2 describes the costs associated with such an effort in detail.

2.0 Upgrading the Present RF Control Module for >12 MV/m Operation

There are eight hardware subsystems in the present RF control:

1. CAMAC crate controller and peripheral cards for tuners, ADC, DAC and digital input and output,
2. Interface chassis containing arc/IR detectors,
3. MOPS, multiple output power supply, which powers the RF control module,
4. CPU (i186 microprocessor) board,
5. I/O board containing ADC, DAC and digital in/out,
6. Analog board, controls feedback gains for phase and amplitude,
7. IF board provides signal processing for phase and amplitude and
8. RF Converter board

Each subsystem will reach its planned lifetime in the next five to ten years. Some of the sub−systems are complex, or obsolete and require modifications. Included in each modification assessment are estimated labor costs to upgrade a subsystem. Material costs for the upgrade will equal the manpower costs.

2.1 CAMAC and Peripheral Boards

a. Eliminate the indirect CAMAC interface to the control system,
b. Replace CAMAC peripheral boards (DAC, ADC, digital in/out) with VME substitutes
c. Design and implement Peizo controller (hardware and software).

Costs
NRE: 1 man−year

2.2 Multiple Output Power Supply

This is a simple but important system, which supplies dc to the RF control modules. It also powers the cryomodule heater resistors. This may need a minor redesign with more efficient switching power supplies.

Costs
NRE: 1/4 man−year

2.3 CPU board

There are two basic limitations in this module; 1. The communication interface is convoluted and 2. It has very limited memory(256 Kb?). Since the module resides in a custom back plane, it is not possible to buy a commercial unit. This is a major design task. (Low Level RF Control System Requirements 3.x.x, development environment)

Costs
NRE: 4 man−years

2.4 I/O Board

This board is the digital link to the rest of the control system. While redesigning the CPU board, it would be wise to upgrade this unit with more modern parts.

Costs
NRE: 3/4 man−year

2.5 Analog Board

The analog board is a tribute to what you can do with discrete analog IC's. It is an extremely complex system and is difficult to maintain. The module also contains a number of obsolete parts. The present module does not support feed−forward and RF pulsing (Low Level RF Control System Requirements 3.x.x and 3.x.x).

Costs
NRE: 1 man−year

2.6 IF Board

The IF board uses one multiplier (AD834) for most of the signal processing. It is still readily available and appears to be a mainstay for similar work for the next ten years. Since the time of the design of this board, (over 10 years ago), many IC vendors have designed signal−processing IC's that integrate into one IC the functionality that required multiple Ics on this board. A redesign with modern components will simplify the board and provide amplitude and gain control (Low Level RF Control System Requirements 3.x.x).

Costs
NRE: ½ man year

2.7 RF Converter Board

There is a new design of these sub−system using more modern and inexpensive components. One item that still needs upgrade is the RF detector/oven assembly.

Costs
NRE: was ~ 1/3 man year
New design reduced the cost by ~ $2000/board (It used to cost $3000, now it costs $1000 per board).

3.0 Conclusion

From the above sections, it is clear that the present system shall not meet the requirements for energy upgraded RF system without significant changes. We believe that it is better to invest the effort and expense in a new design that will meet the requirements set forth in this document than to modify the present system.

Appendix IV: Glossary and Acronyms

AES − Accelerator Electronics Support. A group whose primary function is to ensure that the accelerators operate smoothly by executing maintenance and preventive maintenance tasks.

Alarm − An indicator of device malfunction or misbehaviour that can lead to device failure. In the Accelerator Control System (EPICS), an alarm may be a visual or an audio indicator.

Alarm Handler − An Accelerator Control System (EPICS) program that fields and organizes the alarms generated in the accelerator.

Arc detector: A sensor that senses any photons in a normally dark confines area. Typically this can be a photo−multiplier tube or if less sensitivity is needed a photo−diode can be used. In Jlab system, this senses arcs between the warm and cold wave guide windows.

Autotune: An automated procedure that brings the cavity to resonance using the Low Level RF control system.

Bandwidth: The term used describe the pass band of an amplifier, control loop etc. Some times known as the 3 dB bandwidth, which is the ½ power point, in the system's transfer function.

Beam Availability − Experiments require a certain beam energy and current along with limits on the energy spread, current fluctuation and beam divergence. Beam availability means that the end user receives beam with the required attributes, with an effective duty factor > 90% averaged over 30 min. periods. For example, if beam with the required attributes was on for 25 mins and was off did not have the acceptable qualities for 5 mins, then the effective duty factor is 83 %.

Beam Loading: A term used in accelerator community to denote when an accelerating cavity is affected by the electron beam passing through it. Superconducting cavities can be heavily beam loaded because of their high Q_{ext} and low wall losses, but any cavity can become beam loaded given a large amount of current. In a beam loaded cavity a large portion of the forward power is consumed by the electron beam.

Body Current − Leakage current that flows on the body of the klystron. High body current can result in tube failure due to arcing or heating that causes the tube to fracture.

Bunch − A group of particles captured in a phase space area for acceleration.

Bunch length − The length in time of the bunch. For proper acceleration by a cavity, the head and tail of the bunch must arrive within a specified time of each other. (See longitudinal emittance)

CAMAC − Computer Assisted Measurement And Control. Modular Instrumentation standard for data acquisition (IEEE 583−1982)

Cathode Current − The klystron tube conduction current that originates from the tube cathode. The current is dependent on the filament setting and the tube characteristics.

Cathode Voltage − The high voltage applied to the cathode of a klystron.

Cavity bandwidth − The difference between the highest usable frequency and the lowest usable frequency of the device measured at half−power points. i.e. the 3dB bandwidth (1/2 power point) of a resonant cavity. Can be defined as $f_{bw} = f_r/Q_{ext}$, where f_r is the resonant frequency. For Jlab's 5−cell cavities, it is $1.5*10^9 /6.6*10^6 =$ 230 Hz. For the 7− cell cavities, this is = 70 Hz.

Cavity Bypassing − A mode in which a cavity and Low Level RF control system can be by passed and beam operated.

Cavity Cross talk: The electrical isolation between adjacent cavities. In CEBAF this is typically 60 dB at 1497 MHz.
Cavity Detuning: The act of detuning a cavity from resonance

Cavity Heater: A resistor that is placed in the cryomodule to keep the cryogenic losses constant as seen from the refrigerator. The goal is to balance the RF losses with the heater as the cavity gradients are changed

Cavity Probe: The small antenna that is located in the HOM arm of the cavity that is used to measure the transmitted power through the cavity. The probe signal is used in the feedback to control the cavity Field.

Cavity Quench − Cavity going from superconducting to normal conducting mode.

Cavity Vacuum: The vacuum in the cavity also beam line vacuum.

CEBAF − Continuous Electron Beam Accelerator Facility. Jefferson Laboratory's Accelerator for Research in Nuclear Physics. The accelerator provides continuous (as opposed to Pulsed) beams of electrons to three experimental halls. Presently, the beam current can range from a 100 pA to up 200 mA per experimental Hall and the beam energy can range from 500 MeV to 6 GeV.

CHL − Central Helium Liquifier − Jefferson Laboratory's cryogenics plant that provides liquid Helium at 2^0 K for the accelerator. The CHL also supports cryo target (Hydrogen and He) and superconducting magnets for the experimental halls through its auxiliary End Station Refrigerator(ESR).

Circulator − A three port RF device that protects the output of an amplifier (klystron) from damage caused by power reflected by the load. One port is an input from the amplifier; one port is an output to the load. Power reflected from the load/cavity returning to the output port is diverted to the third port. The third port is terminated with a load that absorbs the reflected power.

Clipping/Railing: When an analog signal is saturating an amplifier or other component in the signal chain. Typically the signal may look as if it has been "clipped".

Correlated/Uncorrelated errors: Correlated errors are perturbations that have a common source between cavities i.e 60 Hz line noise. Uncorrelated errors are errors between cavities that have nothing in common. Uncorrelated errors are easier to live with because they can be statistically small in a large number of similar systems i.e. accelerating cavities in a linac. Correlated errors are harder to minimize and can add in phase making them more difficult to reduce.

CPS − Cathode Power Supply. The high voltage DC power source used by the klystron amplifier. The klystron converts the DC power to an RF output.
CRFP − Acronym that stands for Cavity RF Forward Power. Represents the output power of the source (HPA) going into the cavity.

Crowbar − A fast shutdown mechanism for the Cathode power supply high voltage. Under certain klystron fault conditions it is necessary to remove the high voltage and stored energy from the CPS so that a high voltage arc is not sustained. A sustained arc can physically damage the tubes. The electronic crowbar circuit quickly (~ 10’s of microseconds) shorts out the high voltage and provides a discharge path for stored energy, thus protecting the tubes.

CRRP − Acronym that stands for Cavity RF Reverse Power. Represents the RF power reflected from the cavity and returning towards the source. The amount of reflected power is a function of the impedance match between the RF source (HPA) and load (cavity), the power losses in the cavity and the amount of RF power delivered to the accelerator electron beam.

Cryomodule: The structure that insulates the super conducting cavities from room air. Very similar to a thermos bottle using a vacuum space as the insulator.

Database − A collection of data with well defined formats and interfaces for its manipulation.

dBm: A unit of power commonly used in RF and microwave circles. 1 dBm = 1 mW.

DSP: Digital Signal Processor. A mircroprocessor whose instruction set and architecture are optimized for fast floating point multiplications and additions.

Energy Jitter − Deviation from energy centroid of the particle beam (see energy spread also)..

Energy Recovery −. Normally, unused beam deposits all its power in a beam dump. Energy recovery is technique to extract RF power from waste beam by decelerating the beam.

Energy Spread − The distribution of energies around a central value in a particle beam.

EPICS − Experimental Physics and Industrial Control System. Jefferson Laboratory’s control system for the two accelerators as well as the experimental halls.

Ethernet − Single wire (electrical or optical) interface whose protocol enables multiple intelligent devices to communicate among each other at 10, 100 or 1000 Mbits/se . (IEEE 802.3).

Fast Feedback − A system that keeps the accelerator energy constant within a part in 10000 by manipulating the gradient in the last cryomodule in the South Linac.

Fault/Trip − A state of a system that terminates normal operation. For example, a PSS fault terminates beam delivery.

Fault Logging − Recording, (usually by means of the control system), a fault and optionally relevant parameters that aid in system diagnosis.

Feed Back: The method of control that looks at an error signal in a closed loop system and corrects for the error. The most common example is a house thermostat that controls the temperature. When the temperature goes beyond a certain level the heater/AC is activated to bring the temperature back to the value.

Feed Forward: The method of control that anticipates an error and corrects for it. Typically used in pulsed machines where the gain and the bandwidth of a feedback system does not have the speed to correct for the initial turn on droop of the pulse. In this case the pulse duty cycle and amplitude are well known and the corresponding waveform can be summed into the feedback to reduce the turn on droop.

FEL − Free Electron Laser. Jefferson Laboratory's second accelerator that extracts tunable optical energy from accelerated high current (up to 10 mA) electron beam.

FFT (Fast Fourier Transform) − An algorithm to compute the Fourier Transform of a signal. Fourier Transform extracts frequency content of a signal.

Filaments − Part of the klystron tube structure which, when heated by applying a voltage, causes electron emission from the cathode. This electron emission becomes the tube conduction current when high voltage is applied between the tube cathode and anode. Proper operation of the filaments is fundamental to control and health of the klystron.

FSD − Fast Shut Down. A Machine Protection System signal, (either + 24 V or 5 Mhz), loss of which stops the electron beam production.

GASK/PASK: Acronyms for the present Low Level RF control system's gradient drive and phase drive signal respectively.

GSET/PSET: Acronyms for the present Low Level RF control system's gradient and phase set point respectively.

GPIB − General Purpose Instrumentation Bus(IEEE−488.2) used for computer control of multiple laboratory instruments.

GUI − Graphical User Interface − A user interface that allows interaction with the system via icons, radio buttons etc.

He Pressure − The pressure of liquid He in the cryomodule. The control system monitors the He pressure to determine the temperature of liquid He.

Heartbeat/watchdog − A periodic event that monitors a system's normal operation. For example, one may require that a CPU perform a specific operation once per second. If that operation does not successfully occur, it may be necessary to take action such as rebooting the CPU.

Heliax − A type of coaxial cable used for transmission of RF signals

High Level Apps − A set of programs that run on the Unix workstations of the control system that provide essential services. e.g. Keeping the electron orbits and energy stable.

Interlock − A measure whose purpose is to prevent damage to equipment or injury to personnel. Interlocks use Permissive to enable and disable operations.

IOC − Input Output Controller. In the EPICS control system, usually a VMEbus based microprocessor that communicates with the Unix processors and controls hardware devices.

I&Q: A method of recovering a signal by obtaining the in phase portion "I" and quadrature portion (90^o) "Q". It allows for a receiver to fully recover the signal with all of its components. Commonly used in communications. Mathematically it can be shown to be equivalent to phase and amplitude.

IR detector − Infra Red detector which detects the heating of the waveguide window at the cryomodule (see Waveguide window). In Jlab system, it observes the vacuum space between the warm and cold wave guide windows.

Klystron − An electron tube amplifier in which electron beam velocity variations in a resonant structure are converted to a Radio Frequency (RF) energy/field for transmission.

LCW − Low Conductivity Water. De−ionized water used for cooling electrical equipment that is energized and requires electrical isolation.

Lem++ − Linac Energy Management. A high level application that sets up the cavity gradients and a number of magnets in the accelerator to provide beam of required energy. The application also calculates heat loads in the cavities and manages a database.

Local Control − System Operation bypasses EPICS control system.

Longitudinal Emittance − A measure of beam energy spread in units of energy*time (eV.sec)

Long−term (> 1 sec) Field Stability (Phase and amplitude): The slow field stability requirement. Usually associated with cw electron accelerators. It is typically minimized using global feedback on a linac.

Lorentz Force: Force of interaction between the RF magnetic field and RF wall current in a cavity. This force shifts the cavity resonance frequency as a function of cavity gradient. The frequency shift typically goes as $Df = KV_c2$, where K is typically ~ 2 and V_c is the cavity gradient. For high gradient and high Q_{ext} cavities, the effect can be substantial; shifting the frequency by more than a few cavity bandwidths and making field control difficult.

Loop Filter: The pole in a feedback loop used to lock the loop and role the gain off. Typically this can be an integrator. In the case of Low Level RF control system, it is the superconducting cavity.

Loop gain: The gain within a feedback loop used to control an element some times known as the plant.

LOTO − Lock Out Tag Out. A safety procedure that prevents personal injury by locking out power source and tagging the lock with the name of the person who locked the power source. For example, a person servicing a high voltage power supply, will lock out the AC breaker that powers the power supply and keeps the key in his or her person. Jefferson Laboratory requires such persons to undergo LOTO training.

Master Oscillator: The master timing reference for the accelerator. All cavities are synchronized to this. At CEBAF and the FEL this is 1497 MHz.

MCC − Machine Control Center. The area from which a group of people operate both the CEBAF and FEL accelerators.

Mechanical Tuner: A tuner that is typically controlled with s stepper motor that lengthens and shortens the cavity to tune it. It has the ability to tune cavities beyond 100 kHz.

Microphonics − Low frequency (< 1 Khz) noise due to mechanical vibration. For example, a heavy truck passing by the area can generate microphonic noise and can move the cavity off resonance.

Miram Curves − A measurement performed on cathodes (tubes) for optimizing both lifetime and performance. The cathode heater/filament voltage is varied and the resulting cathode current is measured at different cathode operating voltages. The series of curves indicates the optimum heater/filament setting for each cathode voltage that provides for the maximum emission current from the cathode and hence output power capability while minimizing the cathode heating. Excessive cathode heating shortens tube lifetime without providing any additional output current.

Mixer: An RF component that allows for a higher frequency to be reduced to a lower frequency where signal processing can be performed.

Mod−anode − Modulating Anode, a control grid in the klystron that can be used to reduce the cathode current in order to control both the DC power consumed by the tube and limit the RF output power at constant input drive (gain control).

MPS (Machine Protection System) − Jefferson Laboratory’s equipment protection System to prevent damage to accelerator equipment from electron beam. The system turns off the electron beam when a potential for radiation exposure exists.

MTBF − Mean Time Between Failure.

Open Loop − When a system does not automatically correct for variation of output, it is an Open Loop system. (No feed back compensation).

Permissive/Permit − An interlock signal, whose presence permits the operation of a device. Lack of a permissive disables the device. For example, presence of PSS and permissives allows the electron gun to generate beam. Absence of any of these permissive prevents beam generation.

Phase imbalance − Refers to a protection circuit on a multiphase (3) AC power system. Power draw should normally be identical and symmetrical on all phases. An imbalance indicates a fault condition.

Piezo Tuner: A tuner that uses the electro−mechanical effect of a Piezo crystal to adjust the cavity length. Typically this may only have ~ 1 kHz of useable range. It can be relatively fast when compared to a stepper motor.

PPC − Power PC − A commercial family of microprocessors with a common instruction set. In the EPICS context, an IOC with such a microprocessor.

Pre−amp − Shortened term for Pre−amplifier. Usually an early or intermediate stage amplifier in a chain of amplifiers. In the case of an HPA, the 5 Watt driver amplifier in front of the klystron.

PSS (Personnel Safety System) − Jefferson Laboratory's Safety System which prevents exposure to the radiation from the electron beam. The system turns off the electron beam when a potential for radiation exposure exists. The PSS has the following states:
Restricted Access: Trained personnel may enter the accelerator tunnel and end station without the knowledge of the MCC crew chief. There is no beam or RF power.
Controlled Access: Trained personnel may enter the accelerator tunnel and end station only with the express knowledge of the MCC crew chief. There is no beam or RF power in the accessed areas..
Power Permit: The accelerator is preparing for beam operations. RF power may exist. No personnel access. There is no beam.
Beam Permit. The accelerator is ready for beam delivery. There may be beam in the machine. No personnel access.

Q_0 (intrinisic Quality Factor) – Ratio of stored energy to the power dissipated in a cavity. $Q_0 = w_0 U/P_c$; w_0 = 2p times the RF frequency, U = stored energy and P_c is the power dissipated in the cavity walls. The Quality factor of a resonant cavity is associated with the wall losses. For sc cavities these values are huge, ~ >10^9

Q_{ext} (external Q) – "External" Quality Factor for the RF input coupler. In analogy with Q_0, $Q_{ext} = w_0 U/P_e$, where P_e is the power loss through the input coupler.

Q_L (loaded Q) – "Loaded" Quality Factor of the cavity takes into account all rf couplers to the cavity $1/Q_L = 1/Q_0 + 1/Q_e + \ldots$
Q_L/Q_{ext}: The Quality factor associated with the coupling to the cavity. Typically for sc cavities these values are much larger, ~10^6, than normal conducting cavities, ~10^4.

Quench detector: A method of determining if the sc cavity has quenched by looking at the rate of rise of the klystron drive signal. Typically in a quench situation the cavity is horribly detuned causing the drive signal to increase very quickly to compensate of the detuning.

Remote Control − System Operation through EPICS control system.

RF Control Module: A subsection of the present Low Level RF (LLRF) control system that performs many of the field control, resonance control, and interlock and HPA functions. The present system is made up of five boards located in 6u euro−crate.

RMS Field Stability (Phase and amplitude) < 1 sec: The minimum residual rms. field stability required by the accelerator to meet beam specifications. Most notably this would affect energy jitter of the accelerated beam.

Rs (Shunt Impedance) − Shunt impedance of the cavity is a useful term in describing its efficiency as an accelerating cavity. The shunt impedance can be calculated from the geometric properties of the cavity. It is most useful when determining the accelerating voltage across the gap of the cavity that the accelerating particle would see/feel. Note the greater the shunt impedance the larger the beam loading will be. The ratio of the square of accelerating voltage on the cavity to the Power dissipated in the cavity. (V_C^2/P_C).

SC − Superconducting. A property of materials, normally at low temperatures, to offer virtually zero resistance to electric current.

Serial Interface − Any of EIA−232 (RS−232), EIA−485 (RS−485), USB (Universal Serial bus), Firewire or similar interfaces that transmit data bit serially.

Self Excited Loop: A method of feedback control which uses an unstable positive feedback loop that is referenced to a master oscillator. The loop by itself is similar to an oscillator built around a tank circuit where in this case the tank is the sc cavity. This method has great advantages for cavities that have relatively high Q_{ext} and large turn transients.

VME − Versa Module Europa. An industry standard commercial bus for microprocessors. (IEEE 1014−1987)

Warning − An indication of abnormal system functioning, which does not terminate operations, but draws attention to potential problems that may eventually cause down time.

Wave guide: A structure that is used to deliver microwaves to a cavity or other structure such as an antenna. Typically it is rectangular and looks very much like HVAC duct work!

Wave guide vacuum: The vacuum space between the warm window and the cold window in the CEBAF five cell cavities. This will go away in the seven cell cavities and the vacuum will be shared with the beam line and cavity.
Wave guide window: A window that separates a vacuum area from atmosphere or a pressurized wave guide.

Appendix V: References